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Quantitative Models in OPERATIONS AND SUPPLY CHAIN MANAGEMENT

PHI

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QUANTITATIVE MODELS IN OPERATIONS AND SUPPLY CHAIN MANAGEMENT
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Preface

About fifteen years ago, when I started teaching Operations Management to undergraduate students, I faced the difficulty of identifying a textbook from which I could teach the subject. I could neither get a book to my satisfaction nor suggest an affordable book to my students. Today, however, many popular foreign books are available in Indian reprint for graduate students, particularly the MBA students. Very good books written by Indian authors are also available for the benefit of MBA students.

Then why do we need another book on this subject? Is it because I have added supply chain management to the title? Or, is it because of the quantitative emphasis that I have tried to provide in this book? Or, is it because I believe in a more quantitative approach to the subject? Or, is there a real need for a book that starts with principles of operations management and leads to a more complex subject of supply chain management?

When I started teaching Supply Chain Management (SCM) in 2002 to MBA students, I again faced the problem of identifying a textbook for the subject for my own benefit and for use by my students. I spent the first two years teaching the course in a more qualitative and descriptive manner and later shifted to a more quantitative approach since most of the students had a background in engineering (and science). I could understand the importance of quantitative models and the need to highlight the concepts in SCM from an understanding of the basics of operations management.

The three major activities that constitute an effective supply chain management are manufacturing, distribution, and information technology. Topics from operations management and operations research are central to the understanding and appreciation of the decision-making processes in SCM. Hence this book that addresses largely the quantitative models in operations and supply chain management.

This book has a quantitative bias, as the name suggests. It is meant to understand the models used in decision-making in operations and supply chain management. It is primarily designed for the students of mechanical and industrial engineering. Besides, the book will also be the useful to postgraduate students of management.

G. Srinivasan

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Introduction to Operations and Supply Chain Management

■ Chapter Topics ■

- Changing Customer
- Requirements of Manufacturing
- History of Manufacturing Systems
- Improvements Based on Manufacturing Methodologies
- Improvements Based on Human Resources and Processes
- Methodologies Based on Information Systems and Decisions
- Improvements to Business Performance
- Synchronous Manufacturing (SM)
- Agility Principles
- Supply Chain Management
- Logistics
- Bullwhip Effect
- Role of Manufacturing and Operations Management

The volumes and variety of manufactured products have increased considerably in the last two decades. Today, manufacturing organizations should have the capability to produce a large variety of products in smaller lots and volumes so that the customer demand can be met. Manufacturing organizations have been applying several tools, techniques and methodologies to help them optimize their costs and profits to achieve customer satisfaction.

Consider yourself wishing to buy a mobile phone. You are aware of several models from different manufacturers that are available in the market. You can identify and see your choice of the product through the internet. When you go to a nearby retailer to buy the equipment of your choice, you want it to be available in the store. Many times you confirm if the product is available before you even go to the shop simply because you want it then and there.

Assume that the retail store deals with products from five manufacturers and has a total of fifty or more models at a time. It is necessary for the retailer to have exactly the same model from the manufacturer that you have asked. Otherwise, the retailer loses the profit as well as the goodwill because a customer has been lost. The retailer would also incur inventory cost for the items that have not been sold. The retailer, therefore, should ensure that as much variety has to be available and should be replenished quickly so that the next customer leaves with the product of her (his) choice.

Consider the company that makes the mobile phones. It has to make a large variety of products because the customer of today wants to choose from a variety. These have to be produced in the right quantities and distributed to the various retailers so that the customer is able to buy the model of his choice. Also newer varieties have to be introduced so that the customer continues to buy the same product by changing the model more because it has become obsolete.

1.1 CHANGING CUSTOMER

Customer preferences and approach to buying have changed. The customer was once satisfied with a "black car" because that was the only car available, when the customer wanted to buy a car. The customer was initially not worried about variety, but wanted volume and availability simply because he wanted to buy. It was also true that these decisions were governed by the limitations of manufacturing, which did not gear itself to handle variety.

Once manufacturing met the requirement by producing large quantities, both manufacturing and the customer wanted variety. This was necessary because when the customer went to buy the product a second time, he did not want to buy the same model. Manufacturing systems geared themselves to provide variety. The type of manufacturing moved from product-based manufacturing to process-based manufacturing. The layouts and other production requirements changed to meet this requirement.

Along with volume and variety, cost was of concern to the customer because the product has to be affordable. The emphasis was more on minimizing the cost of the product so that more people can buy. Manufacturing systems started using concepts and techniques of optimization so that cost can be minimized. This led to the development of various qualitative and quantitative models for cost minimization. With the advent of computers and tools of operations research this could be addressed significantly.

The next emphasis was on quality. Aspects such as performance, after sale service, life of the product, warranties, etc. had to be looked into because these became the differentiators in a more competitive and intense market. Manufacturing organizations concentrated on these aspects. Quality Control systems and Quality Management systems were introduced such that quality became a way of life in manufacturing. Customer requirements related to quality were met.

The customer next wanted new products to be available. This not only is an offshoot of the requirements to increase variety, but also to meet the need for better and newer products with more features for the same price. A typical example would be to have mobile phones with features such as storage, text messaging, music, camera and e-mail facility. Newer products provide additional features that make the product compact, versatile and flexible. Manufacturing systems geared themselves to meet this requirement also.

The present day customer wants all the above aspects such as volume variety, cost, quality and new products. In addition the customer is impatient and wants very quick delivery at the preferred time of the customer. This has been necessitated due to the changes in the size and structure of families. This poses the additional requirement that manufacturing has to combine with distribution to ensure that the products are sold and delivered exactly as the customer requires. The customer also wants product knowledge and the businesses have started customizing products using data from choices and preferences of customers.

1.2 REQUIREMENTS OF MANUFACTURING

Manufacturing systems produce a variety of products that can be sold to customers. The purpose of existence of these organizations is to make money (Goldratt, 1983). Organizations make their money and stay in the business by manufacturing a product or by providing a service to the customer. Today, the customer is the most important person in an organization, which survives by satisfying the requirements and wants of the customer profitably for both.

Today's customer requirements are to have products with

- High volume
- Large variety
- Less cost
- High quality
- New products
- Quick delivery

Manufacturing systems have to be designed and equipped to meet these requirements. The requirements of manufacturing as defined by Skinner (1985) are:

> *Make an increasing variety of products, on shorter lead times with smaller runs and flawless quality. Improve ROI by automating and introducing new technology in process and materials so that price can be reduced to meet local and foreign competition. Mechanize, but keep schedules flexible, inventories low, capital costs minimal and workforce contented.*

Skinner's definition, though about two decades old, clearly establishes the requirements of manufacturing. It addresses all the customer requirements in terms of volume, variety, cost, quality and new products. Since it only looks at the manufacturing processes and systems, it does not add the requirements of distribution, which is equally important in today's context.

Skinner's definition also addresses the requirements of manufacturing systems and methodologies that have evolved (or necessary) to meet the challenges of manufacturing.

Before we define supply chain management and its features, let us trace some aspects of history of manufacturing systems and the traditional methodologies that were used. We will also trace the advancements in manufacturing methods and their characteristic features.

1.3 HISTORY OF MANUFACTURING SYSTEMS

One could start this discussion with the realization of the need and desirability of a factory system involving capital and labour. This was the contribution of Adam Smith. This was made possible by the invention of the steam engine by James Watt in 1764, where for the first time man could convert one form of energy into another and one form of motion to another, and understood the importance and versatility of rotary motion. The industrial revolution happened in the nineteenth century and manufacturing systems and factories were established. The era of scientific revolution happened in the first-half of the twentieth century.

Dale Carnegie is credited with introducing scale in manufacturing industry with the introduction of steel plants. The Steel Industry was credited with a large stable output. It also started the concept of cost control to increase profits.

The principles of scientific management were enunciated by F.W. Taylor in 1910. Taylor is also called the Father of Scientific Management, after whom the principles of scientific management and industrial engineering started. The focus here was on bringing efficiency into the manufacturing systems. The standard of performance was benchmarked against the best performing worker. The approach followed was the carrot and stick, where the worker who is fast and efficient was rewarded, while the inefficient was discharged. This stick approach was subsequently modified by Gantt, where the inefficient were expected to perform at a minimum acceptable level, while the efficient workers got a bonus.

The next important contribution is from Gantt, where the focus was on providing a chart to represent the time table of a schedule in a pictorial way. Emerson, who is credited with creating dispatching rules in scheduling also agreed on the modification to the carrot and stick approach.

Franklin and Lilian Gilbreth created the concept of motion study and incorporated the human aspects of work study.

Perhaps the most significant contribution was from Henry Ford, who concentrated on speed and efficiency. He believed in taking the work to the man and not man to the work. The Ford production system did not concentrate on variety.

Traditional manufacturing systems used continuous production systems when the volume was high and batch manufacturing systems when the variety increased. The product or line layout was used for continuous manufacturing and the process layout was used for batch manufacturing. Figure 1.1 shows the various types of production systems depending on volume and variety.

The early twentieth century was the era of Industrial Engineering. With the advent of computers and management science techniques (operations research tools), the decade of the 1950s onwards saw the extensive use of optimization and computers in the management of manufacturing systems. The 1970s onwards saw the advancements in manufacturing methodologies and technologies with the introduction of cellular and flexible manufacturing systems, and automation. The decade of the 1980s onwards saw the emphasis on quality with quality control being changed to total quality management with focus on employee empowerment and quality management systems. Meanwhile production control methods such as just-in-time manufacturing systems and synchronous manufacturing were introduced in 1962 and 1983 respectively.

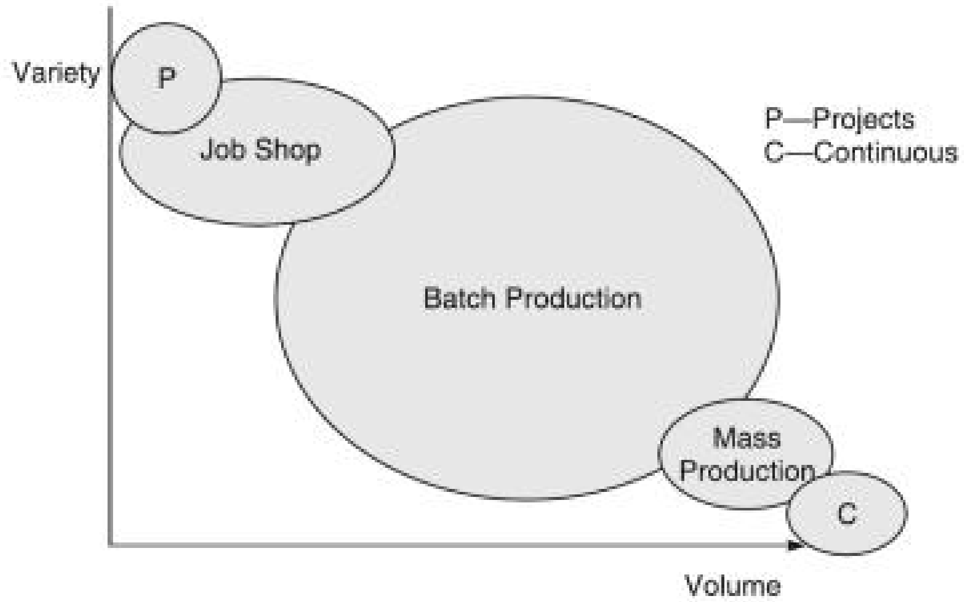

Figure 1.1 Different types of production systems.

Since the early 1990s and in the last few years, the emphasis has shifted to combining manufacturing and distribution into a single entity for analysis and performance excellence. This is possible with the advent of enterprise resources planning systems and principles of supply chain management. The present era of knowledge and data management along with the supply chain management practices helps organizations in achieving the requirements of manufacturing, distribution and service.

1.4 IMPROVEMENTS BASED ON MANUFACTURING METHODOLOGIES

Though several improvements and changes in manufacturing methods came about, we will briefly mention three important changes that have taken place over the years. These are cellular manufacturing, just-in-time manufacturing and flexible manufacturing.

As already mentioned, process and product layouts were used for batch and continuous type manufacturing depending on volume and variety. Most manufacturing systems involved production of several parts that are assembled into the final product. This meant that process layout with functional specialization was used extensively. The process layout concentrated on pooling of similar resources to minimize cost by maximizing utilization of resources. Here, the parts move from one department to another. Quality was inspected between the various stages of the manufacturing process.

The process layout also called functional layout has several disadvantages. There was a lot of material movement among the departments and this increased the unproductive time in the system. The set-up and changeover times in between processes were large because consecutive parts produced on a machine was dissimilar. Since set-up times were large, batch sizes were large increasing the inventory in the system. When defects were observed, the entire batch had to be reworked increasing the time taken to produce the products. Scheduling the operations were complex and time-consuming, and non-availability of machines and ineffective scheduling increased the waiting time for the parts in front of the machines.

It is also necessary that in order to meet the increased variety of products, the time taken to manufacture should be reduced. Lesser time in the system would also reduce the cost of making the products, which would increase the profit to the organization.

To reduce the production times and production costs, it was necessary to try and change the manufacturing system that can handle middle volume and variety. It was also observed that the functional specialization concentrated on ownership of the processes, while the ownership and responsibility for the product was missing.

Burbidge (1963) is credited with the concept of Group Technology or Cellular Manufacturing, though others earlier had mentioned the possibility moving into simpler systems. The fundamental principle behind Group Technology is that *similar "things" should be done similarly*. Similar things would include product design, process planning, fabrication and assembly, production control and administrative functions. In cellular manufacturing, we divide the manufacturing facility into small groups or cells of machines. *Here machines are grouped into cells and parts into families such that the parts are manufactured completely within the assigned cells.*

Figure 1.2(a) shows a schematic representation of a functional layout.

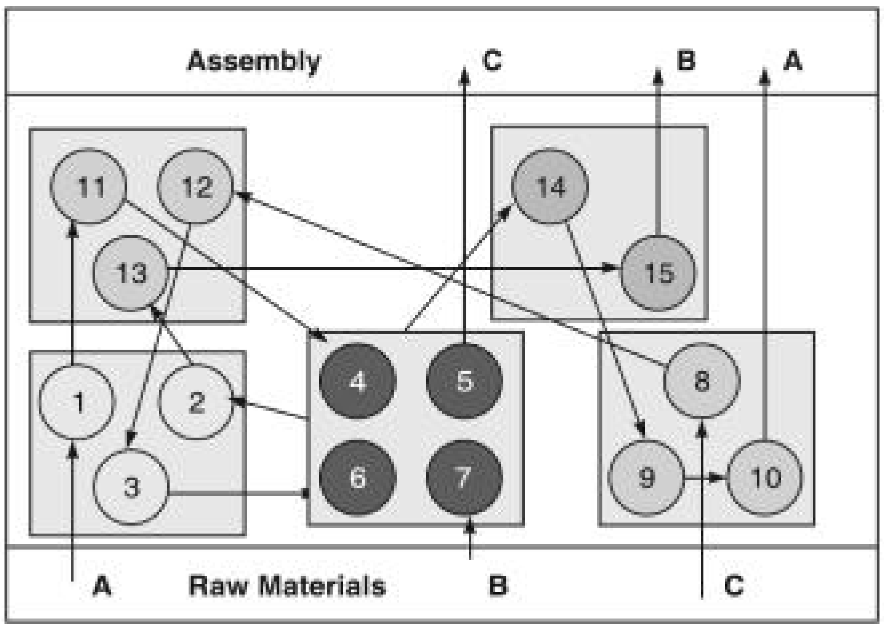

Figure 1.2(a) Functional layout.

