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MODELING MULTILEVEL SUPPLY CHAIN SYSTEMS TO OPTIMIZE ORDER QUANTITIES AND ORDER POINTS THROUGH MATHEMATICAL MODELS, DISCRETE EVENT SIMULATION AND PHYSICAL SIMULATIONS

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DOCTOR OF PHILOSOPHY

in

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OLD DOMINION UNIVERSITY
May 2005

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ABSTRACT

MODELING MULTILEVEL SUPPLY CHAIN SYSTEMS TO OPTIMIZE ORDER QUANTITIES AND ORDER POINTS THROUGH MATHEMATICAL MODELS, DISCRETE EVENT SIMULATION AND PHYSICAL SIMULATIONS

Alok K. Verma
Old Dominion University, 2005
Director: Dr. Han P. Bao

Managing supply chains in today's distributed manufacturing environment has become more complex. To remain competitive in today's global marketplace, organizations must streamline their supply chains. The practice of coordinating the design, procurement, flow of goods, services, information and finances, from raw material flows to parts supplier to manufacturer to distributor to retailer and finally to consumer requires synchronized planning and execution. Efficient and effective supply chain management assists an organization in getting the right goods and services to the place needed at the right time, in the proper quantity and at acceptable cost. Managing this process involves developing and overseeing relationships with suppliers and customers, controlling inventory, and forecasting demand, all requiring constant feedback from every link in the chain. Base Stock Model and (Q, r) models are applied to three tier single-product supply chain to calculate order quantities and reorder point at various locations within the supply chain. Two physical simulations are designed to study the above supply chain. One of these simulations is specifically designed to validate the results from Base Stock model. A computer based discrete event simulation model is created to study the three tier supply chain and to validate the results of the Base Stock model. Results from these mathematical models, physical simulation models and computer based simulation model are compared. In addition, the physical simulation model studies the impact of lean implementation through various performance metrics and the results demonstrate the power of physical simulations as a pedagogical tool for training. Contribution of present work in understanding the supply chain integration is discussed and future research topics are presented.

In loving memory of my late mother

Mrs. Kamala Devi

for her selfless and dedicated service to our family.

With respect and gratitude to my father

Mr. J. P. Verma

for his support and guidance

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Finally this work would not be possible without the support from my family. Through all these years, my wife Rashmi, was supportive of my endeavor and took care of all responsibilities including, taking care of our children and thus allowing me to focus on my research. I am grateful to my children Shalini and Shivesh for their understanding of my absence. Sincere appreciation to my parents in-law Dr Ram Chandra Gupta and Mrs. Bimla Gupta, my uncle Dr. D. K. Singh and, my brother Prof. V.K. Verma for their persistent encouragement and support. Drs Ram Bachan Ram, Sudhir Mehrotra, Rahul Gupta, K. P. Singh, Satyajit Verma and Arun Verma were also constant source of encouragement. Thanks to Amol Sonje for helping me run various cases of mathematical models and to Harsh for his help with supply chain simulation development. Thanks to Tiffany Brittingham and Diane Mitchell for providing help with formatting the manuscript.

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Chapter - 1

INTRODUCTION

Supply chain management is the integration of key business processes from end user through suppliers and provides products, services, and information that add value for customers and other stakeholders. In today's highly competitive environment, companies must manage costs if they are to survive. Cost management must be applied across the entire life of the product by everyone involved in its design and manufacture. Cost management cannot be limited to the four walls of a factory, it must spread across the entire supply chain and cover all aspects of the value chain of the company's products or services.

However, it is more than just cost management that must extend across the organizational boundaries between buyers and suppliers. Suppliers are major source of innovation for lean enterprises [1] & [4]. The key point is that the supply chain must be managed for competitive advantage, not just to reduce cost. [13]

At the beginning of the Century, supply chains were paper chains, linearly connecting manufacturers, warehouses, wholesalers, retailers and consumers. The chain ranged from one or two to dozens of tiers and logistics were a nightmare. People and paper physically connected various tiers together. Furthermore, the linear nature of the chain made communication between the front-end and back-end of the chain messy and time consuming.

The advent of Internet and computers has changed the structure of supply chain in the later third of the 20th century. The following quote from the Stanford University web site provides a glimpse of the new paradigm in supply chain and is illustrated in Figure 1.

"The latest generation of supply chain management is Web-Centric. It is characterized by the marriage of the Internet and the supply chain and has resulted in the birth of electronic business (e-business) applications. These Internet enabled, e-business

applications have Internet integrated all branches of the supply chain and emerged as the most cost effective means of supply chain operation. E-business applications (e-procurement, e-commerce, and e-collaboration applications) change the supply chain from a linear, rigid chain into a dynamic chain based on an information hub called an ERP (Enterprise Resource Planner)."

The supply chain, which typically spans multiple companies, has demanding needs that are becoming increasingly more complex and difficult to link together. E-business applications have evolved into the most intelligent and optimized tools with which to execute front-end and back-end operations in a supply chain, using the Internet. E-business applications effectively provide an information system that links multiple companies in the chain.

The center of the e-business supply chain is an information hub (a node in a data network where multiple organizations interact in pursuit of supply chain integration), where incoming information is quickly processed and then sent out to other chain-members. The hub also has capabilities of data storage and push/pull publishing.

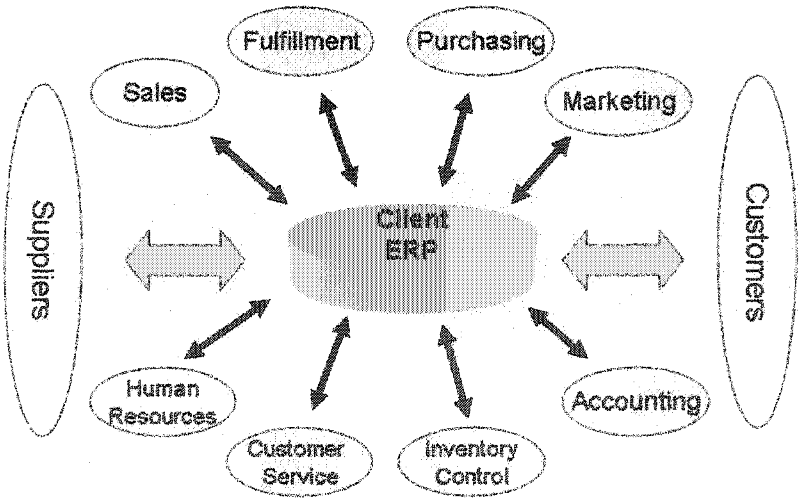


Figure 1. New structure of Today's Supply Chain
Adapted from Stanford Web Site

The emergence of lean supply is the first step in the larger process of creating a lean supplier network. The high degree of outsourcing that characterizes lean enterprises means that every firm in the supply chain is responsible only for small percentage of total value added of a product. Lean thinking requires that participants in the lean supply chain focus on the value creation process and collaborate actively with other participants both upstream and downstream to maximize the value created for customer. While the interaction between players in the supply chain has become more concurrent in nature the flow of parts still takes place in a sequential manner. Figure 2 shows this flow in a typical two tiered supply chain which is the focus of this study.

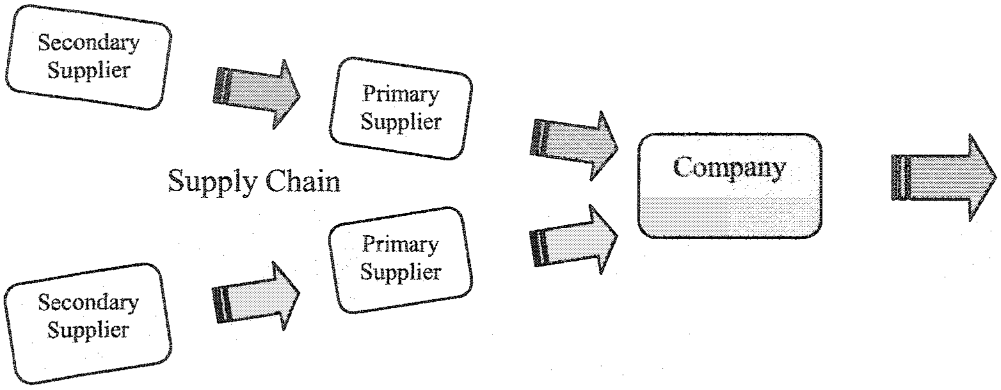


Figure 2. Flow of Parts in a Two Tiered Supply Chain

Chapter – 2

BACKGROUND INFORMATION

2.1. Lean Philosophy

The term lean was first coined about 15 years ago at Massachusetts Institute of Technology and later published in a book called *Machine That Changed the World,* written by James Womack and his colleagues [4]. The generally accepted definition of lean in the industrial community is that it is:

"*A systematic approach to identifying and eliminating waste (non-value-added activities) through continuous improvement by flowing the product at the pull of the customer in pursuit of perfection.*"

The lean principles have evolved from the works of Henry Ford and subsequent development of Toyota Production System in Japan. Lean manufacturing principles improve productivity by eliminating waste from the product's value stream and by making the product flow through the value stream without interruptions [1], [4] & [5]. This system in essence shifts the focus from individual machines and their utilization to the flow of the product through processes [7].

Lean philosophy is people centric in the sense that it focuses on the value for the customer and how this value can be increased by removing waste from the system and increasing flow through the system by changing the way people think about their work. It is more about people than the tools and techniques it employs. Lean defines value in terms of the entire customer experience with the product [1]. A critical step in defining value is the determination of **target cost** based upon the resources required to make a product of given specification if all the **muda** (waste) was removed from the system.

In their book Lean Thinking, James Womack and Dan Jones [1] outline five steps for implementing lean:

1. Specify the value desired by the customer.
2. Identify the value stream for each product and challenge all waste.
3. Make the product flow through the value creating steps.
4. Introduce pull between all steps where continuous flow is possible.
5. Manage toward perfection by continuously improving the process.

Lean philosophy can be described metaphorically as house whose foundation are Lean vision and commitment, the building blocks are various tools used to implement Lean principles and roof is the philosophy of continuous improvement. The entrance to the house is through another tool – Value Stream Mapping. This concept is graphically represented below in Figure 3 as the House of Lean.

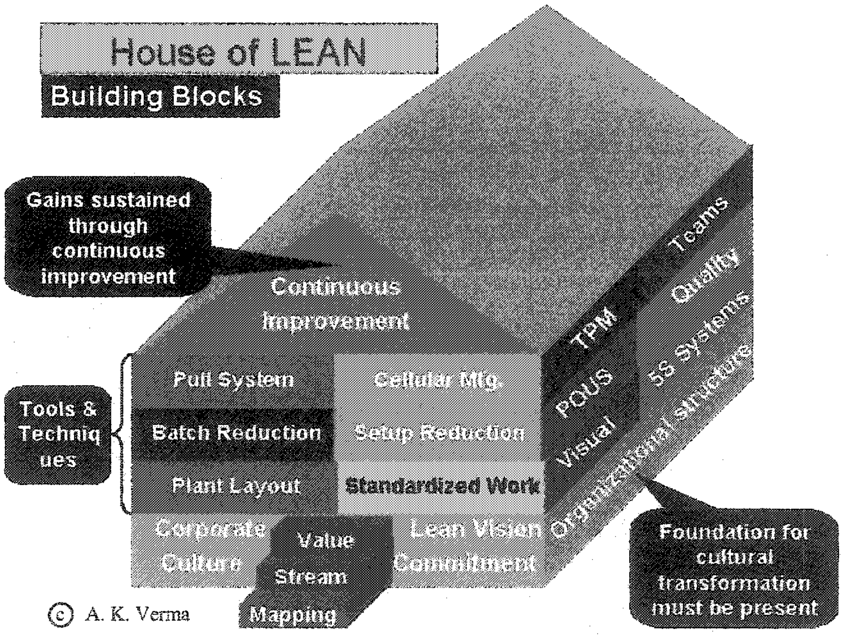


Figure 3. House of Lean and Tools

The power of Lean philosophy can be seen in the benefit it can generate for an organization. It is not uncommon to have a value-added content of only 5-30% within many current business enterprises [55]. This means, there is opportunity to eliminate 70 to 95% of waste in their value streams. Documented results across various industries are indicated in Table 1.

Element	Benefit
Capacity	10 to 20 % gain in capacity by optimizing bottlenecks
Inventory	Reduction of 30 to 40% in inventory
Cycle Time	Throughput time reduced by 50 to 75%
Lead Time	Reduction of 50% in order fulfillment
Product Development Time	Reduction of 35 to 50% in development time
Space	35 to 50% space reduction
First-pass Yield	5 to 15% increase in first-pass yield
Service	Delivery performance of 99%

Table 1. Lean Benefits

2.2. Lean Enterprise

When Lean principles are applied not just to manufacturing but to business operations not only within the organization but across all supply chains, a lean enterprise is created. Lean enterprise therefore is a set of synergistic processes along a value stream to create value for the customer.

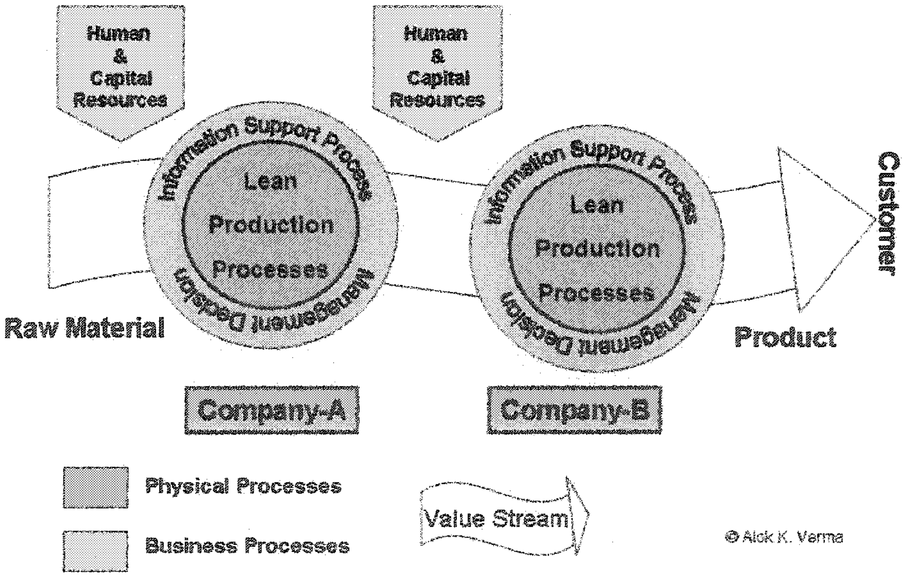


Figure 4. Lean Enterprise

Lean thinking encourages organizations to view itself as just one part of an extended supply chain. It follows that organizations need to think strategically beyond their own boundaries. Lean philosophy contends that because value streams flow across several departments and functions within an organization, a company should be organized around its key value streams. A value stream in general may cut across organizational boundaries of several organizations as shown in Figure 4. Stretching beyond the firm, some form of collective agreement or organization is needed to manage the whole value stream for a product family, setting common improvement targets, rules for sharing the gains and effort and for designing waste out of future product generations. This collective group of organizations is called a lean enterprise.

2.3. Value Streams and Supply Chains

A product is created within a value stream by a set of linked processes either within a single organization or across multiple organizations. A single organization may have its own supply chain that provides it with raw materials, components or services to make the product. Value stream of a small component may merge into the value stream of a larger product as shown in Figure 5. Value streams of different products may cross within a company also.

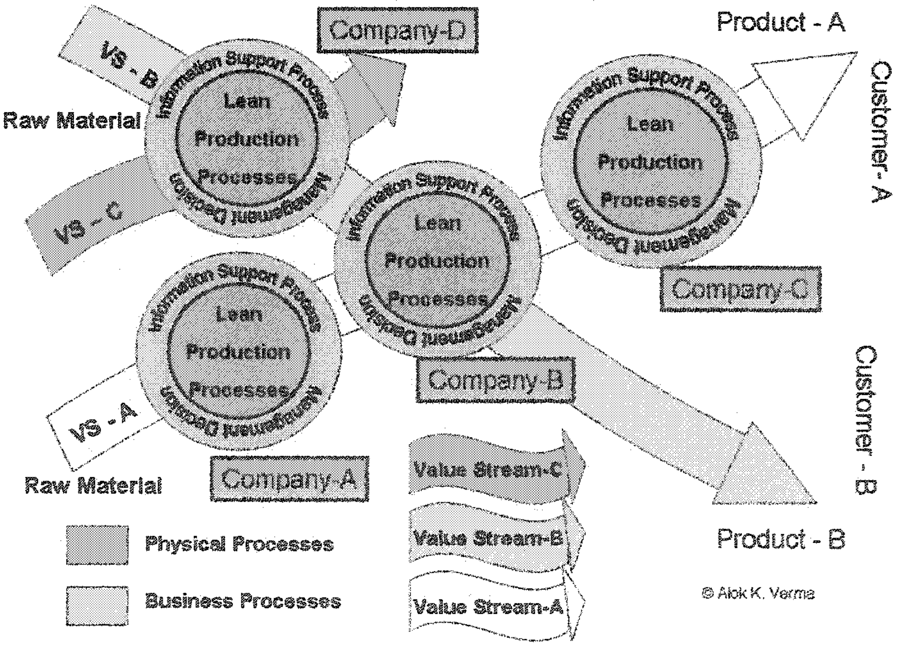


Figure 5. Intersecting and Merging Value Streams

It is important to note that while the flow of parts and material may be linear along a value stream, the flow of information may be concurrent and may use an Enterprise Resource Planning (ERP) system. This is further discussed in section 2.4 and illustrated in Figure 7.

Figure 6 shows four value streams for the production of a carton of cola. The cola is produced using essence which is made from caramel from corn which is produced in corn fields. Sugar is used to sweeten the cola which is grown in sugar fields. Cola is packaged in aluminum cans which are produced consecutively by smelting, hot rolling, cold rolling and drawing processes. Cans are packaged in carton which is produced from paper in carton plant.

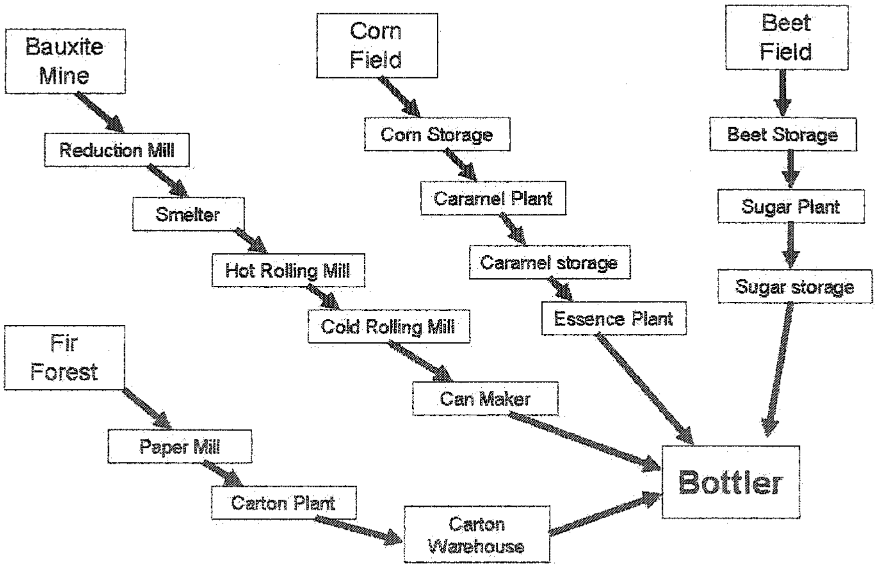


Figure 6. Value Streams for Cola Production
Adapted from Womack & Jones [1]

2.4. Lean Extended Enterprise

The highest generation of Lean is the *Lean Extended Enterprise*. Here, an organization views all participating entities in the value stream (e.g., suppliers, subcontractors, its own enterprise and customers) as part of its own. The Lean Extended Enterprise is an expansion of the traditional notion of Lean to improve velocity, flexibility, responsiveness, quality and cost across the entire value stream. The effectiveness of each partner determines the effectiveness of entire value stream [55]. Supply Chain Management (SCM), Enterprise Resource Planning (ERP), Customer Relations Management (CRM) and Suppliers Relations Management (SRM) and Product Lifecycle Management (PLM) form an integral part of the Lean Extended Enterprise as shown in Figure 7.

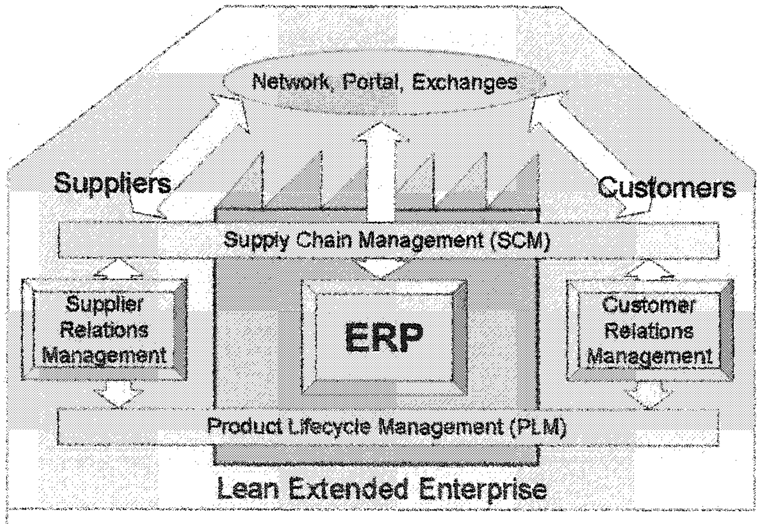


Figure 7. Lean Extended Enterprise
Adapted from Burton & Boeder [55]

Chapter – 3

SUPPLY CHAIN AND INVENTORY MANAGEMENT

3.1 Issues in Supply Chain Management

Traditional supply chains are plagued with inefficiencies resulting from adversarial relationships among key players. These inefficiencies result in long lead time, high cost, late deliveries, high inventory and un-satisfied customers. A survey was conducted to identify the key issues related to supply chain facing the ship building industries in this area. The ranked issues are listed in Table 2.