Figure 1.2(b) shows a schematic representation of a cellular layout.

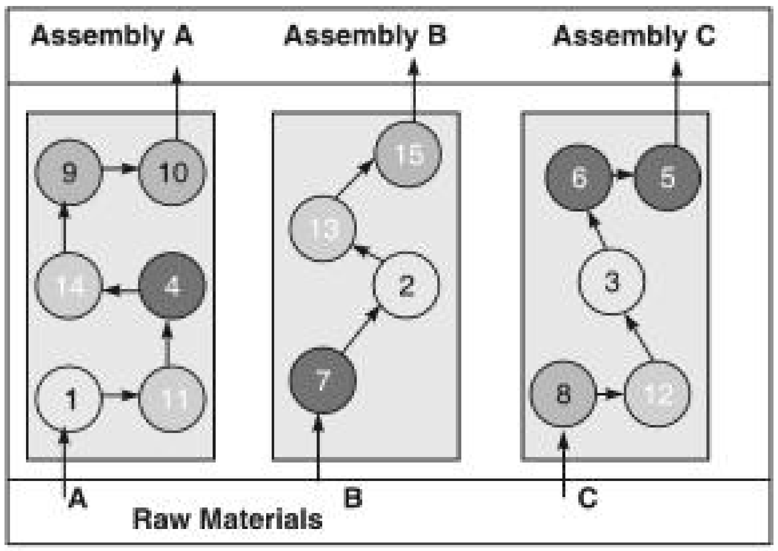

Figure 1.2(b) Cellular layout.

In Figure 1.2(a), machines 1, 2 and 3 are similar and belong to one department. In Figure 1.2(b), machines 1, 4, 9, 10, 11 and 14 are functionally dissimilar, but are grouped together based on the manufacturing requirement of a part family that has a group of parts all made in this machine cell.

The advantages of cellular manufacturing include reduced material handling time, reduced changeover times, better quality and better throughput, less space and above all increased ownership and responsibility. This is because the cell is completely responsible for all the parts made within. Disadvantages could be increased number of machines, less machine utilization, inability to address fluctuating demands and sudden increase in demand and less flexibility.

Organizations that implemented cellular manufacturing observed that the advantages far outweighed the disadvantages. They reported a set-up time reduction of 41%, throughput time reduction of 24% and an increase in number of machines 10%.

The Toyota Production System was started in 1962 in the Toyota Motor Company and is the starting point of what is called Just-in-Time Manufacturing (JIT) systems. JIT is a manufacturing system where the goal is to optimize processes and procedures by continuously pursuing waste reduction. Waste is anything other than the *minimum* amount of equipment, materials, parts, space, and worker's time, which are absolutely essential to *add value* to the product.

JIT is a philosophy of manufacturing based on planned elimination of all waste and continuous improvement of productivity. The primary elements of JIT are to have only the required inventory; to improve quality to zero defects; to reduce lead times by reducing set-up times, queue lengths and batch sizes; to improve the operations themselves; and to accomplish these at minimum cost. In the broad sense, it can be applied to all forms of manufacturing including job shop and repetitive. Along with JIT came the production control method called kanban where the desired inventory is released into the system using containers and cards. Through these methods organizations adopted the policy of "make daily–sell daily".

Organizations implementing JIT reported set-up time reduction of 20%, finished goods inventory reduction of 30%, scrap reduction of 20%, and work in progress inventory of over 50%.

Potential benefits of JIT include reduced inventory, improved quality, lower costs, reduced space requirements, shorter lead time, increased productivity, greater flexibility, better relations with suppliers, simplified scheduling and control activities, increased capacity, better use of human resources and more product variety.

Flexible Manufacturing System (FMS) is a manufacturing philosophy based on the concept of effectively controlling material flow through a network of versatile production stations using an efficient and versatile material handling and storage systems. Each workstation in an FMS is capable of processing a variety of part types with relatively small change over times.

There are several advantages in using FMSs over conventional manufacturing systems. Because of the inherent flexibility, meeting demand fluctuations or changes in product mix is a simple matter of readjusting part routing and adjusting workstation capability. Market competitiveness is enhanced by the shorter lead times. Because of reduction of set-up times, delivery times have been reduced. There is also a significant reduction in WIP inventory and the corresponding reduction in floor space and carrying costs. Automation of work cells and elimination of human handling results in better quality. Since the entire production organization is structured, it is also easier to have better real time control.

Organizations are increasingly using FMSs fully or partly in situations where there is a very large variety and high volume. Products involving mass customization such as electronics goods are produced using this type of manufacturing system. Here the accuracy is high, production time is faster and ability to increase variety is high.

Among other things production systems have started using automation and computer-integrated manufacturing systems in addition to the above-mentioned methodologies and technologies.

1.5 IMPROVEMENTS BASED ON HUMAN RESOURCES AND PROCESSES

Organizations started concentrating on quality and the human aspects by which quality can be improved. Here, we will restrict ourselves to Total Quality Management and Quality Management Systems.

As mentioned earlier, quality was restricted to inspection and quality control. When the defects increased, quality control tools were used to measure whether the processes were under control. With increasing emphasis on quality, the quality control techniques were replaced by quality management methods.

Total Quality Management (TQM) is defined as an approach of an organization centred on quality based on participation of all its members and aiming at long-term success through customer satisfaction, and benefits to all members of the organization and to society. TQM is based on continuous improvement and involves a cultural change.

Traditional definitions of quality such as "fitness for purpose" and "conformance to specifications" were replaced by definitions that concentrated more on the customer. ISO 8402–1994 defined quality as, "the totality of characteristics of an entity that bear on its ability to satisfy the stated and implied needs of the customer". A more recent definition of quality is that it is the "ability of a set of inherent characteristic of a product, system or process to fulfill requirements of customers and other interested parties".

TQM implementation would involve the organization and its top management to:

- Develop deep understanding and conviction that quality is important.
- Develop a vision and promote it.
- Set clear directions based on data and analysis.
- Practice QC way of thinking.
- Provide continuing education for all.
- Ensure participation.

Organizations started defining their vision (long-term goals), mission (purpose of existence), quality policy (ways to achieve the vision and mission) and core values and started synchronizing the goals of the individuals towards the goal of the organization.

Organizations also started implementing practices such as quality circles, kaizen, and suggestion schemes such that there is participation and involvement from all the people including the operators.

Organizations also started developing quality management systems that led to ISO 9000 certification. These certifications represented the commitment of the organization towards quality and helped in getting more business. Subsequently, these have become a minimum requirement than a competitive advantage and organizations started to look at other techniques as competitive advantage in the market.

Apart from showing their commitment to quality, organizations today show their commitment to environment, health and safety of employees, social accountability and responsibility by creating and implementing management systems for each of these. Organizations adopt green practices through which they also strive to protect and preserve the environment.

1.6 METHODOLOGIES BASED ON INFORMATION SYSTEMS AND DECISIONS

The earliest application of information in improving the manufacturing processes was the Materials Requirement Planning (MRP) software. The Bill of Materials (BOM) was computerized using this software and this resulted in consistency in BOM. Purchasing decisions could be linked once the BOM was computerized. Once the demand for the end products was known, demands for all items could be computed and lot sizes for ordering items could be computed and implemented. This, along with efficient manufacturing and production control methods also helped organizations moving towards pull systems from traditional push systems. The MRP systems helped in significant inventory reduction and also reduced errors in planning and control because of the computerization. MRP systems were expanded to include capacity planning and resulted in Manufacturing Resources Planning (MRP II) systems.

Enterprise Resources Planning (ERP) was a logical extension of MRP systems, where all aspects of the organization or enterprise were integrated into a large information system. The ERP systems integrated the various functions of the organizations such as finance, human resources, marketing, maintenance, purchase, stock, production planning, etc. There is also another school of thought that ERP is not a logical extension of MRP, but a full-fledged approach in its own right. The ERP systems are expensive and require a long period before the benefits can be realized. Organizations that have spent the money and have waited till they have yielded results have benefited immensely by using these systems.

One of the gains that came along with the ERP systems was the concept of e-commerce. Purchasing systems that were part of the ERP systems could be integrated with customers so that businesses could be carried out electronically. The entire purchasing systems, tender systems and auction systems changed with the implementation of electronic commerce practices. Reverse auctions, where the lowest bidder gets the order, are carried out in real time and are replacing traditional tender systems. Electronic business also enables the customers in being able to know the status of their orders.

Retail businesses use Customer Relationship Management (CRM) techniques where customers order items that are delivered at home. The CRM systems provide information about the demand for the various items and imitate real time shopping electronically.

Lastly and most importantly, organizations use supply chain management tools and methods in their decision-making. These systems integrate production and distribution decisions.

We will describe supply chain management in detail in the next section. Before doing so, we will also describe certain newer practices that are used to improve business performance by organizations.

1.7 IMPROVEMENTS TO BUSINESS PERFORMANCE

Business Process Reengineering (BPR) was introduced by Michael Hammer and James Champy. BPR can be defined as, "the FUNDAMENTAL rethinking and RADICAL redesign of business PROCESSES to achieve DRAMATIC improvements in critical, contemporary measures of performance, such as cost, quality, service, and speed" It is more than automation but, has a strong automation and information technology component in it.

The method suggests that we must examine the "root" of business processes, structures, and policies. It recommends not modifying old processes to meet newer requirements but to cast away the old processes and begin anew. It recommends rethinking rather than only change. Reengineering is reinvention and not modification or enhancement.

BPR is not aimed at small, incremental improvements. It seeks order of magnitude improvements in cost, quality, service, and speed and uses information technology to assist in these.

It is not like redecorating an existing house. It is like demolishing it and reconstructing it all over again. It can be viewed as a one change method and not as a continuous improvement technique. It involves both cultural and structural changes in an organization.

BPR becomes necessary because organizations are tending to be virtual. Most sales and purchases have become computerized at IT-enabled. In any virtual organization, there are three important aspects to be considered:

1. Customers take charge and are well informed.
2. Competition intensifies and technology creates opportunity for competition.
3. Change becomes constant due to increased need for new products and reduced time in developing these.

Companies practicing BPR concentrate on mass customization and are well equipped to handle change. Competition also forces organizations to look at practices in a radically different way.

Electronic commerce, smart cards, CRM websites, online educational portals, ATMs are some examples that can be considered as processes and procedures that are radical and dramatic in nature.

1.8 SYNCHRONOUS MANUFACTURING (SM)

This approach was first introduced by Goldratt (1984) in his book "The Goal". He defines that the goal of every organization is "to make money both now and in the future". The measures of performance are defined in accordance with the goal of the organization. These definitions are:

1. **Throughput:** Quantity of money generated by a firm through sales over a period of time.
2. **Inventory:** Quantity of money invested in materials that the firm intends to sell.
3. **Operating expenses:** Quantity of money spent by the firm to convert inventory to throughput over a period of time.

In these definitions, it may be noted that finished goods are not taken into account as throughput, WIP has no value addition and all value additions are taken as operating expenses.

1.8.1 Statistical Fluctuations and Random Events

Random events are those activities that take place at irregular time intervals and disrupt production. Examples are non-availability of raw materials, manpower, machinery, etc. Random events can be introduced into the process from many sources and the element of uncertainty and disruptiveness caused by them cannot be completely eliminated. In manufacturing context, statistical fluctuations refer to the concept that all processes have a certain degree of inherent variability in any system. While statistical fluctuations may be predictable to a certain extent, they introduce certain instability to the process. Examples could be delay from an otherwise reliable supplier, time to set up equipment, time to produce, etc.

These fluctuations and uncertainties result in throughput time increasing beyond the target time. Usual planning and scheduling methodologies do not take care of these to the extent required. Buffers are the only known alternatives to take care of these effects, but buffers in front of all resources will only increase the WIP and hence cost.

The production process can effectively be compared with the troop of marching soldiers. Initially, the pace is even, but as time progresses due to fluctuations, the gap between rows increases. The slowest person in any row decides the pace of the row and since rows cannot pass each other, the gaps can only widen and rows do not come closer. This example helps in understanding several principles in manufacturing.

The lead time is the time between the first and last soldiers in the forced march. In manufacturing, lead time is the time between the release of material and the transformation of these into finished goods. In production process, any material processed by some facility but not by others is called work in process inventory. In the marching analogy, any distance covered by some and not covered by others is inventory. This is the gap between the successive persons in the march analogy. In manufacturing, throughput is the amount of product produced and sold. In the marching analogy, it is the distance covered by the last row of soldiers. Operating expense is the amount of energy spent by the soldiers in completing the march.

The simultaneous presence of statistical fluctuations and dependent events has a serious consequence on the manufacturing operations. Because of the existence of dependent events, the statistical fluctuations do not average out. The negative variances accumulate and disrupt the planned flow.

1.8.2 Principles in Synchronous Manufacturing

Given the inherent nature of resources, it may not be possible to balance the capacity of the resources in plant. Such a balance would be counterproductive and will result in excess inventory. Two types of resources may be identified. These are called bottlenecks and non-bottlenecks. Bottlenecks are those resources which have to be utilized fully, while non-bottlenecks have excess capacity.

SM 1: Do not focus on balancing capacities, focus on balancing the flow.

Bottleneck: Any resource whose capacity is less than or equal to the demand placed on it.

Idle time: Time not used for set-up or processing.

Waste time: Time spent on processing materials that cannot be converted to throughput.

At a bottleneck resource (X), all the time available should be used in set-up or production. Lost time in bottleneck is time lost in production for the entire plant. It is necessary to reduce number of changeovers in bottleneck machines and work with buffers so that production increases.

Non-bottlenecks (Y) have more capacity than demand. Time gained in these does not contribute much and are in fact idle times.

SM 2: Marginal value of time at a bottleneck resource is equal to the throughput of the product.

SM 3: Marginal value of time at a non-bottleneck is negligible.

SM 4: Level of utilization of a non-bottleneck resource is controlled by other constraints in the system.

SM 5: Resources should be utilized and not simply activated. Activation refers to employment of a resource to process material, while utilization is activation that increases throughput.

1.8.3 Capacity Constrained Resource (CCR)

Any resource which if not properly scheduled and managed is likely to cause the actual flow of the product through the plant to deviate from the planned product flow. A CCR may or may not be a bottleneck.

1.8.4 A Systematic Approach to Improve Performance

It is necessary to understand the role of constraints in system performance and to build logically a framework for improving the system performance. Goldratt suggested a five-step approach, which is given below:

1. Identify the constraints in the system.
2. Determine how to exploit the constraints to improve the performance.
3. Subordinate all the parts of the manufacturing system to support step 2.
4. Carry out steps necessary to improve the performance of the system.
5. If in the previous step, a constraint has been broken and a new constraint develops, go to step 1.

The above five-step approach emphasizes the fact that there are only a few constraints that primarily limit the firm's performance at any given time. This approach also provides a basic structure that can be used to implement synchronous manufacturing.

It is necessary to obtain a single unit flow in manufacturing where every piece moves to the next machine immediately after completion in a machine. If this is not possible, small batches are to be produced and transported. The production batch size can be more than the transfer batch size so that material is fed continuously.

SM 6: Transfer batch need not and should not be equal to process batch.

SM 7: Process batch should be variable along its route and over time.

It may be observed that the transfer batch is similar to the transportation kanban in the just-in-time (JIT) environment and some of the ideas are common to both JIT and SM. It may be noted that JIT is ideal for repetitive manufacturing, while SM can be used anywhere. JIT solves problems as they come, while SM plans and eliminates problems.

Synchronous Manufacturing is an all encompassing management philosophy that includes a consistent set of principles, procedures and techniques where every action is evaluated in terms of the common goal of the organization.

SM is a currently evolving manufacturing philosophy that is being practiced by many industries. An appropriate combination of SM, JIT and MRP will help organizations in achieving their ultimate goal.

1.9 AGILITY PRINCIPLES

The concept of agile manufacturing was coined to look beyond current best practice towards the enterprise of the future.

Agility is being used as an all in one phrase to describe the various changes and ideas being promoted, such as lean production, business process re-engineering, time compression and so on.

Agility is a dynamic, context-specific, aggressively changed embracing and growth-oriented concept. It is about succeeding and about winning profits, market share and customers in the very centre of competitive storms that many companies now fear. (Goldman, Nagel and Preiss, 1995).

Agility is the capability of an organization to respond rapidly and effectively to unanticipated opportunities and to proactively developed solutions for potential needs. It is the result of an organization and the people who comprise it working together in ways which benefit the individual, the organization, and their customers.

The important principles in agility are

- Enriching the customer
- Leveraging human resources
- Cooperate to compete
- Create virtual organizations

Organizations are increasingly practicing agility principles to make themselves more competitive and customer oriented.

1.10 SUPPLY CHAIN MANAGEMENT

Cost, quality, delivery and flexibility were the traditional requirements from the products of a firm. The firm leveraged on one of them, mostly at the expense of the others. Trade-offs were made in achieving the objectives of the firm. If a company competed on flexibility and quality, cost was of secondary concern. Customers were willing to pay a premium price.

The quality revolution in 1980s changed the thinking process and flawless quality was required at extremely competitive prices for all products. Quality became a necessary instrument for survival than a competitive advantage. Today, most organizations do not try to use quality as a unique selling point, but as a necessary condition for survival. They make sure that quality is flawless, well documented and recognized by their customers.

To meet the customer expectations, manufacturing has to reorient itself. The requirements of manufacturing as defined by Skinner (1985) are given under Section 1.2.

In the context of customer expectations, and the corresponding requirements of manufacturing, organizations do not trade off one priority against another, but try to simultaneously prioritize all of them. Cost, flexibility, quality and delivery are not traded off against one another, but are simultaneously prioritized.

As discussed earlier, organizations adopted newer methodologies in achieving their objectives. Total Quality Management (TQM) helped organizations to achieve flawless quality. Flexible Manufacturing Systems (FMS) were used to achieve quick response, and provided the ability to produce large variety and high volumes if necessary. Just-in-time manufacturing gave focus on waste minimization, and production control. Lean manufacturing for low cost and ownership and responsibility to people and supply chain management to deliver products quickly with low inventories.

A supply chain is defined as a network of facilities and distribution options that performs the functions of procurement of materials, transformation of these materials into intermediate and finished products, and the distribution of these finished supply chain management (Lee and Billington, 1992).

A supply chain is the sequence or network organizations—their facilities, functions, and activities—that are involved in producing and delivering a product or service. The facilities in a supply chain are factories, warehouses, processing centres, distribution centres, retail outlets, offices, etc.

A typical supply chain would consist of three stages—purchase, production and distribution. Supply chains differ slightly between manufacturing and service. A typical supply chain for a manufacturer would start with the purchase and would have many storage points between purchasing, production and distribution. A typical supply chain for a service would involve purchase of spares, storage and the customer. Within a manufacturing system in an organization, we have material moving from one workplace to another. This is sometimes called an internal supply chain where every entity acts like a customer to the previous entity and as a supplier to the next entity.

Figure 1.3(a) shows the typical supply chain for manufacturing.

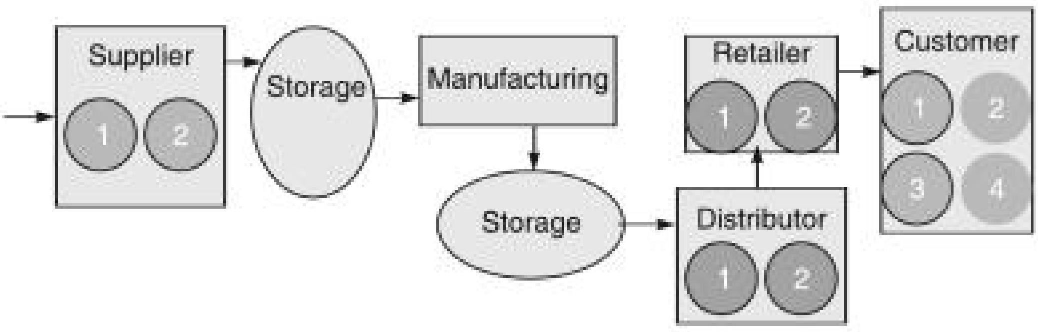

Figure 1.3(a) Supply chain for manufacturing.

Figure 1.3(b) shows the typical supply chain for service.

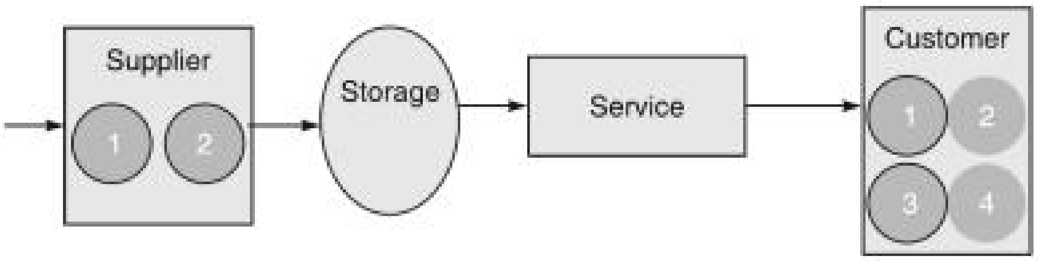

Figure 1.3(b) Supply chain for service.

Some of the reasons based on which organizations feel a need for supply chain management are:

1. Improve operations
2. Increasing levels of outsourcing
3. Increasing transportation costs
4. Competitive pressures
5. Increasing globalization
6. Increasing importance of e-commerce
7. Complexity of operations
8. Manage inventories

Most of the above reasons are self-explanatory. Increasing levels of outsourcing brings the need to manage the production and distribution. Increased variety of products also necessitates outsourcing. Increasing globalization makes new products available quickly and increases the varieties available for a product. The importance of e-commerce is significant because this forces speed into manufacturing and distribution. The customer is impatient and expects the good to be delivered quickly. This is largely because the customer gets used to the speed of electronic business.

Several organizations have benefited using supply chain management. The benefits are increase in inventory turnover rate due to less inventory in the system and less supply and distribution cost. These help in meeting customer expectations and increase the profits of the organization.

The elements in supply chain management in terms of facilities, systems and people are as follows:

1. Customer
2. Demand forecasting
3. Design
4. Manufacturing
5. Inventories
6. Distribution
7. Suppliers
8. Location
9. Logistics
10. Information technology

The customer is the most important person whose wants and requirements are met by the organization. We need forecasting and demand planning systems to understand what the customer wants in terms of variety, volume and new products. The suppliers provide the raw material to manufacture these products. The manufactured items have to be distributed efficiently to the retailers so that they are available to the customer. Sufficient inventories have to be available with every retailer to meet the fluctuating demand at high service level. The factories, warehouses and the retailers have to be located effectively to minimize costs and to maximize reach. Logistics support such as warehouses, packaging, kitting and returns management are to be made available and these functions have to be carried out at least cost quickly. Information technology provides access, information, knowledge and contents to the various players and more importantly the customer so that demand can be increased.

1.10.1 Supply Chain Decisions

The various decisions in supply chain management are classified (Ganeshan and Harrison, 1995) as:

1. Location decisions
2. Production decisions
3. Inventory decisions
4. Transportation decisions

These decisions are both qualitative and quantitative in nature and are addressed with both qualitative and quantitative models. This book aims at providing quantitative models to help effective decision-making in operations and supply chain management. We now proceed to detail the various decisions.

The location decisions are concerned with the geographic placement of production facilities, stocking points and sourcing points. These are strategic in nature and are usually solved through an optimization routine that considers production costs, taxes, duties, tariffs, distribution costs, production capacities, etc.

The important production decisions are what product to produce and which plants to produce them in. This involves allocation of suppliers to plants, plants to distribution centres, and distribution centres to customers. Production decisions also involve detailed production scheduling, construction of master production schedules, scheduling on machines, equipment maintenance, workload balancing and quality control. These decisions are tactical and operational in nature and are solved using a combination of optimization, simulation, empirical models and heuristics.

The inventory decisions include determining the amount of stock of raw material, semifinished and finished goods. They also address the quantities in process between locations. These inventories are aimed to provide buffers against any uncertainty. The inventory decisions are the control policies, optimal level of order quantities, reorder levels and safety stock levels at each location based on customer service levels. These decisions are tactical and are addressed using quantitative models ranging from deterministic to stochastic models.

The transportation decisions are largely the trading-off between the costs of transportation with the indirect cost of holding inventory. They also consider customer service levels, geographic locations and desired buffer and inventory levels. Transportation costs are found to be more than 30% of the logistics costs. Shipment sizes, routeing and scheduling of equipment are key factors that influence transportation decisions. These are tactical in nature and are solved using mathematical programming and heuristics.

Several questions have to be addressed in solving production and distribution planning problems in the context of decision-making in operations and supply chain management. These are:

- How many suppliers should be there for each category of items?
- What criteria are used in selection of suppliers?
- What is the volume and frequency of deliveries from each supplier?
- How many distribution centres to be operated and where should they be located?
- How much inventory to be held in intermediate distribution centres?
- What decisions should be used to control inventory in these centres?
- Which supplier supplies in what quantities to each distribution centre?
- What is the network configuration of the transformation process?
- Where should the transformation process be located?
- What effect do inventory practices of one plant have on other plants?
- What is the configuration of the distribution network?
- How are customer demands met?
- Are there intermediate stocking points?
- What is the aggregate capacity of the distribution centre?
- Which demands does each centre meet?
- What is the amount of inventory maintained at each centre?
- What is the inventory policy in each centre?

1.10.2 Purchasing in Supply Chain

Purchasing is an important task in the management of supply chains. This is due to increasing outsourcing, lean production and increasing globalization. More the outsourcing, more important is the purchase function. The number of suppliers also increases with increase in outsourcing. Lean production among other things, emphasizes the minimizing costs and the choice of good suppliers who can provide quality items at less cost is necessary. Increasing globalization brings more competition and variety and this results in the ability to identify suppliers for diverse products and are flexible with respect to changes in variety. It is also well known that about 60% of the cost is in raw materials bought through the purchasing function.

Some important tasks in purchasing include negotiation process with suppliers, contracts, identifying new suppliers, and administration of the supply process. A strategic partnership between buyer and supplier involves understanding demand uncertainty and understanding supply characteristics.

1.10.3 Electronic Commerce

Today, more and more organizations resort to electronic commerce (E-commerce) which is the use of electronic technology to facilitate business transactions. E-commerce applications include internet buying and selling, order and shipment tracking, electronic and data interchange. The advantages include improved competitiveness and quality, ability to collect and analyze customer buying patterns, reduced supply chain response time, etc.

Electronic purchasing systems have now replaced traditional systems. Online auctions and reverse auctions (where the price goes down and the lowest bidder gets the order) have replaced traditional tender-based systems. These systems provide unprecedented speed and reach to the purchasing process. The reach comes because the required item could be available in an organization that may not be in the same business and the speed comes from the internet and the instantaneous decision-making of the online auction systems. The process is also very transparent and hence is increasingly accepted by organizations. These have to be designed and operated in accordance with the regulatory requirements of the country.

1.10.4 Types of Supply Chain

Fisher (1997) categorized supply chains into two. These are:

1. Efficient supply chain
2. Responsive supply chain

The efficient supply chain is to be designed for functional products and responsive supply chain for innovative products. Fisher also stressed the need to understand the category of the product based on its characteristics and then decide the right kind of supply chain for the product.

Functional products have less forecast error, high product life cycles, less profit margins, higher volumes, less variety, less stock out and more production lead times. Innovative products have large forecast error, large margins, less volume, more variety and less production lead times. Efficient supply chains concentrate on cost minimization, while responsive supply chains concentrate more on meeting customer demand.

Efficient supply chains use continuous replenishment programmes for information sharing. They capture Point-of-Sale data for accurately and immediately updating forecast. The emphasis is more on in bound logistics and purchasing. They also concentrate more on the optimization and cost minimization of their operating processes and procedures. They also develop optimized inventory control mechanisms to accurately fix reorder points and order quantities.

Responsive supply chains accept uncertainty in demand and large forecast errors as reality and devise strategies for managing uncertainty. They try to improve responsiveness by cutting lead times, using postponement strategies and delayed differentiation. Manufacturing processes concentrate more on time reduction and variety so that more of customer demand is realized.

Both the supply chains concentrate on coordination with suppliers and customers, obtaining accurate and reliable data to be used in demand planning and on efficient manufacturing processes. All the principles of production/operations management are relevant. The only difference is the increased emphasis on cost minimization in efficient supply chains and responsiveness maximization in the responsive supply chains.

1.10.5 Supply Chain Metrics

The efficiency of a supply chain is measured through supply chain metrics. Depending on the type of supply chain and depending on the organization, the measures may be different. The important supply chain performance drivers are quality, cost, flexibility, speed and customer service. The metrics are used to measure these directly or indirectly. Commonly suggested and used metrics are:

1. On-time delivery
2. Order fulfillment lead time
3. Fill rate (fraction of demand met from stock)
4. Service level (perfect order fulfillment)
5. Supply chain management costs
6. Total inventory days of supply
7. Cash realization time
8. Value added per employee

1.11 LOGISTICS

Logistics refers to the movement of materials and information within a facility and to incoming and outgoing shipments of goods and materials. Logistics is an integral part of supply chain management and is invariably concerned with the distribution function and material movement. It includes transportation, warehousing, packaging, distribution planning and coordination, data exchange on material movement and position, tracking. Today's advanced logistics systems enable transportation of goods just-in-time so that excess inventory is reduced and transportation times are brought down to reduce production lead times. Logistics systems also used in facilitating electronic transfer of funds once the material is supplied. These result in improved control of operations, reduction in clerical labour, increased accuracy and efficient customer response.

Several advances have taken place in designing and executing efficient logistics systems. Depending on the product, shelf life and demand, organizations dispense with large warehouses and have resorted to milk runs where the products are exchanged without being stored. There is also more of cross docking where warehouses act only as docking areas and not as storage areas.