No.	Issues
1	Scheduling Problem
2	Adversarial Relationship with Supplier
3	No Involvement of Supplier in Product Design and Development Process
4	Long Lead-Time
5	High Costs
6	High Inventory
7	Challenge in Synchronizing Flow with Suppliers.
8	Vendors Furnishing Information Late
9	Irregular Performance
10	Higher Price to US Shipyards
11	Shrinking Choice of Vendors
12	Frequent Engineering Changes

Table 2. Issues in Supply Chain Management

3.2 Basic Components of Supply Chain

Supply chain management is the combination of art and science that goes into improving the way a company finds the raw components it needs to make a product or service, manufactures that product or service, and delivers it to customers. The following are five basic components for supply chain management.

a. Plan - This is the strategic portion of supply chain management. One needs a strategy for managing all the resources that go toward meeting customer demand for one's product or service. A big piece of planning is developing a set of metrics to monitor the supply chain so that it is efficient, costs less, and delivers high quality and value to customers. Of many planning approaches that exist in business today, Management by Planning (MBP) is unparalleled in its ability to articulate the objectives to be delivered, the plans by which objectives will be delivered, the ownership of the team in delivering the objectives, and management's responsibility in aiding the team in meeting those objectives. In Management by Objective (MBO), the stated objective becomes the focus and not the process by which objective is achieved. By contrast, in Management by Planning the goal is to become a learning organization through the activity of planning and the implementation of theses plans [11]. Thus, MBP is a process oriented approach to supply chain management.

Applying MBP to the integration of lean SCM and activities first involves identifying common overarching objectives. Overarching objectives simply are the highest level objectives based directly on strategic intent of the company.

b. Source - Choose the suppliers that will deliver the goods and services needed to create product or service. Develop a set of pricing, delivery and payment processes with suppliers and create metrics for monitoring and improving the relationships. And put together processes for managing the inventory of goods and services received from suppliers, including receiving shipments, verifying them, transferring them to manufacturing facilities and authorizing supplier payments.

c. Make - This is the manufacturing step. Schedule the activities necessary for production, testing, packaging and preparation for delivery. As the most metric-intensive portion of the supply chain, measure quality levels, production output and worker productivity.

d. Deliver - This is the part that many insiders refer to as "logistics." Logistic activities include locating facilities, coordinating the receipt of orders from customers, developing a network of warehouses, picking carriers to get products to customers and setting up an invoicing system to receive payments etc. These activities have been integrated over the past 50 years and are an essential function of supply chain management.

To achieve highest level of service at the lowest possible cost, it is necessary for managers to examine the entire logistic system and not just one isolated facility or activity such as transportation. The logistic system is concerned not only with the physical placement of the facilities, but also with the levels of inventory and the flow of material through those facilities [16]. Logistic includes the activities of sourcing and purchasing, conversion, including capacity planning, technology solution, material planning, scheduling etc. [12].

e. Return - The problem part of the supply chain. Create a network for receiving defective and excess products back from customers and supporting customers who have problems with delivered products.

3.3 Lean Supply Chain Management (SCM)

The concept of single-piece flow lies at the heart of lean supply, with the supplier acting as an extended just-in-time factory for the buyer. While mass production relies on inventories at buyer as well as supplier. When both buyer and supplier have adopted lean thinking, the safety net of inventory is removed. This results in endless search for perfection in the supply chain. [11]

The heavy reliance on the suppliers forces the lean producers to develop rich relationships with its suppliers because the firms are tightly connected through their production processes.

SCM and Lean manufacturing intersect most significantly in profitability objectives, customer satisfaction objectives, and quality objectives. It is typically these three areas and the resulting strategic activities that drive the coordinated operational actions.

While lean manufacturing has been widely practiced internally, most manufacturers have failed to realize the importance of extending those same lean principles to their suppliers. Lean philosophies must be applied consistently to the supply chain, just as they are embraced internally to maximize the elimination of waste. Lean manufacturing requires a different sourcing philosophy—one that is focused on sole sourcing, supplier selection criteria beyond cost such as capabilities and culture. For lean manufacturing to work effectively, the suppliers in the chain take on a greater role and take over some of the activities that the buyer previously handled. This requires a system of mutual trust and respect between the buyer and its suppliers. The supplier relationship must be more tightly integrated in terms of sharing information and interlocking business processes. As a result, supplier relationships become much more strategic, and supplier certification programs are more rigorous to determine a supplier's ability to support a lean customer. This results in more strategic suppliers with longer relationships and longer term contracts. Strategic relationships are a prerequisite to extending lean concepts to suppliers.

The main focus of lean is the goal of continuous single piece flow. When applied to replenishment, this is reflected in the pull model, most commonly supported through a kanban system. The problem with most lean manufacturers is that after all their focus internally on heijunka (defined as "production smoothing") and takt time (defined as "net operating time divided by customer requirements"), they end with simply providing their supplier with a kanban signal. Furthermore, when driving to single-piece flow and requiring suppliers to deliver smaller lot sizes more frequently, they end up shifting excess inventory up the supply chain. They have achieved lean deliveries, but have not eliminated the waste. The supplier's need to hold a larger inventory to support the customer's JIT requirements simply creates hidden costs and waste elsewhere in the supply chain. A much more beneficial approach is to extend the lean principles beyond suppliers' finished goods inventory and into their production processes. Of course, this requires the type of strategic relationship discussed earlier. By breaking down the supplier's production lead time, it is possible to provide the supplier earlier visibility to demand signals that can drive shorter overall lead times. Specifically, this could include providing forecast and historical consumption data for planning in conjunction with the kanban signal that authorizes shipment. This also allows the suppliers to perform their own heijunka or leveling process that is more aligned with the end customer demand.

Finally, measuring supplier performance is critical to building a lean supply chain. Coupled with the benefits of mutual trust and respect comes accountability on quality, delivery, costs reduction and responsiveness. Defining and measuring the key metrics of the supplier relationship is the best way to ensure that supplier performance is aligned with a manufacturer's strategy and goals.

3.4 Supply Chain Dynamics

To succeed in the serious competitive market, firms take many actions to improve their supply chain performances. One of the hot points is supply chain planning under uncertainty. In this context, Supply Chain Dynamics (SCD) is meant to be dynamics associated with the variability of the system. Supply Chain Dynamics (SCD) makes the planning more difficult, and results in unpredictable business performance. Sen, Scott, Thomas et. al. [56] studied the effect of SCD on the proportion of Build-to-stock and Build-to-order in supply chain planning and evaluated the effects of SCD on the business performance and improvement. They look at the effects of SCD due to demand forecast, capacity, and information and materials delay, on business performance and planning.

There are many factors that amplify the complexity of SCD [56]. Some important factors are:

a. Demand Forecast: Companies do operate according to their forecast of the future customer demand, at least partially. As it is a rolling horizon forecast, it keeps changing and so do the orders. So, there will be a difference between the quantity produced and the actual demand quantity.

b. Capacity: Obviously, if the demand is less than the capacity, the unpredictability due to SCD will become a mute point. Otherwise extra dynamics will be incurred due to limited capacity.

c. Information Delay: Obviously, it always takes some time for the information to flow from the purchasing intention of customers to the Master Production Scheduling. It also takes some time for the information on directions of production and operation to flow from the MPS to the operational unit. These information delays not only make forecast more difficult, but also lengthen the total cycle time of delivery.

d. Material Delay: It is common that sometimes materials are in short supply. In this case, firms may order more than that they really need to ensure that their material supply is enough and in time.

3.5 Lean Buyer Supplier Relations

Lean buyer-supplier relations have four major characteristics. The first deals with *reduced supplier base*. Lean enterprises rely on the smaller number of suppliers than their mass production counterparts. This helps them in creating tighter linkages with their suppliers. Sustaining these tighter linkages requires rich relationships with the suppliers. The second characteristic deals with *level of relationships*. Buyer-supplier relations depend heavily on the degree of reliance that the buyer is placing on the supplier for design innovation. When virtually no reliance is placed on supplier for design innovation, the supplier is either a common supplier of commodities (such as nuts, bolts etc) or a subcontractor for simple components designed by the buyer. When design innovation is required, the supplier is either a major supplier or family member. Major suppliers design and manufacture group components and family members produce major functions. As the level of supplier shifts from common to family member, their number typically drops. The third characteristic captures the *nature of buyer-supplier relationship*. In particular buyer-supplier relationships are characterized by interdependence- the buyer depends on supplier for its design expertise, and supplier depends on buyer for both business and technical support. The outcome of this interdependence is buyer-supplier relations that are stable over time, have high degree of cooperation and operate for mutual benefit. While interdependence is the glue that holds the buyer-supplier relations together, it is the trust that enables the buyer and supplier to interact in the sophisticated and mutually beneficial ways. Trust is created primarily through the stability of the buyer-supplier relationships. It is created because there is a high level of cooperation between buyer and supplier [11]. This nature of buyer-supplier relationship is shown in Figure 8.

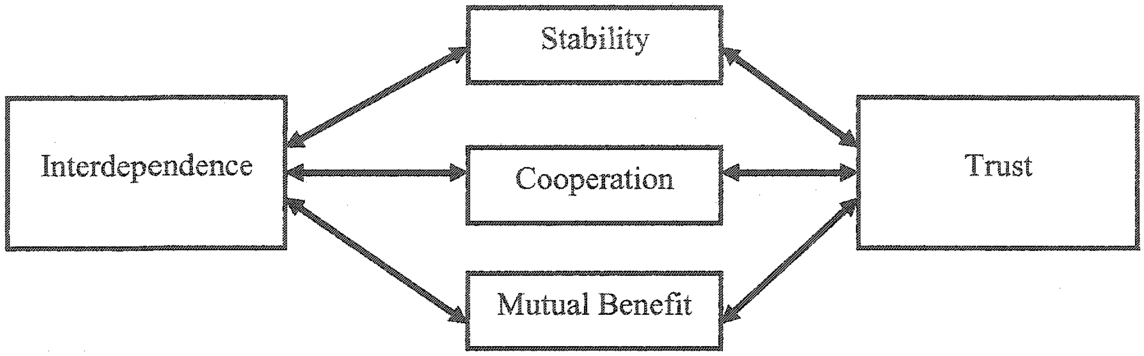


Figure 8. Nature of Buyer-Supplier Relations

The final characteristic looks at *the way that organizational boundaries are blurred as firms begin to share resources dynamically.* Once the right type of relationships has been developed, buyer and supplier can take advantage of that relationship.

The advantage of these lean buyer-suppliers relations lies in increased ability and willingness to share information about product design, manufacturing processes and product costs. This shared information enables buyer and supplier to increase their degree of innovation, leading to products that have higher functionality and lower cost.

3.6 Reducing the Number of Suppliers

The level of coordination required between lean buyers and suppliers is much greater than in the world of mass production. The tight interaction between buyer and supplier makes it difficult for lean producers to rely on a large number of suppliers because transaction costs will be high. There are three ways to reduce the number of suppliers: reduce the number of suppliers for each part; reduce number of suppliers for each family of parts; and outsource fewer parts. The advantage of having multiple suppliers is reduced reliance on a single source while the disadvantage lies in loss of economies of scale and minor differences in the parts supplied by two suppliers that may cause problem on production floor. Most lean producers rely on single lean supplier for each part.

Lean producers opt to select several competing suppliers at the parts-family level. Thus individual part is single sourced but part family is multi-sourced. The advantage of this approach lies in the creativity induced by the competition and sharing the improvements among the suppliers involved. When major functions are outsourced then multiple suppliers approach is not adopted. Instead single supplier is identified and near-equal partnership is created.

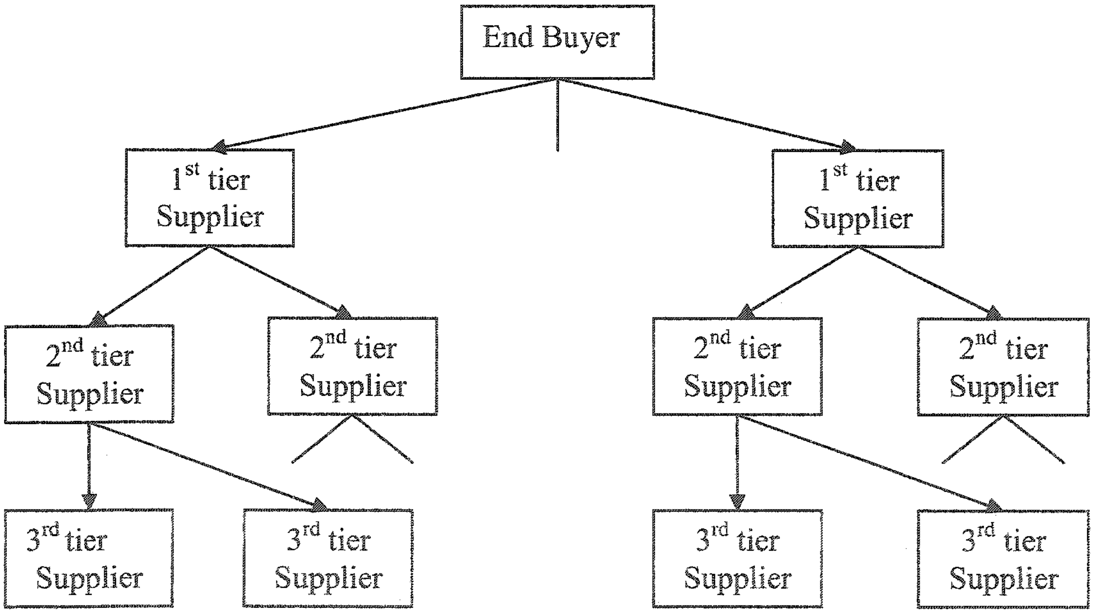


Figure 9. Tiered Supply Chain

The number of outsourced parts can be decreased by manufacturing more in-house and by outsourcing group components and major functions as opposed to individual components. The decision to outsource group components or major functions leads to tiered supplier structure. The direct or first tiered suppliers are responsible for design and manufacture of group components and major functions that are being outsourced. In turn they identify the secondary supplier for the components that they outsource. The result of this approach is that each firm deals with relatively small number of suppliers and that overall there are fewer number of suppliers. Figure 9 shows an example of tiered supply chain.

3.7 Four Levels of Buyer-Supplier Relations

Four distinct levels of buyer supplier relations can be identified: common suppliers, subcontractors, major suppliers, and family members. This four level categorization to a certain extent oversimplifies the complex relationships between buyers and suppliers that are observed in practice. Common suppliers supply components that are commonly available and are purchased by many buyers. Examples include nuts, bolts etc. The buyer's relationship with its common supplier is the least sophisticated of all the supplier categories. Typically common suppliers are viewed as interchangeable and cost is often the deciding factor in the choice of supplier. The subcontractors are brought into the process after buyer has designed the product. The subcontractor's task is to manufacture these parts to buyer specifications. Their design responsibility is limited to the suggestions for minor improvements to the component design. The buyer's relationship with subcontractors is richer than that with common supplier but still fairly unsophisticated.

For major suppliers, the buyer provides high-level specifications and then requests the supplier to design the major function or sub-assembly. Major suppliers get involved in the design process after the product has been conceptualized but before detailed design is established. The buyer's relationship with its major supplier is much richer than with its common suppliers and subcontractors. Family members are responsible for completely designing and delivering a major function of the final product. They have highest degree of autonomy and act almost as an integral part of the buyer's design team. The buyer's relationships with its family members are the richest of all the supplier categories.

3.8 Lean Supplier Networks

The emergence of lean supply is the first step in the larger process of creating a lean supplier network. The high degree of outsourcing that characterizes lean enterprise means that each firm in the supply chain is responsible for only a small percentage of total value added of a product. To achieve full advantages of lean design and production, all the firms in the supply chain have to adopt lean buyer-supplier relations. The individual supply chains form a network of suppliers. These lean supplier networks functions in many respects as a single entity dedicated to producing low cost products that have high functionality and quality the end customer's demand. The primary advantages of these networks are their flexibility and responsiveness compared to mass producers. The primary determinant of the type of supplier network is the number of core firms that dominate the network. The first type of network the "kingdom" emerges when a single firm adopts the core position. Typically this is the firm that sells end product to the customer. These networks operate to support the central firm that dominates the entire network. Second type of network "barony" emerges when several firms adopt the core position. Here the barons dominate the other firms but their power is significantly reduced compared to the core firm in the kingdom. Finally the third type of network, a "republic" emerges when there is no core firm. Here, none of the firms has any significant power over the others. Thus one of the primary differentiators of network type is level of power that core firm or firms have over the other members of the network. Table 3 lists the characteristics of these three types of networks.

Type of Network	Kingdom	Barony	Republic
Number of core firms	One	Several	None
Contracting Power	High	Medium	Low
Network Objectives	Top-down enforced	Enforced by suppliers	Mutual agreement

Table 3. Types of Network

3.9 Performance Metrics in Supply Chain Management

A key element of improved supplier relationships is the presence of an objective performance measurement system, which is used to ensure that both parties are operating according to expectations and are meeting stated objectives. [14] Developing and using performance measures are an essential function of management. Managers give directions and achieve control through the use of performance measures. The key question in supply chain management is how to coordinate the efforts of every firm in supply chain and every employee of those firms.

Performance measures drive behavior in any system. The selection of performance measures is crucial inside a firm and throughout the supply chain. Managers coordinate behavior of their employees and of their partners in the supply chain by use of performance measures.

The ideal performance measure pushes every firm in the supply chain and all employees in each firm to direct all of their efforts to increasing the profits made by everyone in the supply chain. The problem is that there is no perfect performance measure which will always push firms and their employees in both the short term and long term to make best decision for the long term benefit of supply chain. Key performance measures that can be used in supply chain are: revenue, logistic costs, logistic profit contribution, return on inventory, return on assets etc. [16]. The companies should try to develop customer driven supply chain measures.

3.10 Supply Chain Management and Information Technology

Supply chain management is driven by the customer. It requires communication to all participants in the supply chain of the customer's needs and wants as well as how well these needs and wants are being met. To facilitate managing the linkages in the supply chain many types of software tools have been developed. These software programs are not the strategy, rather they are the tools to implement a firm's strategy. The strategy is to focus the entire supply chain on satisfying the needs of the customer.

Installing and using these tools is not the goal of the firm; the goal is to improve its supply chain management. Many organizations place huge bets on technology and other supply chain projects with little understanding of payoffs and the risks. The software supply is abundant and vendors constantly produce new products. The manager is on his own in evaluating a solution in the form of software or technique in terms of its fit with company needs. [15]

There are a variety of software packages for each link in supply chain. The available software can be divided roughly into three major categories. The first one focuses on the internal linkages (i.e. software integrating own firm), the second software links the firm to the customers and the third links firm to suppliers. The structure and use of these software was discussed briefly in chapter 2 and illustrated in Figure 7 which is reproduced here as Figure 10.

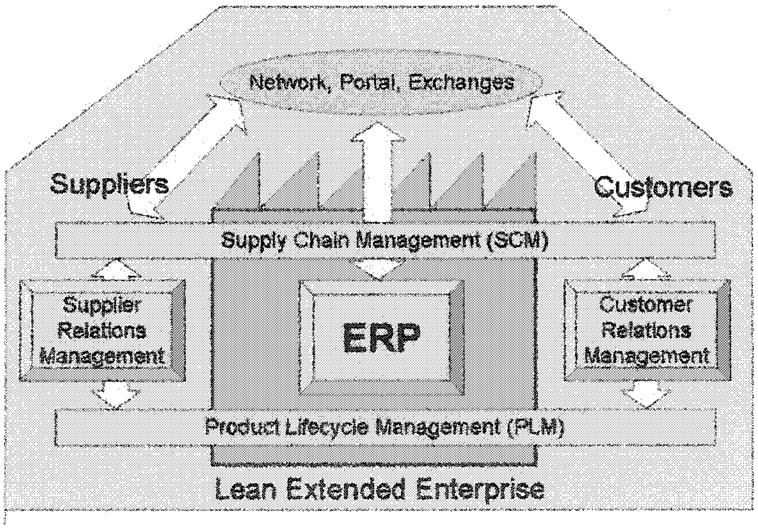


Figure 10. Lean Extended Enterprise
Adapted from Burton & Boeder [55]

Three main software that form the backbone of an extended lean enterprise are: Enterprise Resource Planning (ERP), Customer Relations Management (CRM) and Supplier Relations Management (SRM). Based upon benchmarking data from the 2002 I2 Planet Conference it should be noted that: 65% of companies have ERP in place, 44% of companies have SCM in place and 44% of companies have CRM in place.