There are several challenges that have to be overcome to design and execute a good supply chain management system. Firstly, different organizations have to come together and work together. Usually, several barriers to integration of organizations exist and these have to be overcome. These barriers could in the form of size, culture, practices, trust, risk-taking ability, governance, ownership models, etc. In addition, top management of several organizations has to be on board, planning for the collective success as against success of the individual organization. There will be trade-offs, both short-term and long-term and organizations have to learn to deal with them. The sizes of the various organizations can be a significant factor and large companies should learn to work with smaller businesses that may not have the same electronic infrastructure as large organizations. Variability and uncertainty always pose challenges and organizations should learn to plan strategies to counter their effects. Finally, manufacturing being a time-consuming activity can result in long production lead times, which organizations have to reduce by working together and by supplementing resources.

Supply chain involves several trade-offs. Some of these are:

- Inventory–transportation costs
- Lead time–transportation costs
- Product variety–inventory

There is always a trade-off between inventory and transportation costs. When we want to reduce inventories by reducing the stock with the retailers, there has to be frequent replenishment. The quantity to be stocked will be more because of the loss of pooling synergy. The same can be said of transportation cost vs production cost. If we want smaller runs, the production and transportation costs increase, but, the inventory cost reduces and vice versa. The same is true of variety and inventory. More the variety more is the inventory for the same service level. The same is true of lot-size and inventory. More the variety less is the production lot-size. This increases the product changeover cost.

1.12 BULLWHIP EFFECT

One of the important aspects to be studied in supply chain management is called the bullwhip effect. Let us consider a serial supply chain consisting of supplier, manufacturing, warehouse, distribution centre and retailer. The retailer meets the end customer demand. The retailer while placing order with the distributor adds a buffer to the order quantity to take of fluctuations and uncertainty. This process of adding a buffer continues till manufacturing produces much more than actually demanded. The supplier produces and supplies more than what manufacturing requires and there is high inventory in the system. This keeps increasing as we move upstream in the supply chain. After a while when each entity understands that there is excess inventory, they reduce the ordering quantity. The inventory gradually reduces and redistributed itself into the downstream of the supply chain. This process of redistribution of the extra inventory fro upstream to downstream and back results in what is called **the bullwhip effect** because the inventory position resembles a bullwhip. Figure 1.4 shows the bullwhip effect. The inventory positions at any point in time are shown in the figure.

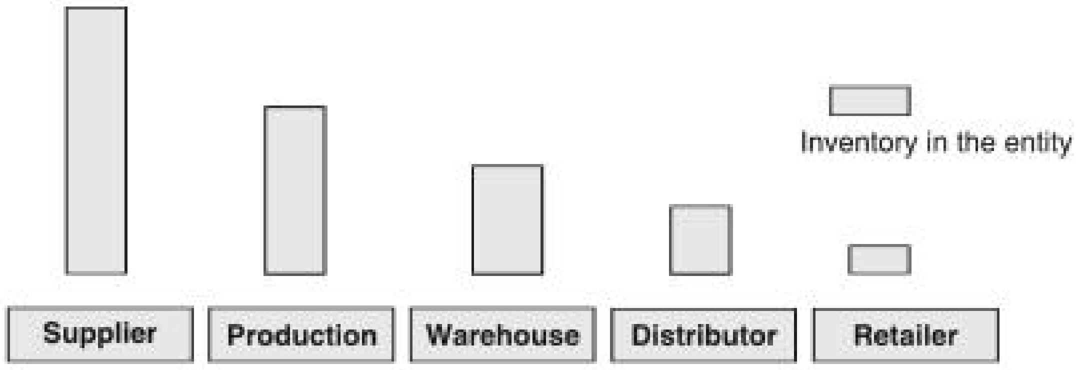

Figure 1.4 Bullwhip effect.

One of the ways to reduce excess inventory and the bullwhip effect is through information sharing. Organizations tend to share demand and stock information so that the excess inventory and the overall cost reduce. This is also enabled electronically through management information systems, ERP systems and through electronic data transfer systems.

Organizations also other ways reduce the overall cost of the supply chain. This could be through common warehouses, common distribution systems, etc. Any activity among the members through which the overall cost of the supply chain reduces is called **coordination.**

A well-coordinated supply chain management system addresses the usual problems such as large inventories, long lead times, cost, quality and variability. Large inventories are reduced by small and frequent deliveries. Long production lead times are reduced by delayed differentiation and postponement. These strategies aim at having a large set of common parts that are ordered and produced together. These are finally made into different varieties as late as possible so that pooling reduces production set-ups and inventories. Cost and quality are addressed through better supplier management, outsourcing and just-in-time deliveries. Variability is reduced by bringing down the overall lead time and by using better computer-controlled forecasting (demand planning) systems and information sharing.

1.13 ROLE OF MANUFACTURING AND OPERATIONS MANAGEMENT

We have seen that supply chain management integrated the various stages from supplier, manufacturing and distribution. In order for the supply chain to deliver the right quantity of the products at the right time and with least cost, manufacturing should gear itself to meet the requirements (Skinner, 1985) and reduce production time and cost. In this context, we will discuss the various aspects and topics in operations management.

Every organization is in business by making and selling products or services. There is a need which is converted to a business opportunity that results in a product or a service. Organizations use resources such as men material, money and time to manufacture products that are sold to end customers. The manufacturing or operations function should be well integrated with other management functions such as Finance, Marketing and Human Resources such the overall management of the organization is efficient and successful.

The starting point is the forecasting that says what the products are to be produced, in what quantities and how long. The long-term forecasts tell the organization the timeframe to change the various products. The system capacity is usually designed for the medium-term and the aggregate planning determines the extent of outsourcing and overtime for the short and medium-term. The inventory and materials management systems and the maintenance and quality systems provide information on availability of finished products, materials and machines for production and the master production schedules are created in which the quantities of specific products to be made are provided. The scheduling allots the available time on the various machine to carry out the production. This draws information from inventory, quality and maintenance regarding materials, inspection and machine availability. The manufactured products are used by the customers. Figure 1.5 captures the relationship among the various functions in the organization and within operations management. These relationships provide the various parameters for cost optimization of the production system within the organization.

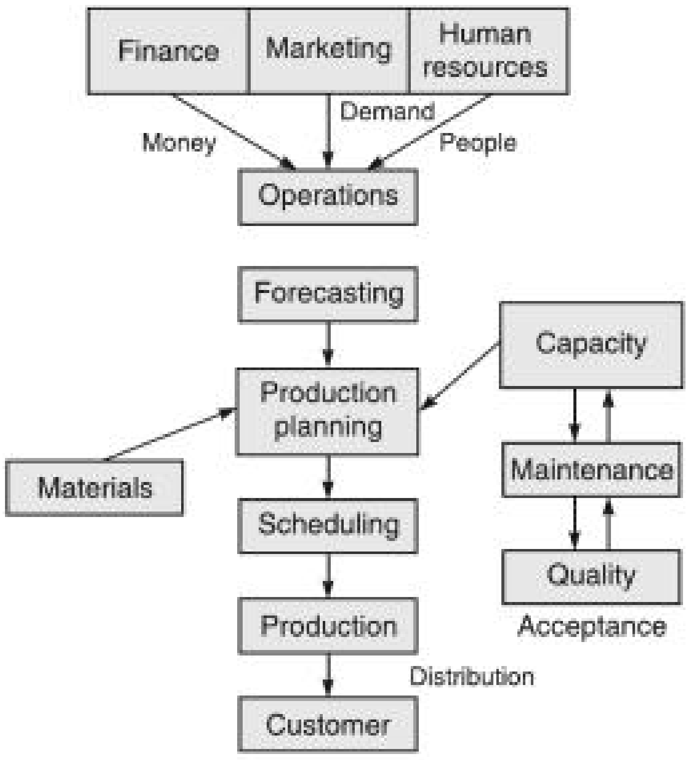

Figure 1.5 Relationship among the various functions in the organization.

We have stressed the need for shorter production lead times so that smaller runs and more variety can be produced. We will now see the various reasons for delay within a manufacturing system and identify the corresponding methodology to minimize the delay.

Firstly, the correct quantity of the correct item should arrive. This is carried out by efficient purchasing systems, vendor management and using just-in-time manufacturing system. There should be less raw material waiting time and these purchased items come directly into stores or manufacturing area rather than get stored in the warehouse. The next delay happens when material has to wait for machines. Good scheduling systems minimize waiting time of both jobs and machines. The machine should be available when the job arrives and organizations resort to total productive maintenance systems to make the machines available when required. These systems plan carry out preventive and repair maintenance activities quickly and make the machines available. The set-up time is the net component where the material spends time in front of the machines. Every organization concentrates on set-up reduction techniques such as single minute exchange of dies so that the set-up times are kept within a single digit. The processing times are made faster by using flexible manufacturing systems and computer-integrated manufacturing systems. There should be very few rejects and well-established quality control, process control systems take care of this aspect. Organizations have Total Quality Management (TQM) and ISO 9000 systems that plan and execute the various quality and other related initiatives. Six sigma programmes ensure that rejects are kept to a bare minimum. The transportation times among the machines are reduced by efficient material handling systems and by switching over to cellular manufacturing systems. Production control systems such as kanban systems and synchronous manufacturing principles ensure that production lead times are shortened and due dates are met. Finally, efficient logistics and distribution systems ensure that less inventory is stored and the products reach the customers in time.

Thus, supply chain management encompasses all the essential components of operations management and distribution management.

QUESTIONS

1. What is the goal of every organization?
2. What are the requirements of manufacturing?
3. What are the customer expectations in today's business setting?
4. Mention some important landmarks in the history of manufacturing management.
5. Mention three new methodologies based on changing the production systems.
6. Define quality.
7. What is total quality management?
8. What is ISO 9000?
9. What is business process engineering?
10. What is ERP?
11. What is cellular manufacturing? Why do organizations follow this technique?
12. Define JIT. Why do organizations follow this technique?
13. What is synchronous manufacturing?
14. What are the seven principles of synchronous manufacturing?
15. What are statistical fluctuations and random events? How do they influence the performance of manufacturing systems?
16. What is supply chain management?
17. How have e-purchasing systems helped organizations?
18. What are the four types of decisions in supply chain management?
19. What is bullwhip effect?

20. What are the challenges in the successful implementation of SCM systems?
21. Mention some commonly used SCM metrics.
22. What is logistics?
23. What are the important functions within operations management?
24. Mention the possible delays in manufacturing.
25. How organizations overcome these delays?
26. What is agility? What are the principles of agility?

2

Location and Layout Decisions

■ Chapter Topics ■

- Model 1: *p*-Median Location Models
- Model 2: Fixed Charge Problem or Location–Allocation Problem
- Model 3: Fixed Charge with Dedicated Facilities
- Model 4: Supply Chain—Location and Allocation in Multiple Stages
- Model 5: Supply Chain—Location and Allocation in Multiple Stages and Dedicated Supply
- Facilities Layout
- Mathematical Programming Formulation
- Heuristic Algorithms
- Cellular Layout—Cellular Manufacturing Systems
- Production Flow Analysis
- Rank Order Clustering
- Methods Involving a Distance Matrix

In this chapter, we will consider the location and layout decisions. Location decisions are about locating factories, warehouses and distribution centres, while layout decisions are about relative allocation of facilities in a given location. It is also customary to study location and layout together. We will also discuss the various issues and models in layout and include various forms of layout in manufacturing such as functional and cellular layout.

chosen medians is the largest. Point 6 qualifies as the third median. The rest of the points are allotted to the median with minimum distance. This would give us the solution

$$X_{33} = X_{44} = X_{66} = 1 \text{ and } X_{16} = X_{24} = X_{53} = 1 \text{ with } Z = 50.$$

Here points 3, 4 and 6 act as medians where the plants have to be located. Points 1 is attached to median 6, point 2 is attached to median 3 and point 5 is attached to median 4. Point 5 is equidistant with respect to both 3 and 4 and can be allotted to either of the medians resulting in an alternate solution with the same distance. We would prefer the given solution because all the medians attract a point. The solution to the corresponding grouping problem is {1, 6}, {2, 3} and {4, 5}.

2.2 MODEL 2: FIXED CHARGE PROBLEM OR LOCATION–ALLOCATION PROBLEM

Consider an illustrative network shown in Figure 2.2.

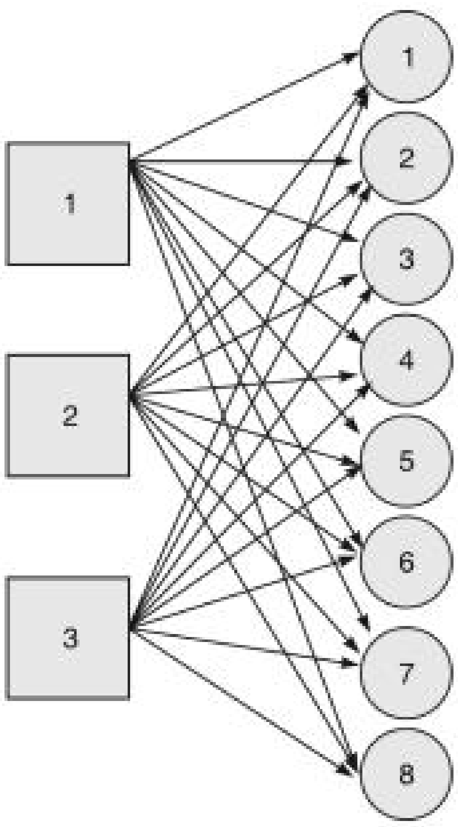

Figure 2.2 Network for fixed charge problem.

We show eight demand points (in circle) and three potential locations for factories (or warehouses, shown in square). In general, we may have n demand points and m potential locations. There is a fixed cost f_i of locating a facility in site i. There is a capacity K_i if a facility is located in site i. There is a demand d_j in point j and there is a transportation cost of C_{ij} between i and j. The formulation is as follows:

Let $Y_i = 1$ if a facility is located in site i.

Let X_{ij} be the quantity transported from site i to customer (demand point) j.

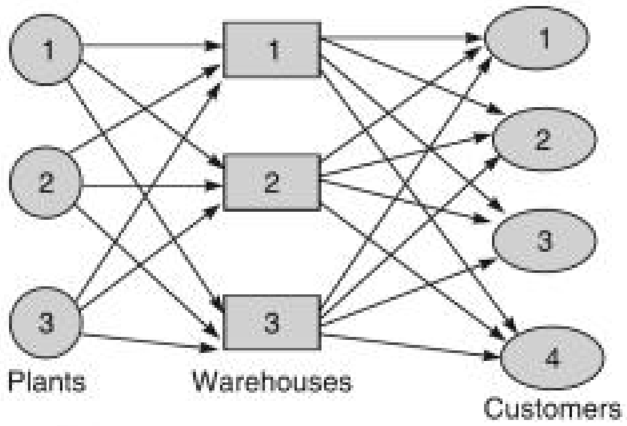

Figure 2.3 A two-stage network.