In the following sections, we will discuss issues related to inventory management within an organization and across several organizations within a supply chain.
Inventories in supply chain can be divided into four categories:

1. Raw materials – These are the components, subassemblies, or materials that are purchased from outside the plant and used in fabrication/ assembly processes inside the plant.
2. Work in progress – WIP includes all unfinished parts or products that have been released to a production line.
3. Finished goods inventory: It includes finished product that has not been sold.
4. Spare parts – These are components that are used to maintain or repair production equipment.

3.11 Reasons for Holding Inventory

a. Raw Materials: If a company could receive raw materials from its suppliers in just-in-time fashion, it will not need to carry any raw materials inventory. Since this is very difficult to happen, all manufacturing systems carry stocks of raw materials. Three main factors influence the size of these stocks.

1. Batching: Quantity discounts from suppliers, limited capacity of the plant's purchasing function, and economies of scale provide incentives to order raw materials in bulk. Inventory that addresses the batching considerations is referred as cycle stock.
2. Variability: Due to variability in various manufacturing processes the extra stocks are planned for directly as a safety stock.
3. Obsolescence: The changes in demand or design can render some materials obsolete. This inventory is termed as obsolete inventory.

b. Work in Progress: Despite JIT goal of zero inventories, firm can never operate a manufacturing system with zero WIP since zero WIP implies zero throughput. Under realistic conditions actual WIP levels frequently exceed the critical WIP level by large amount. WIP can be divided into five categories as:

1. Queuing: if parts are waiting for resources
2. Processing: if part is being worked on by a resource
3. Waiting for batch: if WIP has to wait for other jobs to arrive in order to form a batch.
4. Moving: if it is actually being transported between resources.
5. Waiting to match: if it consists of components waiting at an assembly operation for their counterparts to arrive so that an assembly can occur.

As illustrated in Figure 11 below, the fraction of WIP in most manufacturing systems that is actually moving or being processed is small. The majority of WIP is in queue, waiting for batch, or waiting for match. Clearly, a WIP reduction program must address these later categories.

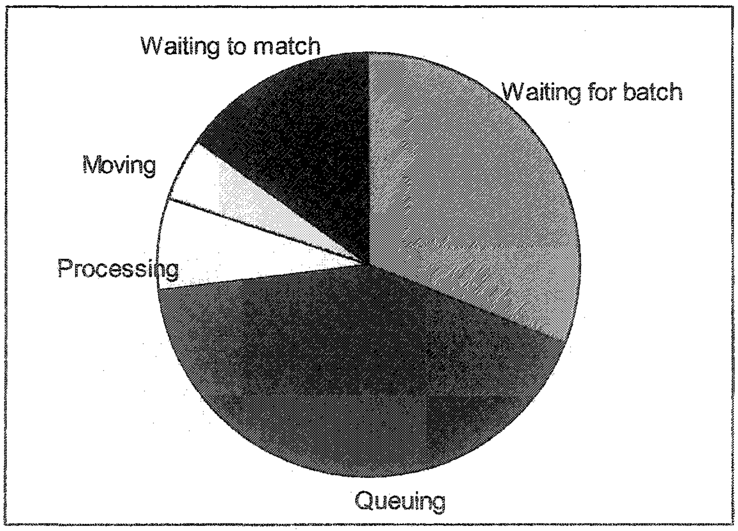


Figure 11. Breakdown of WIP in Manufacturing Systems

c. Finished Goods Inventory: If a company is able to ship everything it produces directly to customers as soon as processing is complete, there will be no need for FGI. Although some manufacturing systems can achieve this, many cannot. The basic reasons for carrying FGI are: Customer responsiveness, batch production, forecast errors, production variability, and seasonality. All these factors interact with each other.

d. Spare Parts: Spare parts are not used as direct inputs to finished products, but they do support the production process by keeping the machine running. In many systems the dollar value of inventory involved is not large but the consequences of shortfalls can be severe. In theory spare parts inventory systems are not much different from FGI systems. In both parts are stocked, possibly in batches to satisfy an uncertain demand process with some level of service.

3.12 Managing the Inventory

The objective in managing the inventory is to have them available when needed by the production process without carrying any more inventory than necessary. Some strategies can enhance our ability to do this for all parts while others are economically viable for only certain classes of parts. A few strategies are discussed below.

a. Improved Forecasting and Scheduling:

Due to long manufacturing cycle times and purchasing lead times, companies are required to purchase at least some of the materials before they have firm customer orders. In short term company may not have any option other than to maintain safety stock of raw materials but in long term, company can improve the situation by following policies such as: improving forecasting, reducing the cycle times, and improving scheduling.

b. ABC Classification:

In most manufacturing systems, a small fraction of the purchased parts represent a large fraction of the purchasing expenditure. To have maximum impact management should focus on these parts. To achieve this, ABC classification for purchased parts and materials is used. 'A' parts are the first 5 to 10 percent of parts accounting for 75 to 80 percent of total annual expenditures. 'B' parts are the next 10 to 15 percent of parts accounting for 10 to 15 percent of annual expenditure. 'C' parts are the bottom 80 percent or so of the parts accounting for only 10 percent or so of total annual expenditure. Because their number is relatively small and their cost is high it makes sense to use sophisticated, time consuming methods to tightly coordinate the arrival of A parts. But such efforts are not warranted for C parts. The B parts are in-between so they deserve more attention than C parts but not as much as the A parts.

d. Just-in-Time:

The way to maintain the absolute minimum level of inventory of a part is to coordinate deliveries with use in the production process. This is the idea behind JIT. A typical JIT contract with supplier calls for frequent deliveries in small quantities closely matched to what is required by the production schedule. To give suppliers reasonable chance of meeting delivery requirements well managed JIT procurement systems provide visibility of production schedule to suppliers. In concept JIT systems are very attractive. However in order for them to work suppliers must be reliable, with regard to both delivery timing and quality.

e. Setting Safety Stock/ Lead Times for Purchased Components:

It makes sense to link the purchases of expensive parts close to the production schedule. In MRP language this means that parts should be ordered on lot-for-lot basis. This approach is different from JIT because the parts are ordered according to planned schedule, rather than having them delivered in synchronization with actual production. The main drawback of this approach is that if schedule changes, production of the desired amounts may be impossible due to lack of appropriate raw material. This implies that short delivery lead times are less difficult to work with than long ones.

f. Setting Order Frequencies for Purchased Components:

JIT and lot-for-lot purchasing schemes are reasonable options for part A and they might work for intermediate B parts but are generally not appropriate for inexpensive C parts. It doesn’t make sense to order screws, washers, etc to be delivered in tight synchronization with production schedule. The increased risk of stockouts and extra purchasing can’t be justified by reductions in inventory investment. The problem of managing inexpensive purchased parts can be thought of in terms of lot sizing. The essential economic tradeoff is between inventory investment and purchasing cost. Lot size can be calculated using the standard EOQ formula:

$$Q = \sqrt{\frac{2AD}{h}} \tag{1}$$

Where D = Demand rate in units per year

A = Constant setup cost to produce a lot

h = Holding cost in dollars per unit per year

Q = Lot size in units

And the average number of lots per year can be calculated using equation (2)

$$F = \frac{1}{N}\sum_{j=1}^{N} D_j / Q_j \tag{2}$$

Where D_j = Demand rate in units per year

N = Number of periods

Q_j = Lot size in units

3.13 Managing Work in Progress (WIP)

The first thing to note about managing WIP is that Little's law written as

Cycle Time = (WIP/Throughput) (3)

implies that, for fixed throughput, reducing WIP and reducing Cycle Time (CT) are directly linked. Therefore measures that are used to reduce cycle time can be used to decrease WIP. The second important point concerning WIP management is that, the bulk of WIP in most production systems is in queue, waiting for batch or waiting for match. Thus WIP reduction program should be directed at smoothing out variability, reduce batching or improving synchronization. It should be noted that a byproduct of WIP reduction program is lower machine utilization.

a. Reducing Queuing:

For single-machine workstation, with mean processing time t_e, coefficient of variation of processing time c_e, coefficient of variation of arrivals c_a, and utilization u, cycle time can be approximated by:

$$CT \approx \left(\frac{C_a^2 + C_e^2}{2}\right)\left(\frac{u}{1-u}\right)t_e + t_e \tag{4}$$

So by Little's law and the fact that $u = r_a\, t_e$, where r_a is the average arrival rate to the workstation.

$$WIP = CT \times r_a \approx \left(\frac{C_a^2 + C_e^2}{2}\right)\left(\frac{u}{1-u}\right)u + u \tag{5}$$

Thus WIP and CT at workstation can be reduced by reducing variability of arrivals to the station, effective variability of processing times at the station or utilization. This can be achieved by using one of the following tools:

Equipment changes/ addition, pull systems, Finite-capacity scheduling, setup reduction, improved reliability/maintainability, enhanced quality, floating work.

b. Reducing Wait-for-Batch WIP

Anything that enables jobs to move from one workstation to the next in smaller batches and hence with less waiting, will clearly reduce WIP and cycle time. Specific approaches for doing this include lot splitting, Flow-oriented layout, Cart sharing etc.

c. Reducing Wait-to-Match WIP:

Ideally company will like to release the work orders for the various subcomponents and process them in the fabrication lines so that they arrive at assembly at exactly the same time, in close coordination with the final assembly schedule. Variability makes this impossible but the synchronization can be improved by using tools like
Pull Systems, Work Balancing, Batching etc.

3.14 Managing Finished Goods Inventory (FGI)

Finished goods inventory acts as buffer between production and demand. Such a buffer may be needed to insulate customers from manufacturing cycle time, perhaps to provide "instant" delivery, to absorb variability in either the production or demand process or to level out capacity loading (due to seasonality). These imply that anything that links production and demand processes more closely will allow less FGI to be carried. Options for doing this include improved forecasting, dynamic lead time quoting, cycle time reduction, and cycle time variability reduction, late customization, balancing labor, capacity and inventory.

3.15 Managing Spare Parts

Managing spare parts is an important component of overall maintenance policy, which can be a major determinant of operational efficiency in manufacturing system. Because of it's importance and complexity, a wide variety of spare parts practices are observed in industry.

There are two distinct types of spare parts, those used in scheduled preventive maintenance and those used in unscheduled emergency repairs. Scheduled maintenance represents a very predictable demand source. The standard MRP logic is probably applicable to these parts. On the other hand unscheduled emergency repairs are by definition unpredictable. There using MRP logic for these parts tends to work poorly. Various approaches such as Backorder Model, Stockout Model can be used for maintaining sufficient safety stock of spare parts whose demand is unpredictable.