The mathematical programming formulation of the problem is as follows:

Let $Y_i = 1$ if plant i is opened.
Let $W_j = 1$ if warehouse j is opened.
Let X_{ij} be the quantity of the product transported from plant i to warehouse j.
Let T_{jk} be the quantity of the product transported from warehouse j to customer k.

The objective function is to minimize the total cost of location and allocation. This is to

$$\text{Minimize } \sum_{i=1}^{m} f_i Y_i + \sum_{j=1}^{p} g_j W_j + \sum_{i=1}^{m}\sum_{j=1}^{p} C_{ij} X_{ij} + \sum_{j=1}^{p}\sum_{k=1}^{n} C_{jk} T_{jk}$$

Subject to

$$\sum_{j=1}^{p} X_{ij} \le P_i Y_i \;\forall\; i$$

$$\sum_{i=1}^{m} X_{ij} \ge \sum_{k=1}^{n} T_{jk}\, W_j \;\forall j$$

$$\sum_{j=1}^{p} T_{jk} \ge d_k \;\forall\; k$$

$$Y_i,\, W_j = 0,\, 1$$

$$X_{ij},\, T_{jk} \ge 0$$

ILLUSTRATION 2.4 Consider the two-stage network given in Figure 2.3.

The unit cost of transportation from the plants to the warehouses is given in Table 2.3.

Table 2.3 Transportation cost between plants and warehouses

	*W*1	*W*2	*W*3
Plant 1	4	5	4.5
Plant 2	3	3.6	4
Plant 3	4.2	5	4.5

We have both qualitative as well as quantitative models for layout. Both types consider the load that moves among the facilities and the distances the load has to travel. Minimizing the load distance travelled is the most important objective in layout problems.

The qualitative models start with a matrix where the user provides information on how much the user wants two facilities to be closed to each other. This is given in the form of a matrix where the entry represents the importance. The following letters are used representing various levels of importance:

A = Absolutely essential
E = Essential
I = Important
O = Ordinary closeness desirable
U = Unimportant
X = Not to be placed next to each other

We explain a qualitative model using Illustration 2.6.

ILLUSTRATION 2.6 Consider the problem of relatively placing four departments (called 1 to 4). The matrix of closeness is given in Table 2.6.

Table 2.6 Matrix of closeness

	1	2	3	4
1	—	O	A	I
2		—	E	E
3			—	O
4				—

We are given that the area requirement for the four facilities are 240, 160, 260 and 140 square units. An area of 40 × 20 is available.

We start the algorithm by randomly picking a department for allocation (say, 2). Let us assume that we will pick any department that has an A with an already picked department and place it nearby. We do not have any department having an A with department 2. Therefore, we randomly pick another department (say, 4) and place it next to 2. Again we do not have any department with A in row 4. We pick 3 randomly and place 1 next to it. Since it has an A rating with department 3. A possible layout where the departments are shown next to each other is given in Figure 2.4.

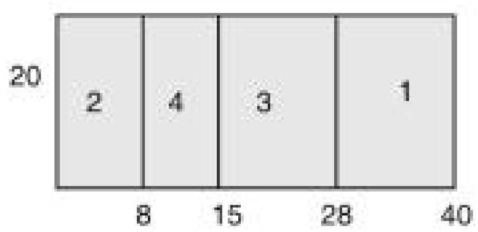

Figure 2.4 A layout for Illustration 2.6.

Let us assume that we will pick any department that has an A or E with an already picked department and place it nearby. We start the algorithm by randomly picking a department for allocation (say, 2). We pick another department 3 that has an E ranking and place it next to 2. We place 1 next to 3 since it has an A rating with department 3. We pick 4 and place it next to 2 because of an E ranking. A possible layout where the departments are shown next to each other is given in Figure 2.5.

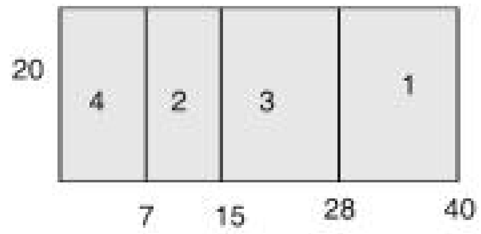

Figure 2.5 Another layout for Illustration 2.6.

Let us give scores for the rankings as follows:

A – 64, E – 16, I = 4, O = 1, U = 0 and X = –512

The score associated with the layout in Figure 2.4 is E + O + A = 81

The score associated with the layout in Figure 2.5 is E + E + A = 96

The layout in Figure 2.5 preferred to the layout in Figure 2.4.

The above algorithm explains the principles of a popular computer-based package called **ALDEP**.

From the rank matrix, we may observe that department 3 has the highest total ranking among the four departments. We pick department 3 and place it as a 26 × 10 rectangle. From row 3, we observe that there is an A ranking with department 1. Therefore, department 1 placed as a 24 × 10 rectangle next to department 3. Department 2 is placed next to department 3 (E rank) and department 4 is placed next to department 2 (E rank). The layout is shown in Figure 2.6.

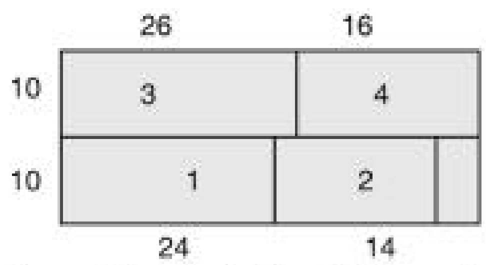

Figure 2.6 A layout for Illustration 2.6 based an CORELAP.

The total score associated with the closeness in the layouts shown in Figure 2.6 is A + E + O + E + I = 101. Closeness between departments 1 and 2 is not considered since they do not share a common boundary.

The above steps are the basis of another computerized layout package called **CORELAP**. The above two algorithms are qualitative in nature and are construction algorithms. We explain a quantitative model using Illustration 2.7.

ILLUSTRATION 2.7 Consider the problem of relatively locating 4 facilities in four sites. The load matrix (in tons) among the four facilities is given in Table 2.7.

Table 2.7 Load matrix

	1	2	3	4
1	—	3	7	4
2		—	6	5
3			—	2
4				—

The loads are assumed to be symmetric and $w_{ij} = w_{ji}$.

We assume that the facilities require equal area (and of same shape) and the four sites are shown in Figure 2.7 (marked site1 to site 4).

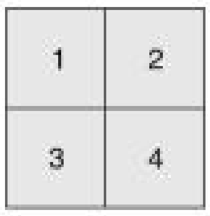

Figure 2.7 A layout for Illustration 2.7.

Considering the given layout, the distance among the sites is given in Table 2.8 (as a multiple of a unit distance).

Table 2.8 Distance matrix

	1	2	3	4
1	—	1	1	2
2		—	2	1
3			—	1
4				—

The distances are rectilinear distances and not Euclidean (or crow flying). The rectilinear distance between two points (x_1, y_1) and (x_2, y_2) is given by $|x_2 - x_1| + |y_2 - y_1|$.

Let us use a notation where $a(i)$ represents the site to which facility i is allotted. $a = [2\ 1\ 3\ 4]$ would indicate that facility 1 is allotted to site 1, facility 2 is allotted to site 2, facility 3 is allotted to site 3 and facility 4 is allotted to site 4.

The ton–km or load–distance associated with $a = [2\ 1\ 3\ 4]$ is given by

$$Z = 2(w_{12} \times d_{21} + w_{13} \times d_{23} + w_{14} \times d_{24} + w_{23} \times d_{13} + w_{24} \times d_{14} + w_{34} \times d_{34}).$$

This is given by

$$Z = 2(3 \times 1 + 7 \times 2 + 4 \times 1 + 6 \times 1 + 5 \times 2 + 2 \times 1) = 78$$

Due to the symmetry of the load matrix and the distance matrix, we have calculated six terms and have multiplied with 2.

The problem is to find the allotment that minimizes Z.

2.7 MATHEMATICAL PROGRAMMING FORMULATION

Let $X_{ik} = 1$ if facility i is allotted to site k and $X_{jl} = 1$ if facility j is allotted to site l.

Each facility goes to exactly one site and each site gets exactly one facility. These are given by

$$\sum_{i=1}^{n} X_{ij} = 1 \ \forall j, \text{ and}$$

$$\sum_{j=1}^{n} X_{ij} = 1 \ \forall i$$

$$X_{ij} = 0, 1$$

Given X_{ik} and X_{jl}, their contribution to Z is $X_{ik}X_{jk}w_{ij}d_{kl}$. The objective function is, therefore, to

$$\text{Minimize} \sum_{i=1}^{n}\sum_{j=1}^{n}\sum_{k=1}^{n}\sum_{l=1}^{n} w_{ij}d_{kl}X_{ik}X_{jl}.$$

This can also be written as

$$\text{Minimize} \sum_{i=1}^{n}\sum_{j=1}^{n}\sum_{k=1}^{n}\sum_{l=1}^{n} C_{ikjl}X_{ik}X_{jl}$$

The above problem has a quadratic objective function and the usual assignment constraints and is called the **Quadratic Assignment Problem.** It is not a linear Integer Programming (IP) problem, but is a quadratic problem. It is a difficult problem to solve.

The optimum solution to our example is given by a = [1 4 2 3] with Z = 64. There are several alternate optima, such as [1 4 3 2], [2 3 1 4], [3 2 1 4], [4 1 3 2], etc.

2.8 HEURISTIC ALGORITHMS

We explain the heuristic algorithm using the data given in Tables 2.7 and 2.8.

ILLUSTRATION 2.8 We may start with an arbitrary solution a = [1 2 3 4] with Z = 74. If we consider, pairwise exchanges in this solution, we get six new solutions where the four numbers are exchanged pairwise. These are:

[2 1 3 4] with Z = 78
[3 2 1 4] with Z = 64
[4 2 3 1] with Z = 74
[1 3 2 4] with Z = 74
[1 4 3 2] with Z = 64
[1 2 4 3] with Z = 78

We can choose the best solution and repeat the pairwise exchanges till there is no improvement. Choosing the best among the pairwise solutions is called the **Method of Steepest Descent** and is a widely used heuristic to solve the problem.

For our example, the method terminates with the optimal solution with $Z = 64$. This method is only a heuristic algorithm and does not guarantee the optimum solution always.

We may start with an arbitrary solution $a = [1\ 2\ 3\ 4]$ and try adjacent pairwise exchanges. Three such solutions are possible. These are:

[21 3 4] with $Z = 78$

[1 3 2 4] with $Z = 74$

[1 2 4 3] with $Z = 78$.

The adjacent pairwise interchange does not show any improvement for our example and the algorithm terminates with a solution with $Z = 74$.

2.8.1 Computerized Algorithm for Layout CRAFT

Let us consider the modification or adaptation of the pairwise interchange heuristic to consider different area requirements for the facilities. This is explained using the same workload data in Table 2.8.

ILLUSTRATION 2.9 Let us assume that the area requirements of the four facilities are 240, 160, 260 and 140 square units. Let us assume that a total of 800 square units of area is available and we start with a solution shown in Figure 2.8. Here we represent the facilities as A, B, C and D.

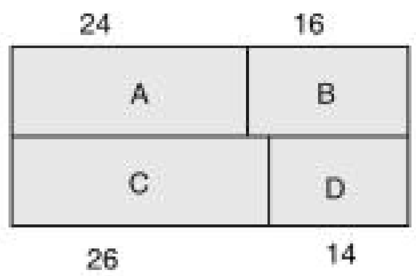

Figure 2.8 A layout for Illustration 2.9.

The coordinates of the centroids of the four areas are

$$A = (12, 15),\ B = (32, 15),\ C = (13, 5) \text{ and } D = (33, 5)$$

The rectangular distances in the above layout between the pairs of facilities is given by

A to B = 20, A to C = 11, A to D = 31, B to C = 29, B to D = 11 and C to D = 20

The load–distance is given by

$$Z = 3 \times 20 + 7 \times 11 + 4 \times 31 + 6 \times 29 + 5 \times 11 + 2 \times 20 = 530$$

(The actual load–distance should be multiplied by 2, but due to symmetry we consistently use the computed values for comparison, which is half the actual load–distance).

We consider the pairwise interchange A to B. Temporarily, we shift only the centroids and the new centroids are

$$A = (32, 15), B = (12, 15), C = (13, 5) \text{ and } D = (33, 5)$$

The rectangular distances in the above layout between the pairs of facilities is given by

A to B = 20, A to C = 29, A to D = 11, B to C = 11, B to D = 31 and C to D = 20

The load–distance is given by

$$Z = 3 \times 20 + 7 \times 29 + 4 \times 11 + 6 \times 11 + 5 \times 31 + 2 \times 20 = 568$$

The exchange A and C gives Z = 481

The exchange B and C gives Z = 593

The exchange B and D gives Z = 503

The exchange C and D gives Z = 572.

We exchange facilities only when we have a common border. We, therefore, consider the exchange A to D since these facilities do not have a border.

The best exchange is between B and D which has a value lesser than the starting value of 530. We carry out the exchange by inserting the smaller area into the larger area and giving the rest to the larger area. The new layout is given in Figure 2.9.

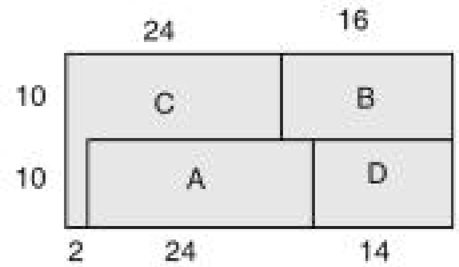

Figure 2.9 Improved layout using CRAFT.

From Figure 2.9, the centroids for the facilities are A = (14, 5), B = (32, 15) and D = (33, 5). Facility C now has been split into two rectangles and the centroid is calculated as

$$\left[\left(\frac{240 \times 12 + 20 \times 1}{260}\right), \left(\frac{240 \times 15 + 20 \times 5}{260}\right)\right] = (11.15, 14.23)$$

The rectangular distances in the above layout between the pairs of facilities using the new centroids is given by

A to B = 28, A to C = 12.08, A to D = 19, B to C = 21.62, B to D = 11 and C to D = 31.08

The load–distance is given by

$$Z = 3 \times 28 + 7 \times 12.08 + 4 \times 19 + 6 \times 21.62 + 5 \times 44 + 2 \times 31.08 = 491.44$$

With the solution in Figure 2.9, we carry out five possible pairwise exchanges and the results are shown as follows:

The exchange A and B gives Z = 507.29

The exchange A and C gives Z = 534.74

The exchange A and D gives Z = 620.44

The exchange B and C gives Z = 615.36

The exchange B and D gives Z = 538.28

We do not consider the exchange between the facilities C and D, since they do not share a border. Otherwise exchanging them would be difficult.

We do not have an improvement in the load–distance measure with the exchanges. The algorithm terminates with the layout given in Figure 2.9.

The above algorithm is called the **CRAFT (Computerized Relative Allocation of Facilities Technique)** by Armour and Buffa (1964). This algorithm is considered as one of the most significant contributions in the area of layout design/Industrial Engineering. The significance comes from the fact that a computer program written in FORTRAN generated the layout on a screen/print out. Several organizations benefited by using this algorithm to determine a good layout.