3.16 Multiechelon Supply Chains

Many supply chains including those for spare part, involve multiple levels as well as multiple parts. Inventories can be stocked in central location such as warehouse or distribution center which allows holding less safety stock than holding separate inventories at individual demand sites. On the other hand holding inventories in distributed fashion enables swifter response to demand because of geographic proximity. The basic challenge in multiechelon supply chains is to balance the efficiency of central inventories with the responsiveness of distributed inventories so as to provide high system performance without excessive investment in inventory. The complexity and variety of multiechelon supply chains make them very challenging from an analysis standpoint.

a. System Configurations:

The defining feature of a multiechelon supply chain is that lower level locations are supplied by higher level locations. However within this framework there are many possible variations, and if transshipment between locations at same level are allowed then very definition of level becomes hazy. Thus multiechelon systems can be very complex. It is important to point out that system configuration itself is a decision variable. Determining the number of inventory levels, the locations of warehouses, and policies for interconnecting them can be among the most important logistics decisions a firm can make about its distribution system.

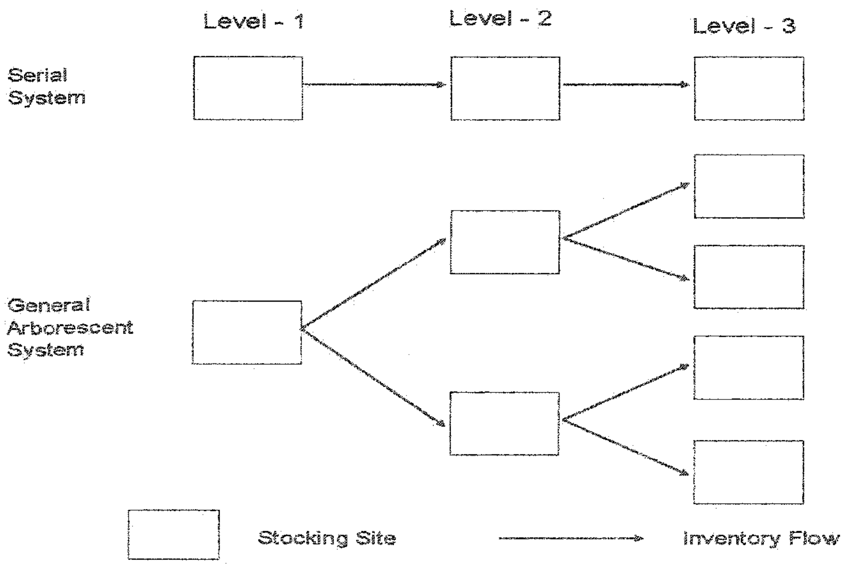


Figure 12. Arborescent Multiechelon Supply Chains
Adapted from Hoop and Spearman [20]

This study focuses on a three level serial, single product supply chain system as shown on top of Figure 12.

b. Performance Measures:

To make design decisions or develop a model, it is essential that desired system performance be specified in concrete terms. Few performance measures are discussed here.

i. Fill Rate - It is the fraction of demands that are met out of stock. This could apply at any level in the system. However measure applied to higher levels is only a means to an end. It is the performance of the low levels that actually service customers that determines the ultimate performance of the system.

ii. Backorder Level - This is the average number of orders waiting to be filled. This measure applies to the systems where backordering occurs.

iii. Lost Sales - It is the number of potential orders lost due to stockout. This measure applies to systems in which customers go elsewhere rather than wait for backordered item.

iv. Probability of Delay - This is the likelihood that an activity will be delayed for lack of inventory. This measure is often used in systems where high reliability is required.

c. The Bullwhip Effect:

An important issue that arises in multiechelon supply chains is that of channel alignment. This refers to coordination of policies between various levels and can involve information sharing, inventory control and transportation, among other management decisions. The natural response to the complexity of multiechelon supply chains is to treat the various levels independently. That is allowing each level to use local information to implement locally "optimal" policies. Consequence of this is the bullwhip effect, which refers to the amplification of demand fluctuations from the bottom of supply chain to the top. Figure 13 illustrates the bullwhip effect. The demand at the retail level seems to be steady but at the manufacturer's level it is volatile. The amplification of variability as we go up the supply chain is a result of bullwhip effect.

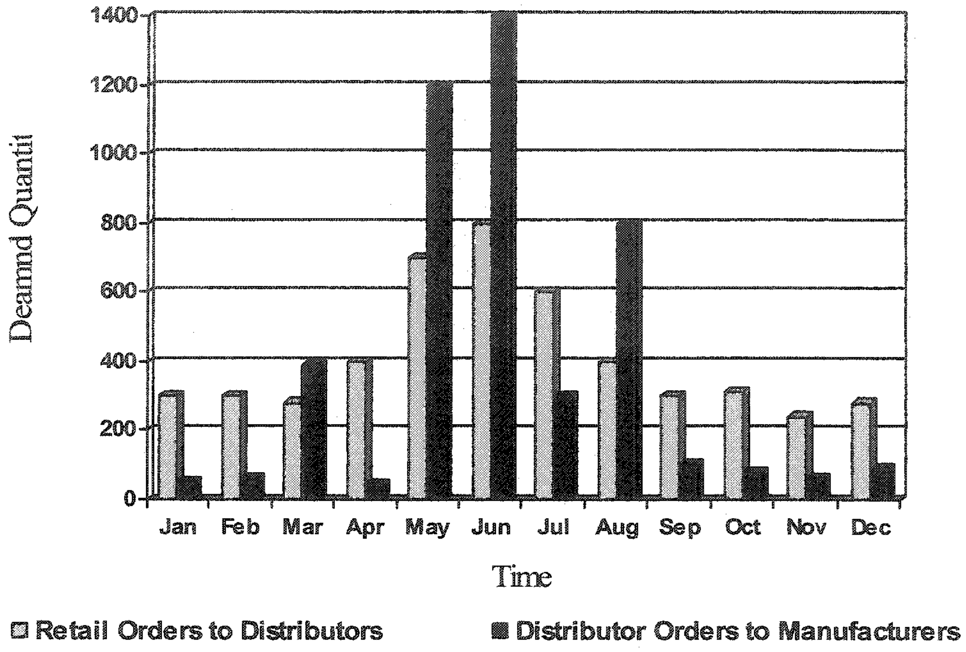


Figure 13. Variation in Demand at Different Levels of Supply Chain
Adapted from Hoop and Spearman [20]

3.17 Flow in Supply Chain

One of the key attributes of a successful winner in today's highly competitive marketplace is the ability to respond rapidly to the end consumer demand. To maximize competitive advantage all members within the supply chain should "seamlessly" work together to serve the end consumer. The main idea surrounding partnership sourcing is that via closer ties and the resulting information sharing the partners will be more able to effectively meet their customers' demands. Basically the pipeline is a mechanism by which materials and information flow through a supply chain. Pipelines are smooth, well defined passages enabling undisrupted movement, therefore requiring some form of design by the supply chain members. All companies belong to a supply chain but unfortunately not all have developed to operate effective pipelines. The term "pipeline management" was first coined by Forrester. As outlined by Farmer and Van Amstel the concept is relevant to many situations where the organizational system is required to balance a flow of incoming materials against outgoing components/products.

To compete effectively in the marketplace much pressure has been exerted on supply chains and individual companies to improve pipeline performance by optimizing their response to customer demand. As an important contribution to this improvement, organizations have implemented specific pipeline process improvement techniques such as just-in-time (JIT) and manufacturing resources planning (MRP). Methodologies such as "lean manufacturing" have shown improvements to a whole host of industries, most notably the automotive sector where extensive research has been carried out. More recently this approach has been broadened to encompass "lean thinking" and shown to apply to a very wide range of industries. [17]

a. Functional Flows in Supply Chain

Flows within a supply chain can be divided into four categories based upon function they serve. Value creation is achieved by simultaneous integration of these four critical supply chain flows:

i. Product and Service Flow - which represents the value-added movement of products and services from the raw-material provider to end-customers. Product value is increased through physical modification, packaging, market proximity, customization, service support, and other activities that enhance product desirability from the end-customer's viewpoint.

ii. Market Accommodation Flow - which reflects post-sales service administration and reverse logistics, including product recalls and recycling. Market accommodation also enables effective supply chain planning through exchanging information on sales and product use. Examples include product customization requirements, point-of-sale (POS) data, end-customer consumption, and warehouse releases. The market-focused flow provides supply chain participants with channel visibility regarding timing and location of product consumption. Improved overall planning and operations result when participants share a common understanding of demand and consumption patterns.

iii. Information Flow - which is the bi-directional exchange of transactional data and inventory status information among supply chain partners. Typical examples are forecasts, purchase orders, order acknowledgments, shipping and inventory information, invoices, payments, and replenishment requirements. Information exchange initiates, controls, and records the product-service value flow and market accommodation flow.

iv. Cash Flow - which generally moves in the reverse direction of the value-added activities. In situations involving promotions and rebates, however, cash may flow in the same direction as products and services. Cash-flow velocity and asset utilization are essential to superior logistics performance.

These four flows occur in all distribution channels. Yet if not coordinated and integrated among the channel participants, they can be characterized by delay, redundancy, and inefficiency. To improve flow across a supply chain, individual competencies related to operations, planning and control and behavioral management must be integrated [9].

b. Physical Flows in Supply Chain

If we focus on the physical nature of entities flowing within the supply chain, only two types of flows exist: Information flow and material flow. Lean thinking emphasizes streamlining these two types of flows to enhance the value creation process. Traditionally, productivity strategies have focused mainly on the material flow. It must be emphasized that information flow is equally critical if we are to improve the efficiency of the supply chain.

i. Information Flow

The major technology behind improved information flow was the advent of electronic data interchange (EDI). It offers greatly improved information flows and is an extremely important aspect within leading organizations in the fight to decrease lead-times. However, while the introduction of EDI in many companies has offered marked improvement in the speed of transmission of orders (once sanctioned), the current information flow in the vast majority of supply chains is still far from ideal. Unfortunately, in all too many instances the old problems of distortion and magnification of order information remain, not least because the many decision processes which still remain block rapid data transference to where it is really needed.

The main constraint to enriching a supply chain with market sales data is the common attitude that information is power. As a consequence of the traditional culture companies will deliberately distort order information to mask their intent not only to competitors but even to their own suppliers and customers, unbelievable though this may seem. In contrast managers can and should redesign their business processes to gain competitive advantage and must include improved information flow within their new strategy.

Market sales data is the information catalyst for the whole supply chain, holding undiluted data describing the consumer demand pattern. Therefore, the best way to ensure everyone in the supply chain gets the most up to date and useful information is to feed each level of the supply chain directly with the market sales data. Managers should, therefore, be challenging and questioning mechanisms within pipeline, structures which delay order information through the supply chain.

In the traditional supply chain the retailer is the only player who has direct sight of consumer demand; all other members only have the orders from their immediate customer, (i.e. the warehouse only has sight of the distributor's orders).

Therefore, in the traditional mode the market information is distorted initially by the retailer and further distorted with each successive link in the chain. However, in the information streamlined supply chain each player, no matter how far upstream, receives the marketplace data directly.

ii. Material Flow

The concept of simplified material flow is not a new one, in fact the principles can be traced at least as far back as the 16th Century, during which time the Venice arsenalotti regularly delivered a war galley on a daily basis. In more recent times the principles have been adopted by Womack and Jones and can be seen to underpin the Lean Thinking paradigm and the associated concept of Value Stream Management. If material flow is not simplified numerous symptoms are clearly visible that result in ineffective product delivery process performance. Simplified material flow can be achieved via the application of the 12 simplicity rules. These rules are based upon the fundamental theoretical and practical work started in this field by Jay Forrester and Jack Burbidge and has been further extensively developed by Towill. [18]

Rule 1: Only make products that can be quickly dispatched and invoiced to customers, highlights the need for companies to be pull/customer driven.

Rule 2: Only make in one time bucket those components needed for assembly in the next, emphasizes the need to minimize work-in-progress stock levels.

Rule 3: Streamline material flow and minimize throughput time, is of critical importance to all products. Compression of material, information and financial lead times dramatically improves the integration and performance of supply chains. Information lead times can be reduced via the use of the shortest planning periods,

Rule 4. Furthermore, adherence to this rule will reduce the use of old and less accurate information thereby improving forecast accuracy and reducing buffer stocks.

Rule 5: Only take deliveries from suppliers in small batches as and when needed for processing and assembly is a well recognized approach to reducing in-bound inventory levels.

Rule 6: Synchronization of time buckets through the chain. Lack of synchronization results in buffer stocks at every location where the time buckets differ. Consequently information lead times are elongated and out-of date data is frequently used as a result of conflicting time buckets in the planning process.

Rule 7 relates to the need to avoid the conflicting objectives of serving different markets by a single supply chain strategy. Hence, by forming natural clusters of products and designing processes appropriate to each value stream the requirements of diverse customer requirements can be best served.

Rule 8: elimination of all uncertainties in all processes, Rule 8 is universal and only by aiming for this goal will simplified material flow be truly achieved. If the uncertainties in the process are not eliminated the result is poor and variable quality levels and excessive lead times adversely impact on customer service and raw material inventory levels.

Rule 9 relates to the need for a structured approach to change.

Rule 10: Highly visible and streamlined information flows. Rule 10 is important to the simplification of material flow for all supply chains. It is this information that co-ordinates, controls and synchronizes the flow of material.

Rule 11 relates to the need to use proven and robust decision support systems in the management of the supply chain so scientific rigor as opposed to gut intuition guides strategy.

The final **Rule 12** is of critical importance to all types of products and related supply chains. The operational target of the seamless supply chain needs to be commonly accepted and shared by all members so to facilitate the arduous task of change.

3.18 Summary

In summary this chapter provides a general background on the subject of supply chain and its management. While there is ample information on issues in supply chain management, there is a lack of cohesive approach utilizing systems perspective for solving day to day problems that supply chain managers face in today's global manufacturing environment. We hope, this study will result in a set of practical guidelines that the managers can implement to streamline their supply chains. To get closer to the heart of the topic of this dissertation, we need to explore the published literature specifically in the area of supply chain dynamics and bullwhip effect. In next chapter, we look at the published literature

Chapter - 4

LITERATURE SURVEY

Supply chain management (SCM) is the practice of coordinating the design, procurement, and flow of goods, services, information and finances, from raw material flows to parts supplier to manufacturer to distributor to retailer to consumer. This process includes product design, order generation, order taking, information feedback and the efficient timely delivery of goods and services, and typically involves many or more of the business functions in firms that are linked to specific supply chains. Efficient and effective supply chain management assists an organization in getting the right goods and services to the place needed at the right time, in the proper quantity and at acceptable cost. Managing this process involves developing and overseeing relationships with suppliers and customers, controlling inventory, and forecasting demand, all requiring constant feedback from every link in the chain.

To co-ordinate such a complex network is difficult and requires better communication at each stage of the supply chain. The performance of a supply chain depends upon a number of factors. Issues facing the supply chain in today's shipbuilding industry were mentioned in Table 2 in chapter 3. In this section, we look at the published literature dealing with some of these issues.

4.1 The Impact of ERP on Supply Chain Management

Ackkermans et al presented results from a Delphi study on the future impact of enterprise resource planning (ERP) systems on supply chain management (SCM) [22]. The Delphi study was conducted with 23 Dutch supply chain executives of European multi-nationals. Findings from this exploratory study were threefold. The following key SCM issues were identified for coming years:

(1) Further integration of activities between suppliers and customers across the entire supply chain.

(2) On-going changes in supply chain needs and required flexibility from IT.

(3) More mass customization of products and services leading to increasing assortments while decreasing cycle times and inventories.
(4) The locus of the driver's seat of the entire supply chain.
(5) Supply chains consisting of several independent enterprises.

It was also concluded that there is only a modest role for ERP in improving future supply chain effectiveness and a clear risk of ERP actually limiting progress in SCM. ERP was seen as offering a positive contribution to only four of the top 12 future supply chain issues:

(1) More customization of products and services.
(2) More standardized processes and information.
(3) The need for worldwide IT systems.
(4) Greater transparency of the marketplace.

The following key limitations of current ERP systems in providing effective SCM support emerged as the third finding from this exploratory study:

(1) Their insufficient extended enterprise functionality in crossing organizational boundaries.
(2) Their inflexibility to ever-changing supply chain needs.
(3) Their lack of functionality beyond managing transactions.
(4) Their closed and non-modular system architecture.

These limitations stem from the fact that the first generation of ERP products has been designed to integrate the various operations of an individual firm. In modern SCM, however, the unit of analysis has become a network of organizations, rendering these ERP products inadequate in the new economy.

4.2 Made to Store (MTS) vs. Made to Order (MTO)

Hax and Candea proposed that there are two ways to determine whether a product should be produced according to made to store (MTS) or made to order (MTO). The first criterion was service consideration based on lead times, and the second criterion was economic considerations based on cost [38]. In a working paper of MIT, the MTS and MTO manufacturing strategies were compared, and the effect of inventory on delivery time was evaluated [35]. Donald et al first considered them as a set of strategies and called them Production Positioning Strategy (PPS) [39]. Howard et al called it built to store (BTS) and built to order (BTO) strategies, and named them Demand Response Strategies, and considered them as the methods of response to customer demand [40]. Nguyen developed heavy traffic limit approximations for various performance measures in hybrid MTO/MTS systems, governed by base-stock policies [41]. Wang and Yu analyzed the integration of BTS and BTO strategy by a mathematical model and computer programming [42]. In general, the main limitation of the past research is that many researchers do not pay much attention on the integration of the typical strategies, which is very important.

4.3 How Gillette Cleaned its Supply Chain

Duffey [23] discusses about the problems Gillette faced with its supply chain and how it overcame them. Gillette failed to meet its goal for effective customer service. Even though Gillette's products were constantly in demand, they could not reliably ship to its customer's requirements. The major reason for this was its lackluster supply chain performance. The table below gives an idea about the problems Gillette faced, and the measures it took to counter them.

No.	Problems Faced	Steps taken
1	Inventory levels decided based on planners experience, without taking forecast accuracy, demand volatility and manufacturing run frequency into account	Improved supply planning by taking into account new product launches, vendor flexibility, batch sizes, manufacturing flexibility, forecast accuracy and sourcing location. Collaborated with customers to make data uniform. In some cases JIT, where predictable demand.
2	No on-time shipments due to spikes in demand	Segmented forecasting to accommodate spikes in demand resulting due to factors such as seasonality & promotions.
3	For promotions, dependence on dollar accuracy of forecast rather than unit accuracy – resulting in shipment inaccuracies.	Worked closely with sales to ensure dollar forecasts are translated into unit forecasts and that all parties are held accountable for final expectation.
4	No accountability, finger pointing	Had members of both demand side and supply side on project team. Focus more on data.
5	Segmented supply chain process	Integrated value chain organization
6	Different departments responsible for inventory planning, demand planning, promotions, customer service each one reporting to different Vice President.	Staff Co-located and under one management team & single point accountability {Cradle to grave approach}
7	Demand planning more focused on what company wanted to sell rather than how many could be sold	Demand not concentrated on financial targets, giving a true picture of demand. A dedicated manager for demand planning resulting in a less filtered view of demand.
8	Forecast Accuracy: 46 % ... Jan'03 Fill rates: 90 % ... Jan'03	Forecast Accuracy: 71 % ... Nov'03 Fill rates: 98 % ... Nov'03 Inventory reduction by 25 % Cost reduction by 3 %.

Table-4 Problems Faced by Gillette and Steps Taken

4.4 Bullwhip Effect

Demand variability increases as one move up the supply chain away from the retail customer and small changes in customer demand can result in large variation in orders upstream. This phenomenon is known as Bullwhip effect. This results in increased cost and poorer service.

The sources of variability can be **demand variability**, **quality problems**, **strikes**, etc. Variability coupled with time delays in the transmission of information up the supply chain and time delays in manufacturing and shipping goods down the supply chain create the bullwhip effect.

The following can add to bullwhip effect

- No communication through the supply chain
- Delay in flow of information and material
- Large batch size
- Neglecting to order in an attempt to reduce inventory
- Inaccurate demand forecast

The bullwhip effect has been noted and assigned various causes across a range of academic disciplines. Forrester stated that the principal cause of this was the difficulties involving the information feedback loop among companies, and that such systems were too complex for managerial intuition alone to address. Consequently, his remedy lay in understanding the system as a whole, and modeling that system with system dynamics simulation models [43]. Sterman proposed a simple beer distribution game which simulated a supply chain with four players, retailer, wholesaler, distributor, and the beer producer. In the game, customer orders were predetermined but were revealed only period by period as the game progresses. The demand was constant in the first few weeks, and then doubled and kept constant in the subsequent weeks. He found that because of the demand change and the rational actions of the players, the information was distorted, and the demand was amplified [44, 45]. Goodwin and Franklin also did some work on this game [46]. Metters constructed a function to quantify and optimize the discounted expected cost of the bullwhip effect in the supply chain. In the function the inventory holding cost, production cost, and penalty cost of unsatisfied demand were evaluated [47]. Lee et al analyzed the causes of the bullwhip effect, which were demand forecast updating, order batching, price fluctuation, and rationing and shortage game. They used an order-up-to-S, periodical model to quantify their effect and proposed some approaches to reduce the bullwhip effect [36, 37]. Towill discussed the industrial dynamics modeling in supply chains, and Towill and McCullen analyzed the impact of agile manufacturing on supply chain dynamics [48,49]. Song also built a simple model developed from the beer game model and discussed the effect of seven causes on supply chain dynamics (SCD), which were **shortage game**, **capacity**, **information delay**, **poor coordination**, **materials delay**, **demand signaling**, and **order batching** [50]. Fransoo and Wouters proposed a mathematical model to measure the bullwhip effect in the supply chain. In the model, the bullwhip effect at a particular echelon in the supply chain was measured as the quotient of the coefficient of variation of demand generated by this echelon and that received by this echelon. Then based on the model and the data from a project, they discussed how to solve the problems in the measurement of supply chain bullwhip effect [51]. Chen et al. analyzed the effects of demand forecasting, lead times, and information in a simple supply chain, and concluded that the bullwhip effect could be reduced by centralizing demand information [52]. In general, there is a lot of good research in this domain, but the qualitative analysis of SCD and the discussion on its effect on supply chain planning is not enough.