2.8.2 Some Observations

1. Though there is a general feeling that the computer generated layout could be optimal, it is well known that CRAFT does not provide the optimal solution.
2. CRAFT is an efficient pairwise interchange heuristic programme using a computer.
3. CRAFT can also be modified for three-way exchange and in some instances works better than pairwise interchange.
4. CRAFT can also give non-rectangular shapes as in our example.
5. CRAFT uses the centroids as the representative point to compute distances among the facilities. If the areas are very thin rectangles, the distance between the centroids need not adequately represent the distance between the facilities.
6. CRAFT is an improvement algorithm that attempts to give a better layout than a given starting layout.

It is also observed that the layout in Figure 2.9 has facility C occupying a non-rectangular shape. This can now be modified to the layout shown in Figure 2.10. It is also observed that the layouts in Figures 2.6 and 2.10 are the same indicating that CORELAP and CRAFT have given the same solution to our example.

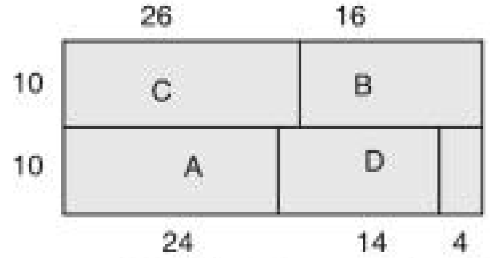

Figure 2.10 Modified layout using CRAFT.

6. Given a time series model of the form $Y = a + bt + \varepsilon$, where ε is a measure of 'random effects'. What is the expected value of ε?
7. As a forecasting technique, exponential smoothing is nothing more than a form of a moving average and it suffers from the same deficiency as moving average methods. It cannot distinguish between random variations and significant changes and is not a forward looking technique, comment.
8. Distinguish between forecasting and prediction using a good example.
9. Why do we need causal and time series forecasting models? When do we choose either? Give an example for each model from your experience.
10. What are the advantages of double exponential smoothing models in the context of forecasting?
11. When do you use double exponential smoothing models to forecast and how do you evaluate the goodness of such forecasts?
12. Give evidences that suggest that forecasting is an important tool in the service sector.
13. What are the salient features of an exponential smoothing model?
14. Why do we use seasonal models for certain types of data?
15. What is forecasting? Why do you need forecasting?
16. Give two measures of goodness of a forecast.
17. What type of time series models would you expect to be suitable for forecasting the following situations? Why?
    (a) Quarterly sales of ice creams
    (b) Daily sales of cars in a dealer showroom
    (c) Monthly sales of shirts in a showroom
    (d) Stock price of a software company

3.2 AGGREGATE PLANNING

Aggregate Planning is an important activity that is the first step in manufacturing planning and control.

To begin with, let us consider that we make one product, whose demand or forecast of demand is known. Table 3.21 shows an example where the forecast is available for 12 months. Here demand means actual demand or forecast of the demand.

Table 3.21 Demand data

	January	*February*	*March*	*April*	*May*	*June*	*July*	*August*	*September*	*October*	*November*	*December*
Demand	3000	3000	2500	1500	2000	2500	3000	4000	3000	2800	2000	1000

It is observed that the demand fluctuates and is not constant every month. The total demand is 30300 units. Let us assume that the plant works 16 hours/day. It takes 10 hours to produce a unit and there are 65 people working. The output per day is

$$\text{Output} = \frac{16 \times 65}{10} = 104$$

If the average number of working days per month is 25, the company can make 2600 in a month and 31200 in a year which is more than the demand. The company cannot follow the approach of making each month's demand and selling it because of two reasons:

1. Some months will require more than the average demand and we will incur shortage and loss of profit by not meeting the demand.
2. Some months may have fewer than 25 working days and the production can be less.

In order to meet the annual demand, two possible approaches exist:

1. To produce exactly the demand of each month in a month. Use over time when necessary. Maintain no inventory and there shall be no shortage.
2. To produce more in months where the demand is less. Use the excess inventory to meet the peak demand. Use only regular time production to the extent possible.

The above two strategies are called **pure strategies**. Sometimes a combination of these two can give better (least cost) solution. The problem is to find a least cost solution that meets demand. Several approaches are available. We will discuss some of them in this chapter.

3.2.1 Graphical Approach

ILLUSTRATION 3.11 Figure 3.1 shows the various graphs used in this approach. Graph 1 is the cumulative demand curve. Graph 2 shows the cumulative regular time (RT) production curve. This has been drawn under the assumption that the company works for 22, 18, 22, 19, 23, 20, 22, 22, 18, 21, 20 and 22 days in the twelve months. The regular time production possible in month 1 is 22 × 104 = 2288 and so on. The initial inventory is assumed to be 1000.

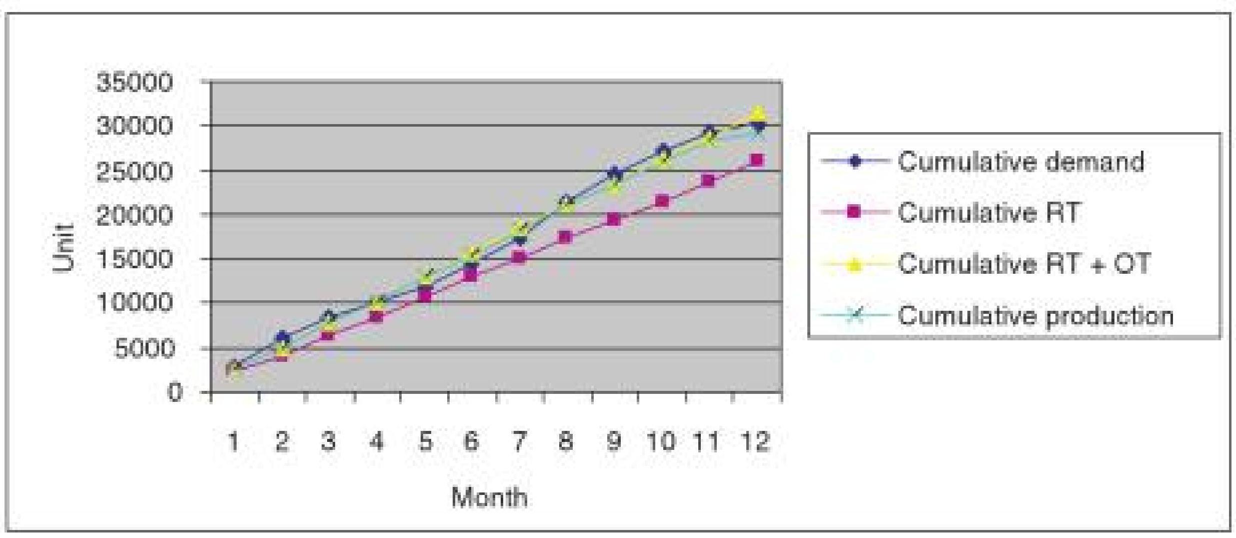

Figure 3.1 Graphical method.

The thrid graph in Figure 3.1 shows the cumulative sum of regular time and overtime (OT) capacities. This is drawn under the assumption that the maximum overtime days in the twelve months are 4, 4, 5, 4, 5, 4, 5, 5, 4, 5, 4, 5. The cumulative RT + OT for month 1 is 2288 + 416 = 2704. The cumulative RT + OT for month 2 is 2704 + 18 × 104 + 4 × 104 = 4992.

The user can draw a curve (Graph 4) as shown in the figure such that the curve lies between Graphs 2 and 3. Graph 4 is drawn under the assumption that cumulative production in the twelve months is between the cumulative RT and the cumulative RT + OT curve. From Graph 4, we may observe that the cumulative production in the twelve months are 2700, 4950, 7600, 9950, 12850, 15000, 17800, 20600, 22850, 25550, 28000 and 29300.

Four costs are considered in this plan. These are

1. RT production cost
2. OT production cost
3. Inventory cost
4. Shortage (backorder) cost

For month 1, the production is 2700. Out of this 2288 is RT and 412 is OT. The demand is 3000. The ending inventory is 700. The cost for month 1 is TC = RT cost + OT cost + Inventory cost + Shortage cost = 2288 × 100 + 412 × 130 + 700 × 20 + 0 = Rs. 296360 = Rs. 2.9636 lakh. For month 2, beginning inventory is 700 and cumulative production is 4950. Production is 4950 – 2700 = 2250. Out of this 1872 is RT and 378 is OT. The ending inventory is 700 + 2250 – 3000 = –50. The cost is 1872 × 100 + 378 × 130 + 50 × 500 = Rs. 2.6134 lakh. Since the ending inventory is negative, we have shortage cost.

Thus, the total cost for the year can be calculated, which is Rs. 40.79 lakh.

3.2.2 Tabular Method

ILLUSTRATION 3.12 In this method, we create a table where the user enters the production quantities for each month. Let us consider the case where the user decides to produce 2700, 2250, 2800, 2350, 2900, 2450, 2800, 2800, 2250, 2700, 2400 and 900 in the 12 months. The costs are calculated as follows:

For January

Beginning inventory = 1000 (given)
Production/day = 104 (given)
Total production = 2700
RT days = 22 (given)
RT capacity = 22 × 104 = 2288
OT days = 4 (given)
OT capacity = 4 × 104 = 416
RT production = minimum (2700, 2288) = 2288
OT production = 2700 – 2288 = 412 (less than 416 and hence possible).
Ending inventory = Beginning inventory + Production – Demand
= 1000 + 2700 – 3000 – 700

RT cost = 2280 × 100/100000 = Rs. 2.288 lakh

OT cost = 416 × 130/100000 = Rs. 0.5356 lakh

Inventory cost = 700 × 20/1000000 = Rs. 0.14 lakh

Shortage cost = 0

Total cost (January) = Rs. 2.9636 lakh

For February

Beginning Inventory = 700

Production/day = 104

Total production = 2250

RT days = 18 (given)

RT capacity = 18 × 104 = 1872

OT days = 4 (given)

OT capacity = 4 × 104 = 416

RT production = minimum (2250, 1872) = 1872

OT production = 2250 – 1872 = 378 (less than 416 and hence possible).

Ending inventory = Beginning inventory + Production – Demand

= 700 + 2250 – 3000 = –50

RT cost = 1872 × 100/100000 = Rs. 0.1872 lakh

OT cost = 378 x 130/100000 = Rs. 0.4914 lakh

Inventory cost = 0

Shortage cost = 50 × 500/100000 = Rs. 0.25 lakh

Total cost (February) = Rs. 2.6134 lakh.

These calculations can be easily modelled using Microsoft Excel. Table 3.22 shows these calculations for 12 months. The total cost is Rs. 35.1676 lakh. The costs of RT, OT, inventory and shortage are considered.

Given the production quantities it is possible to compute the total cost. The optimization problem would be to find the production quantity that minimizes total cost.

So far we have considered four costs—RT and OT costs and inventory and shortage costs. We can have four more costs in the production cost computation. If the production quantity exceeds the RT + OT capacity, we assume that the excess quantity is outsourced. There can be an outsourcing cost. If the production quantity is less than RT capacity, there is underutilization cost.

We may also increase or decrease the people employed in a month. This will increase or decrease the RT and OT capacity. There is a hiring or lay-off cost associated with the increase or decrease of people. We can, therefore, have eight components in the total cost. Here, the production plan would involve the production quantity and the workforce in each month.

Table 3.22 Tabular method for aggregate planning

Month	*January*	*February*	*March*	*April*	*May*	*June*	*July*	*August*	*September*	*October*	*November*	*December*	
Beginning inventory	1000	700	–50	250	1100	2000	1950	1750	550	–200	–300	100	
Demand	3000	3000	2500	1500	2000	2500	3000	4000	3000	2800	2000	1000	30300
RT days	22	18	22	19	23	20	22	22	18	21	20	22	249
OT days	4	4	5	4	5	4	5	5	4	5	4	5	54
RT capacity	2288	1872	2288	1976	2392	2080	2288	2288	1872	2184	2080	2288	25896
RT production	2288	1872	2288	1976	2392	2080	2288	2288	1872	2184	2080	900	24508
OT capacity	416	416	520	416	520	416	520	520	416	520	416	520	5616
OT production	412	378	512	374	508	370	512	512	378	516	320	0	4792
Total capacity	2704	2288	2808	2392	2912	2496	2808	2808	2288	2704	2496	2808	31512
Total production	2700	2250	2800	2350	2900	2450	2800	2800	2250	2700	2400	900	29300
End inventory	700	–50	250	1100	2000	1950	1750	550	–200	–300	100	0	
RT cost	2.288	1.872	2.288	1.976	2.392	2.08	2.288	2.288	1.872	2.184	2.08	0.9	24.508
OT cost	0.5356	0.4914	0.6656	0.4862	0.6604	0.481	0.6656	0.6656	0.4914	0.6708	0.416	0	6.2296
Inventory cost	0.14	0	0.05	0.22	0.4	0.39	0.35	0.11	0	0	0.02	0	1.68
Shortage cost	0	0.25	0	0	0	0	0	0	1	1.5	0	0	2.75
Total cost	2.9636	2.6134	3.0036	2.6822	3.4524	2.951	3.3036	3.0636	3.3634	4.3548	2.516	0.9	35.1676

Let us consider the following workforce and production for 12 months given in Table 3.23.

Table 3.23 Demand and workforce data

	January	*February*	*March*	*April*	*May*	*June*	*July*	*August*	*September*	*October*	*November*	*December*
Demand	3000	3000	2500	1500	2000	2500	3000	4000	3000	2800	2000	1000
Production	2500	2500	2500	1500	2000	3000	3000	4000	3000	3000	2000	300
Workforce	60	56	62	60	66	60	65	64	60	58	55	58

ILLUSTRATION 3.13 We illustrate the calculation of the various costs for the month of January.

Given:

Beginning inventory = 1000
Production/day = 104
Number of people in December = 58
Number of people in January = 60
RT days = 22
OT days = 4
RT cost = Rs. 100/unit
OT cost = Rs. 130/unit
Inventory cost = Rs. 20/unit/month
Shortage = Rs. 500/unit short (backordered)
Hiring cost = Rs. 500/person hired
Lay-off cost = Rs. 400/person
Outsourcing cost = Rs. 150/unit
Underutilization cost = Rs. 2/unit
Units/per person/day = 16/10 = 1.6
RT capacity = 22 days × 60 persons × 1.6 = 2112
OT capacity = 4 days × 60 × 1.6 = 384
Total production = 2500
RT production = minimum (2500, 2112) = 2112
OT production = minimum (2500 – 2112, 384) = 384
Outsourcing = 4
People hired = 60 – 58 = 2
Ending inventory = Beginning inventory + Production – Demand
= 1000 + 2500 – 3000 – 500
RT cost = 211280 × 100/100000 = Rs. 2.112 lakh
OT cost = 384 × 130/100000 = Rs. 0.4992 lakh
Inventory cost = 500 × 20/1000000 = Rs. 0.10 lakh
Shortage cost = 0
Hiring cost = 2 × 500 = Rs. 1000
Lay-off cost = 0

Outsourcing cost = 4 × 150 = Rs. 600

Underutilization cost = 0

Total cost (January) = 2.112 + 0.4992 + 0.1 + 0.001 + 0.006

= Rs. 2.7272 lakhs

Similarly, the cost for 12 months is calculated and it is Rs. 33.91168 lakh. This is shown in Table 3.24.

The tabular method and the graphical method are very similar, except for the difference that in the graphical method, we use cumulative values. In the tabular method, we input the actual values of the production. Changing the workforce in the tabular method is the same as adding a cumulative workforce curve from which the cumulative RT and OT curves can be generated. There are two inputs—the cumulative workforce and the cumulative production curves to the graphical method.

The tabular method is more convenient and can be easily modelled using a spreadsheet. The user can change the input values and compute the total cost quickly. Though this method is an evaluative method and does not guarantee the optimal solution, repeated trials can give a very good solution with less cost.

While we have represented people in numbers, production, inventory and underutilization in units, it is advantageous to represent all the parameters in a single unit called **man-hours**. This would make the aggregate plan independent of the number and type of products made. The capacities and decision variables are represented in man hours. Through this, we are now representing all the products through an aggregate product whose demand is matched with the capacities to determine the *aggregate production plan* that minimizes total cost. The decision variables are the production quantities and the workforce.

3.2.3 Linear Programming Model

Here, the decision variables are the workforce (in man-hours) and the production (in man-hours). The objective is to minimize total cost.

Variables

R_t = Regular time production in period t

O_t = Overtime production in period t

I_t = Inventory at the end of period t

S_t = Shortage (backorder) at the end of period t

W_t = Workforce hours in period t

H_t = Man-hours hired in period t

L_t = Man-hours laid-off in period t

Out_t = Man-hours outsourced in period t

U_t = Man-hours underutilized in period t

Cost Parameters

r = Regular time production cost (per man-hour)

o = Overtime production cost (per man-hour)

i = Inventory cost (per man-hour)

Table 3.24 Tabular method considering variable workforce

Month		*January*	*February*	*March*	*April*	*May*	*June*	*July*	*August*	*September*	*October*	*November*	*December*	
Beginning inventory		1000	500	0	0	0	0	500	500	500	500	700	700	
Demand		3000	3000	2500	1500	2000	2500	3000	4000	3000	2800	2000	1000	30300
RT days		22	18	22	19	23	20	22	22	18	21	20	22	249
OT days		4	4	5	4	5	4	5	5	4	5	4	5	54
Workforce	58	60	56	62	60	66	60	65	64	60	58	55	58	
Hiring		2	0	6	0	6	0	5	0	0	0	0	3	22
Lay-off		0	4	0	2	0	6	0	1	4	2	3	0	22
RT capacity		2112	1612.8	2182.4	1824	2428.8	1920	2288	2252.8	1728	1948.8	1760	2041.6	24099.2
RT production		2112	1612.8	2182.4	1500	2000	1920	2288	2252.8	1728	1948.8	1760	300	
OT capacity		384	358.4	496	384	528	384	520	512	384	464	352	464	5230.4
OT production		384	358.4	317.6	0	0	384	520	512	384	464	240	0	
Out-souring cost		4	528.8	0	0	0	696	192	1235.2	888	587.2	0	0	
Total production		2500	2500	2500	1500	2000	3000	3000	4000	3000	3000	2000	300	29300
End inventory		500	0	0	0	0	500	500	500	500	700	700	0	
RT cost		2.112	1.6128	2.1824	1.5	2	1.92	2.288	2.2528	1.728	1.9488	1.76	0.3	21.6048
OT cost		0.4992	0.46592	0.41288	0	0	0.4992	0.676	0.6656	0.4992	0.6032	0.312	0	4.6332
Inventory cost		0.1	0	0	0	0	0.1	0.1	0.1	0.1	0.14	0.14	0	0.78
Shortage cost		0	0	0	0	0	0	0	0	0	0	0	0	0
Hiring cost		0.01	0	0.03	0	0.03	0	0.025	0	0	0	0	0.015	0.11
Lay-off cost		0	0.016	0	0.008	0	0.024	0	0.004	0.016	0.008	0.012	0	0.088
Outsourcing cost		0.006	0.7932	0	0	0	1.044	0.288	1.8528	1.332	0.8808	0	0	6.1968
Underutilization cost		0	0	0	0.0648	0.08576	0	0	0	0	0	0	0.34832	0.49888
Total cost		2.7272	2.88792	2.62528	1.5728	2.11576	3.5872	3.377	4.8752	3.6752	3.5808	2.224	0.66332	33.91168

s = Shortage cost (per man-hour)
h = Hiring cost (per man-hour)
l = Lay-off cost (per man-hour)
out = Outsourcing cost (per man-hour)
u = Underutilization cost (per man-hour)

These costs are assumed to be constant. If they vary in different periods, we can use a subscript t for the period to capture the correct value in each period.

The objective is to minimize the total costs which include regular time cost, over time cost, inventory cost, shortage cost, hiring cost, lay-off cost, outsourcing cost and underutilization cost. The objective function is to

$$\text{Minimize } \sum_{t=1}^{T} (rR_t + oO_t + iI_t + sS_t + hH_t + lL_t + out\ Out_t + uU_t)$$

The first constraint is to match production, inventory, demand and capacity. This is given by

$$I_{t-1} + S_{t-1} + R_t + O_t + Outt - D_t = I_t - S_t$$

The ending inventory (or shortage) in a period is the beginning inventory (or shortage) + regular time production + overtime production + outsourced production less the demand (or forecast).

The second constraint is to relate the production and utilization to capacity

$$R_t + U_t = W_t$$

The third constraint relates overtime production to capacity

$$O_t \leq kW_t$$

Here k is a suitable constant that relates overtime capacity to regular time capacity.

The next constraint relates the workforce to the hiring (and lay-off) variables.

$$W_{t-1} + H_t - L_t = W_t$$

Here, the workforce for period t is the sum of the worforce in period $t - 1$ and the workforce hired (or laid-off).

If there are restrictions on inventory, we can add a constraint of the form

$$I_t \leq I^*$$

All variables R_t, O_t, W_t, I_t, S_t, H_t, L_t, Out, $U_t \geq 0$

It is not necessary that we use all the variables and all the constraints. We illustrate this through an example.

ILLUSTRATION 3.14 Consider the data shown in the tabular method. We keep workforce constant at 65 and use only RT, OT, inventory and shortage costs. The costs and capacities are now computed based on man-hours. The decision variables are only the production and inventory quantities. There is a beginning inventory of 10000 man-hours in January.

r = 100/10 = Rs. 10/man-hour
o = 130/10 = Rs. 13
i = 20/10 = 2
s = 500/10 = 50
W = 65 people

RT capacity = 65 × 16/10 × number of days × 10 = 22880 man-hours (for 22 days)

OT capacity = 1040 × number of days = 4160 man-hours (for 4 days)

The LP formulation would be to

$$\text{Minimize} \sum_{t=1}^{T} (rR_t + oO_t + iI_t + sS_t)$$

Subject to

$$I_{t-1} + S_{t-1} + R_t + O_t - D_t = I_t - S_t$$

$$R_t \le W_t$$

$$O_t \le kW_t$$

For our example, the complete formulation is to

$$\text{Minimize} \sum_{t=1}^{T} (10R_t + 13O_t + 2I_t + 50S_t)$$

$$\text{Subject to } I_{t-1} + S_{t-1} + R_t + O_t - D_t = I_t - S_t$$

$$R_t \le W_t$$

$$O_t \le kW_t$$

The formulation has 48 variables and 36 constraints. The optimal solution is given by $R_1 = 22880$, $R_2 = 18720$, $R_3 = 22880$, $R_4 = 19760$, $R_5 = 23920$, $R_6 = 20800$, $R_7 = 22880$, $R_8 = 22800$, $R_9 = 18720$, $R_{10} = 21840$, $R_{11} = 20800$, $R_{12} = 10000$, $O_1 = 4160$, $O_2 = 4160$, $O_3 = 5200$, $O_4 = 4160$, $O_5 = 5200$, $O_6 = 4160$, $O_7 = 5200$, $O_8 = 5200$, $O_9 = 4160$, $O_{10} = 5200$, $O_{11} = 120$, $O_{12} = 0$, $I_1 = 7040$, $I_3 = 3000$, $I_4 = 11920$, $I_5 = 21040$, $I_6 = 21000$, $I_7 = 19080$, $I_8 = 7160$, $I_9 = 40$, $S_2 = 80$, $S_{10} = 920$ with Z = Rs. 3301320.

Let us consider the formulation where we include all the eight costs including hiring, lay-off, outsourcing and underutilization costs. The formulation has 108 variables (including the variables for workforce) and 48 constraints.

Before solving the problem, we fix values for a few parameters. We fixed the beginning inventory to be 1000 units. We fixed the initial number of people to be 60. The outsourcing cost is fixed at Rs. 15/outsourced hour, the underutilization cost is Rs. 0.2/hour, the hiring cost is Rs. 50/person and the lay-off cost is Rs. 40/person.

The optimal solution gave a total cost of Rs. 298004. The workforce used in the various months were $W_1 = 60$, $W_2 = W_3 = W_4 = W_5 = W_6 = W_7 = W_8 = W_9 = W_{10} = W_{11} = W_{12} = 104.1667$. The strategy was to produce exactly the monthly demand for all months except September and October where the additional demand of October was met by carrying some inventory at the end of September. The solution did not show overtime and outsourcing. There were no shortages also. The advantage of including varying workforce is that depending on the demand, the workforce can be changed. This strategy along with carrying some inventory when required helped in reducing the total cost.

It may be necessary to define the workforce as integers. When the problem was solved with the additional integer restriction on the variables, the values of the workforce changed to $W_1 = 60$, $W_2 = W_3 = W_4 = W_5 = W_6 = W_7 = W_8 = W_9 = W_{10} = W_{11} = W_{12} = 104$. This necessitated an overtime of 48 hours in September and some inventory at the end of January and March. The regular time production quantities are $R_1 = 20048$, $R_2 = 29952$, $R_3 = 25000$, $R_4 = 15000$,

$R_5 = 20000$, $R_6 = 25000$, $R_7 = 33392$, $R_8 = 36608$, $R_9 = 29952$, $R_{10} = 20048$, $R_{11} = 20000$, $R_{12} = 10000$. The cost was a little more than that of the LP optimum and close to Rs. 2.98 lakhs.

3.2.4 Transportation Problem

If we consider only six out of the eight costs and assume a linear relationship between the quantities and the corresponding costs, we can formulate a transportation problem to solve the aggregate planning problem. The six costs considered are:

1. Regular time production cost
2. Overtime production cost
3. Inventory cost
4. Shortage (backorder) cost
5. Outsourcing cost
6. Underutilization cost

Let us consider T periods. Each period has a regular time capacity and overtime capacity. Each of these is a supply node. The initial inventory and the outsourcing are the additional supplies. There are $2T + 2$ supply points. The demand in each month represents the demand nodes and there are T nodes (assuming no final inventory required). Otherwise, the final inventory is another demand node. Table 3.25 represents the transportation formulation of the aggregate planning problem.

Table 3.25 Transportation table

D_1	D_2									D_{12}	*Dummy*	
0	i	$2i$	$3i$								0	I_0
r	$r + i$	$r + 2i$									u	R_1
o	$o + i$	$o + 2i$									0	O_1
s	r	$r + i$									u	R_2
s	o	$o + i$										O_2
$2s$	s	r										
												R_{12}
												O_{12}
k	k	k	k									*Out*

The supply available with the outsourcing node is the total demand $(= \sum_{t=1}^{T} D_t)$. To balance the transportation table, we have a dummy column (demand) whose quantity is equal to $I_0 + \sum_{t=1}^{T}(R_t + O_t)$. Here R_t and O_t represent regular time production capacity and overtime capacity, which are known. The cost of using existing inventory to meet the first month demand is zero. To meet the demand of every subsequent month we incur inventory cost. Therefore, the unit cost of using I_0 to meet D_2 is i. The unit cost of meeting D_1 by regular production is r and the cost of meeting D_2 through R_1 is $r + i$, because the quantity is in inventory for 1 month. Similarly, the cost of using overtime production for the months is computed. We can meet D_1 using R_2 by allowing backordering. Therefore the cost is s. The unit cost of the outsourced item is k and is used in the table. Also, when *RT* is not used fully, some of the *RT* capacity goes to the dummy and carries an underutilization cost of u.

ILLUSTRATION 3.15 This transportation problem can be solved optimally to get the optimal production quantities.

We apply the transportation model to our Illustration. We have a total of 26 supply points and 13 demand points. The RT and OT capacity corresponding to the twelve months, the initial inventory and the outsourcing (with a capacity of 303000, which is the sum of all the demands) represent the 26 supplies. The demand for 12 months and the dummy (sum of all the supplies other than the outsourcing = 325120) represent the demand points.

The optimum solution to the transportation problem is the same as the LP optimum of the first formulation. There is no outsourcing, but there is underutilization of 12880 man-hours out of the *RT* capacity of month 12. This increases the cost by 2576 and the total cost is 3301320 + 2576 = Rs. 3303896.

The solution indicates that out of the initial inventory of 10000, 2960 is used to meet the demand of the first month and the balance is used to meet the demand of month 2. The rest of the solution is given in Table 3.26.

Table 3.26 Transportation solution

Month	*Demand*	*RT capacity*	*OT capacity*	*Demand met using*
1	30000	22880	4160	2960 from BI, 22880 from RT1, 4160 from OT1
2	30000	18720	4160	7040 from BI, 18720 from RT2, 4160 from OT2, 80 from outsourcing
3	25000	22880	5200	22880 from RT3, 2120 from OT3
4	15000	19760	4160	15000 from RT4
5	20000	23920	5200	20000 from RT5
6	25000	20800	4160	2000 from RT5, 20800 from RT6, 2200 from OT6
7	30000	22880	5200	1920 from RT5, 22880 from RT7, 5200 from OT7
8	40000	22880	5200	22880 from RT8, 5200 from OT8, 11920 from outsourcing
9	30000	18720	4160	18720 from RT9, 4160 from OT9, 7120 from outsourcing
10	28000	21840	5200	21840 from RT10, 5200 from OT10, 960 from outsourcing
11	20000	20800	4160	20000 from RT11
12	10000	22880	5200	10000 from RT12

The above solution uses 20080 hours of outsourcing and 12880 hours of underutilization of RT capacity. The total cost is Rs. 3155936 including the underutilization cost. The cost is lesser than the LP optimum. This can be explained as follows:

1. The LP solution provided in the example did not consider outsourcing as an alternative.
2. The outsourcing cost is fixed at Rs. 15 per man-hour and outsourcing works out cheaper than a three months inventory. Hence the solution uses outsourcing.
3. If we give a very high outsourcing cost (say Rs. 200 per hour), we get the same solution as the LP optimum.

3.2.5 Dynamic Programming

Though the transportation model provides a simple and elegant tool for aggregate planning considering six out of the eight costs, it does not include the set-up cost. When the same machine or facility makes multiple products, there is a set-up cost every time a product is made. The dynamic programming model can be used when set-up costs are to be included in the production plan.

ILLUSTRATION 3.16 Consider the four-period model where a set-up cost is incurred if the item is produced in the period. The data is given in Table 3.27.

Table 3.27 Data for DP model

Month	*Demand*	*Set-up cost*	*Production cost*	*Inventory cost*
1	80	60	5	2
2	60	40	4	2
3	40	60	5	1
4	70	45	5	2

We incur a set-up cost if we choose to produce in a month. Backorders are not permitted.

One of the ways to solve this problem is using dynamic programming (DP), where each stage would be a month. We could use the tabular approach in DP, but the state variable (available inventory) takes many values.

When we consider time-varying demand, two important observations are relevant.

1. It makes sense to produce at the beginning of the period than in the middle. This restricts the number of set-ups to certain fixed points in time.
2. It is also optimal if we produce when the stock on hand is zero. Otherwise we carry additional inventory which can be avoided.

Wagner and Whitin (1958) proposed an approach considering the following two aspects:

1. Orders are placed at the beginning of a period when the stock is zero. The order quantity is always equal to the demand of an integral number of periods starting from the period under consideration.
2. If there is inventory at the beginning of a period, it is enough to meet the demand of the period plus the demand of additional periods.

Wagner and Whitin also proposed a dynamic programming (DP) formulation and under the two rules described earlier, the number of computations in the DP is significantly reduced. The DP works as shown in Illustration 3.17.

ILLUSTRATION 3.17 **Month 1:** The demand of month 1 can be met only by producing in month 1. The cost is 60 + 5 × 80 = Rs. 460.

Month 2: The demand of month 1 can be met in two ways—by producing demands of both months 1 in month 1 and by producing in individual months. The costs are:

$$60 + 5 \times 140 + 2 \times 60 = \text{Rs. } 880$$

$$460 + 40 + 60 \times 4 = \text{Rs. } 740^{*}$$

In the first approach, we also carry an inventory of 60 units at the end of month 1 which attracts an inventory cost of Rs. 120. In the second, we add 460 to the total so that we include the cost of meeting demands of months 1 and 2.

The minimum is 740 (marked with a * mark) and will be used as the best way to meet the demand of the first-two months.

Month 3: Continuing the same way, we can meet the demand of month 3 in three ways. The costs are

$$60 + 180 \times 5 + 2 \times 100 + 2 \times 40 = \text{Rs. } 1240$$

$$460 + 40 + 100 \times 4 + 40 \times 2 = \text{Rs. } 980^{*}$$

$$740 + 60 + 40 \times 5 = \text{Rs. } 1000$$

The minimum is 980 marked with a * sign.

Month 4: Continuing the same way, we can meet the demand of month 4 in four ways. The costs are:

$$60 + 250 \times 5 + 2 \times 170 + 2 \times 110 + 1 \times 70 = \text{Rs. } 1940$$

$$460 + 40 + 170 \times 4 + 110 \times 2 + 70 \times 1 = \text{Rs. } 1470$$

$$740 + 60 + 110 \times 5 + 70 \times 1 = \text{Rs. } 1420$$

$$980 + 45 + 70 \times 5 = \text{Rs. } 1375^{*}$$

The least cost solution is to produce the demand of month 4 in month 4 and use the best way to produce the demands up to 3 months. This happens when we produce the demand of month 1 in that month and produce the demands of months 2 and 3 in month 2. The production quantities are 80, 100, 0, 70 with total cost = Rs. 1375.

Consider the case where backordering is allowed. Let the backorder costs be 1, 2, 1, 2 respectively. We assume that cost per unit backordered for month 1 is Re. 1/unit/month.

A solution with 0, 180, 0, 70 will have cost = 40 + 720 + 80 + 80 + 45 + 350 = Rs. 1315.

We now modify the previous algorithm to consider backordering.

ILLUSTRATION 3.18 Assuming that only one month's demand is produced. Month 1 demand can be met in one way:

$$\text{Cost} = 60 + 80 \times 5 = \text{Rs. } 460^{*}$$

We move on to meeting demand of month 2 by producing two months' demand. The production quantities and costs are given:

Quantities = [140, 0] Costs = 60 + 140 × 5 + 60 × 2 = Rs. 880

= [80, 60] = 460 + 40 + 240 = Rs. 740

= [0, 140] = 40 + 140 × 4 + 80 × 1 = Rs. 680*

We move on to meeting demand of month 3 by producing three months' demand. The production quantities and costs are given:

Quantities = [180, 0, 0] Costs = 60 + 180 × 5 + 100 × 2 + 40 × 2 = Rs. 1240

= [80, 100, 0] = 460 + 40 + 4 × 100 + 40 × 2 = Rs. 980

= [80, 0, 100] = 460 + 60 + 5 × 100 + 60 × 2 = Rs. 1140

= [0, 140, 40] = 680 + 60 + 40 × 5 = Rs. 940*

(Here, only the quantity [0, 140] was considered because it was the best at the earlier stage.)

Quantities = [0, 180, 0] Costs = 60 + 180 × 5 + 40 × 2 + 80 × 1 = Rs. 1120

= [0, 0, 180] = 60 + 180 × 5 + 40 × 2 + 60 × 2 = Rs. 1160

We move on to meeting demand of month 4 by producing four months' demand. The production quantities and costs are given:

Quantities = [250, 0, 0, 0] Costs = 60 + 250 × 5 + 170 × 2 + 110 × 2 + 70 × 1 = Rs. 1940

= [0, 250, 0, 0] = 40 + 250 × 4 + 80 × 1 + 110 × 2 + 70 × 1 = Rs. 1410

= [0, 0, 250, 0] = 60 + 250 × 5 + 80 × 2 + 40 × 2 + 70 × 1 = Rs. 1620

= [0, 0, 0, 250] = 45 + 250 × 5 + 80 × 3 + 60 × 4 + 40 × 1 = Rs. 1815

= [80, 170, 0, 0] = 460 + 40 + 4 × 170 + 110 × 2 + 70 × 1 = Rs. 1470

= [80, 0, 170, 0] = 460 + 60 + 5 × 170 + 60 × 2 + 70 × 1 = Rs. 1560

= [80, 0, 0, 170] = 460 + 45 + 5 × 170 + 60 × 4 + 40 × 1 = Rs. 1635

= [0, 140, 110, 0] = 680 + 60 + 5 × 110 + 70 × 1 = Rs. 1360

= [0, 140, 0, 110] = 680 + 45 + 5 × 110 + 40 × 1 = Rs. 1315

= [0, 140, 40, 70] = 680 + 60 + 5 × 40 + 45 + 70 × 5 = Rs. 1335

= [0, 180, 0, 70] = 1120 + 45 + 70 × 5 = Rs. 1315

The optimum solution has a cost of Rs. 1315 and there are two optimal solutions.

In the above illustration, the cost reduced when we considered backordering. This was because the backordering cost is cheaper than the inventory carrying cost for certain periods. This usually is not the case. Backordering as a strategy has to be considered for implementation only after the backorder cost is correctly estimated, which is very difficult considering that there is a component of goodwill cost which is difficult to define and measure. Many times it is good not to have backorder in the plans even though the cost may be lesser.

3.2.6 Quadratic Model

The various approaches for aggregate planning that we have seen—tabular and linear programming, transportation and dynamic programming models are linear. The assumption is that the various costs increase linearly with increase in the variables. In practice, it is observed that the costs have a non-linear relationship with the variables. This lead to the development of non-linear models for aggregate planning.

The most popular among the non-linear models is the Quadratic Model of Holt, et al., (1960) called the **HMMS model** named after the authors. The model considers regular time payroll, over time payroll, inventory costs and workforce changeover costs. The authors build the following relationships among the costs and the variables:

$$\text{Regular time payroll cost} = C_1 + C_2 W_t$$

$$\text{Overtime payroll cost} = C_3 (P_t - C_4 W_t)^2 + C_5 P_t - C_6 W_t + C_7 P_t W_t$$

$$\text{Inventory cost} = C_8 (I_t - I_t^*)^2, \text{ where } I_t^* = C_9 + C_{10} D_t$$

$$\text{Workforce changeover cost} = C_{11} (W_t - W_{t-1} - C_{12})^2$$

Here, D_t = Demand (in man-hours) during period t

W_t = Workforce employed in period t

P_t = Total production (in man-hours) in period t

I_t = Inventory (in man-hours) at the end of period t.

The coefficients are determined from earlier data using regression analysis. The overtime payroll cost, inventory cost and changeover costs are modelled as a quadratic function of the variables.

The total cost to be minimized is the sum of all the costs. The problem is to

$$\text{Minimize } \sum_t C_1 + C_2 W_t + C_3 \left(P_t - C_4 W_t\right)^2 + C_5 P_t - C_6 W_7$$

$$+ C_7 P_t W_t + C_8 (I_t - I_t^*)^2 \ + \sum_t C_{11} (W_t - W_{t-1} - C_{12})^2$$

$$\text{Subject to } I_t = I_{t-1} + P_t - D_t$$

$$I_t, P_t, D_t \geq 0$$

The above problem is a quadratic programming problem and can be solved using the Wolfe's algorithm.

Since the constraints are equations, a Lagrangean multiplier based method can be used to dualize the constraint into the objective function. The resultant Lagrangean function can be differentiated to get the values of the variables. The advantage of a model with a quadratic objective function and linear constraints is that the resultant equations after setting the first derivatives to zero are linear and can be solved comfortably.

EXERCISES

1. XYZ Ltd. wants to do an aggregate plan for the next periods. Kiran, the Planning Manager is aware of the several models for aggregate planning. He wants to have a model where the decision-maker has a role to play and decides to implement the graphical model. The company wants to consider all possible options such as overtime, undertime, inventory, shortage, off-loading, hiring and lay-off. The various costs and the demands (forecast) are known.
   (a) Would you agree with Kiran's choice of model?
   (b) If you were to develop a graphical model, how would you build it to accommodate all the costs. Define the relationship among the variables and the costs. Assume that you are building software for the model and discuss how the total cost of the plan would be computed. What choices of variables are available for the user?
2. Explain the graphical model for aggregate planning. Indicate the direct decisions to be made by the user and how the user makes those decisions. Assume that the organization is interested in including costs of production, regular time, overtime, inventory, shortage, hiring, lay-off, underutilization and subcontacting in its analysis. Relate each of the costs to the decisions made by the user. Draw free hand graphs to explain your model and the decisions made by the user.
3. Explain the linear programming model for aggregate planning. Indicate clearly the decision variables, constraints and the objective function. Assume that the organization is interested in including costs of production, regular time, overtime, inventory, shortage, hiring, lay-off, underutilization and subcontacting in its analysis. Can an LP solution give a higher value of cost when compared to the cost of actual decisions? Why or why not?
4. A manufacturer has the following information on its major product:

Regular time production capacity	2600 units/period
Inventory costs	$2/unit/period
Overtime production cost	$12 per unit
Backlog costs	$5/unit/period
Beginning inventory	400 units

   The demands for four periods are 4000, 3200, 2000 and 2800 respectively. Develop an aggregate plan and evaluate its cost.
5. XYZ Ltd. is interested in an aggregate plan that determines the production quantities in the next six months. The forecast for the six months in man-hours is given in Table 3.28.

Table 3.28 Forecast for six months

March	*April*	*May*	*June*	*July*	*August*
15000	12000	18000	20000	25000	20000

Initial inventory is 8000 man-hours and the expected final inventory is 10000 man-hours. Regular time production hours available are 15000 man-hours and 6000 hours can be got through over time. The RT production cost is Rs. 20 per hour and OT cost is Rs. 30 for the first day and Rs. 40 for the second day. It may be assumed that the company works for five days a week and hence an additional 20% capacity can be got through OT each day. The cost of changing workforce is given by $d^2 - 2.5d$ where d is the change in production level. Cost of inventory is Rs. 5 per unit per month while cost of shortage is Rs. 20 per unit per month.

Formulate an aggregate plan that decides the production quantities and inventory levels for the company. State clearly your choice of the model and the assumptions.

6. Shakthi Breweries Ltd., at Taramani in Madras wants to do an aggregate plan for the next periods. Mr. Saarang, the Planning Manager is aware of the several models for aggregate planning. He wants to have a model where the decision-maker has a role to play and decides to implement the graphical model at Taarams. He had successfully implemented this model in his earlier job at Vicky's in Bangalore. Mr. Saarang wants to consider all possible options such as overtime, undertime, inventory, shortage, subcontracting, hiring, lay-off and underutilization. The various costs and the demands (forecast) are known.

(a) Explain how Mr. Saarang would build his model.

(b) If Mr. Saarang wants to create a software package for this model, what additional features can he provide?

(c) Is this model optimal?

(d) Mr. Saarang's foreign partner DeBeer & Co. uses an LP formulation and claims that it uses optimization to solve the aggregate planning problem. Can an LP solution give a higher value of cost when compared to the cost of actual decisions? Why or why not?

7. What are the costs included in the transportation model of aggregate planning? Show the transportation model in the form of a table.

8. The forecast of demand of a product in the next four months are 130, 80, 180 and 140 respectively. Normal capacity is 100, overtime capacity is 20 and subcontractors have capacity of 60 per month. Costs are $10, $12 and $15 respectively. It costs $1 to carry one unit per month and no backordering is allowed, formulate your least cost aggregate plan for this situation.

9. A manufacturer has the following information on its major product:

Regular time production capacity = 2600 per period

Regular time production cost = Rs. 400/unit

Overtime cost = Rs. 600/unit

Inventory cost = Rs. 100/unit/period (based on ending inventory)

Backlog costs = Rs. 250/unit/period

Beginning inventory = 400 units

Demands for four periods = 4000, 3200, 2000 and 2800 respectively

Develop a production plan that yields zero inventory at the end of period 4 and balances total production in the period and minimizes total costs.

10. A company makes two products and has two assembly lines. Line 1 can assemble both the products, while line 2 can assemble product 2 only. Assume that the time to assemble for the products as 8 minutes and 6 minutes per piece respectively and there are no changeover times. Each line works for 8 hours a day for 22 days in a month. There is an additional OT of 4 days available at 8 hours per day. The following costs are known:

RT cost = Rs. 10/minute,

OT cost = Rs. 15/minute,

Inventory cost = Re. 1/minute

Backorder cost = Rs. 25/minute,

Underutilization cost = Rs. 5/minute,

The demand for product 1 for the next three months are 2000, 1000, 1000 and for product 2 are 3000, 800 and 500 respectively. Assuming that the company does not want to use the outsourcing option, create a balanced transportation problem for the above situation and answer the following questions:

(a) The number of supply and demand points in the table are ______ and ______.

(b) The dummy has a ______ (supply/demand) of ______.

(c) If the problem has a feasible solution, the company should consider ______ in the first month.

QUESTIONS

1. Why do we need aggregate planning?

2. What is the meaning of the term aggregate production planning? What are its objectives and uses?

3. Aggregate planning involves identifying a representative (aggregate) product and creating a production plan. In today's world where computing facilities are available in plenty, it is possible to do individual plan for each product than do an aggregate plan, comment.

4. Discuss whether the linear programming model for aggregate planning always gives the optimum solution.

5. Give three pure strategies for aggregate planning and explain them.

6. What are the typical outputs of an aggregate plan?

7. In a linear programming formulation of aggregate planning problem, write the two constraints where outsourcing and underutilization appear. Explain them.

8. What is the advantage of using a quadratic model for aggregate planning? How is this solved?

9. When do you use the following aggregate planning models and why?

(a) Linear programming model

(b) Parametric model

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