4.5 Managing Physical, Information and Financial Flows

According to Villa [24], managing different types of physical, information and financial flows become a real challenge for managers and researchers, due to the complexity of the problem. Supply chain management involves a variety of management and technical issues, starting from distributed design of products and processes, the decentralized but efficiently coordinated production of goods through suppliers contracting and outsourcing to the coordination of third party logistics and multi-locations inventories. Often each supplier in the supply chain tries to maximize its own profit, which conflicts with the overall performance goal of the supply chain as a whole. The paper further states that an integrated supply chain can present significantly different performance depending on the types of products and production flows involved.

4.6 Supplier Relationship Management

Improving supply chain execution and leveraging the supply base has become more critical than ever in achieving competitive advantage [25]. Technological developments in the last 10 years aimed at improving the supply chain have mainly fallen into two major areas: optimized Supply Chain Planning, and Customer Relationship Management. However the successful Supply Chain Planning applications of the last decade have been largely focused on optimizing resource utilization within a single enterprise. This paper discusses about a new category of supply chain software applications, called Supplier Relationship Management (SRM) which can dramatically improve supply chain performance and empower a new level of supply base management, and how it can fit into typical manufacturer's supply chain process. SRM solutions are aimed at helping manufacturers maximize the value of their supply base to deliver strategic value. A comprehensive SRM solution supports a broad set of business processes including:

1. Strategic Supply Management
2. Supply Chain Collaboration
3. Procurement Execution

4.7 Improving Extended Supply Chain Performance through Better Control

Many manufacturers struggle with the challenges of shrinking product lifecycles, increased complexity of outsourced or multi-tier supply chains, and volatile product demand [26]. Even after spending millions of dollars on ERP, APS, and Supply Chain Event Management (SCEM) these systems rarely meet expectations. Moreover scope of ERP and APS systems are limited to a single-enterprise. Communication, visibility and control across the multi-tier system have become the most significant challenges for today's manufacturers.

The companies that can smoothly control the flow of materials while matching supply and demand have a significant advantage, and more importantly they have better financial performance. Controlling supply chain means having the capability to either increase or decrease material velocity across the entire supply chain.

4.8 Supplier Development and Supply Chain Management in Small and Medium Size Enterprises

This paper [27] provides the outcomes of a supplier development and supply chain management attitude survey designed to identify current trends in businesses within supply chains. The analysis identifies the adaptation of supplier development and supply chain management techniques. The relationships between customers and smaller suppliers are also examined, giving an indication of the lack of effective adaptation from the traditional adversarial relationships to the modern collaborative supply chain relationships. The outcomes based on a survey of 400 small firms identify issues, which businesses need to address to improve the performance of their supply chains, and so improve their competitive position by grasping the benefits of effective supply chain management

4.9 Information Systems Failure and Its Impact on the Supply Chain Decision Process

The realization that many supply chain managers are still using strategies that were devised for the pre-IS types of supply chains calls for a strategy that considers the effect of Information System Failure (ISF) in supply chain management decision making. Rakotobe et al [28] proposed supply chain decision strategy that addresses the dynamic multi-dimensional socio-technical issues within a heedful supply chain. The framework is based on the high reliability organization and supply chain management techniques.

4.10 Implications of Postponement for Supply Chain

With the increasingly sophisticated customer demand (e.g. product variety and customization), supply chains have to be responsive to constantly changing markets. As forecast and planning become very complex [29], producing and storing all types of finished goods based on forecast will run a high risk of stock out and obsolescence while lead times often makes make-to-order impossible. Therefore, postponement has been increasingly used as an important supply chain strategy.

Postponement centers around delaying activities in the supply chain until real information about the markets is available. The viability of postponement is determined by the structure of the supply chain characteristics. On the other hand, postponement affects the supply chain. The implementation of postponement often leads to the reconfiguration of the supply chain. Postponement application has also resulted in a blurring of warehousing, assembly and retail operations, and the warehouse is often the place where final assembly, labeling and packaging are processed. By employing postponement and combining it with a holistic view, some companies have managed to improve the performance of the supply chain.

4.11 Very High Inventory, No Consistent Approach to Inventory Management

This is also a common problem faced in the supply chain [30]. Various inventory management methods are utilized by firms to minimize supply and demand imbalances in the supply chain. The problem is generally complicated by the fact that the demand is uncertain, which causes stock outs resulting in order not being filled.

In addition to the above issues discussed in the literature, other problems found within a supply chain include high order fulfillment lead time [32], ineffective customer service [31], planning cycles not aligned [33] and a general lack of trust among supply chain members [34].

High order fulfillment Lead Time results in the overall long lead times for the company. Ineffective customer service results when the company is not able to meet its customer demand on-time. If the planning cycles for the entire supply chain is not aligned, it will result in bottlenecks throughout the system. A lack of trust between customer and supplier equates to higher transaction costs since this will lead to companies holding “safety” inventory at multiple stages in the supply chain.

For a company to be a world leader, it has to streamline its supply chain. **Demand forecast accuracy**, **perfect order**, **supply chain cost**, and **cash-to-cash cycle time** are the four most critical metrics a company can use to get a quick, balanced snapshot of its supply chain performance. With these four metrics, a company can see how good a view of demand it has, where it is making trade-offs between cost and service, and how well it is managing the cash flow.

4.12 Summary

Published articles point to a number of issues related to the supply chain management. Chief among these issues is the lack of integration of activities between suppliers and customers across the entire supply chain. Other issues include bullwhip effect, management of flow within the supply chain, supplier relations management, impact of ERP and implications of postponement. A number of authors have focused on one or two specific issues however there is lack of a cohesive approach to address all the issues. For example, there is plenty of research in the area of supply chain dynamics, but the qualitative analysis of SCD and the discussion on its effect on supply chain is not enough. In general, the main limitation of the past research is that many researchers do not pay much attention to the integration of multiple strategies. ERP’s were conceived to improve integration of business activities however they suffer from insufficient extended enterprise functionality and inflexibility to ever changing supply chain needs.

4.13 Intent of Dissertation

This study strives to address the supply chain integration problem by looking at the big picture via three methods; mathematical stochastic modeling, physical simulations and computer based simulations. All three of these methods incorporate variability associated with supply chains. Simulations in general are used extensively for modeling complex systems because of their ability to incorporate system variability. We make the distinction between physical simulation and computer based simulations. Physical simulations are those where participants in a class room are assigned specific roles within an organization and make decisions based upon the situation and rules given to them. Performance metrics are used to track system performance. This is usually done in multiple phases where productivity and management strategies are introduced and their impact studied. Use of physical simulations in manufacturing and management training has grown recently with the advent of Lean philosophy. Computer based simulations use a computer software to model a system with all its inherent variability and track its performance through a number of parameters. Computer based simulations can incorporate much higher level of detail and resolution compared to physical simulations however in terms of mimicking a real life system, physical simulations do a much better job since they incorporate human interactions and dynamics.

To achieve the dissertation intent indicated above, the following chapters are provided in succession. Existing mathematical models (both deterministic and stochastic) are discussed in chapter-5. Application of base stock model and (Q, r) model are discussed in chapter-6 and 7. Physical simulation models are discussed in chapter-8 and 9 and computer based simulation model is discussed in chapter-10.

Chapter - 5

EXISTING MATHEMATICAL MODELS

Taylor's principles of scientific management [59] were precursor to a host of mathematical models designed to solve the problems associated with manufacturing planning and control. These models formed the foundation for instruction in several operations management (OM) areas like inventory control, scheduling, capacity planning, forecasting and quality control. Of these areas, inventory control saw the development of a variety of mathematical models. These models can be subdivided into two broad areas. Those that assumed a known demand, and those that assumed a stochastic demand. Hopp and Spearman [20] provide a survey of existing mathematical models for analyzing inventory management within a supply chain.

5.1 Deterministic Models

One of the earliest deterministic models came out of work of Ford W. Harris [58] (1913). Harris's Economic Order Quantity (EOQ) model has been widely studied. His model makes the assumptions that:

1. Production is instantaneous
2. Delivery is immediate
3. Demand is deterministic
4. Demand is constant over time
5. Each production run incurs a constant setup cost

With these assumptions, he derived the following formula for calculating the total inventory cost per product:

$$Y(Q) = \frac{hQ}{2D} + \frac{A}{Q} + c \qquad (6)$$

Where D = Demand rate in units per year

c = Unit production cost

A = Constant setup cost to produce a lot

h = Holding cost in dollars per unit per year

Q = Lot size in units

The lot size that minimizes Y(Q) in the previous equation is:

$$Q^* = \sqrt{\frac{2AD}{h}} \tag{7}$$

The Economic Production Lot Model (EPL) propose by Taft [60], modifies the EOQ model to include finite and predictable production rate P.

$$Y(Q) = \frac{AD}{Q} + \frac{h(1 - D/P)Q}{2} + Dc \tag{8}$$

Minimizing equation (8) yields:

$$Q^* = \sqrt{\frac{2AD}{h(1 - D/P)}} \tag{9}$$

Wagner-Whitin model [61] considers the problem of determining production lot size when demand is deterministic but varies with time.

5.2 Stochastic Models

Statistical modeling of production and inventory control dates back to Wilson's work [62]. Wilson breaks inventory control problems into two parts:

1. Determining the **order quantity**, which is the amount of inventory that will be purchased or produced with each replenishment.
2. Determining the **reorder point**, or the inventory level at which a replenishment will be triggered.

The following three models have attempted to address this issue with three different approaches:

1. Newsboy Model – Considers only a single replenishment so the only issue is to determine the **order quantity** in face of an uncertain demand.
2. Base Stock Model – Considers the replenishment of inventory one unit at a time as random demand occurs. Thus, the only issue here is to determine the

reorder point. The target inventory set for the system is known as the base stock level.

3. (Q, r) Model – In this case the inventory is monitored continuously and demand occurs randomly and possibly in batches. When the inventory level reaches r, an order of size Q is placed. After a lead time l, during which a stockout may occur, the order is received.

The Newsboy model, while being useful in certain situations, is not realistic in case of a supply chain where multiple replenishments may be required. Thus we will look at the last two models in detail and compare them in the context of a two tier supply chain. Base stock model is closer to the Lean concept of make one move one since the replenishment quantity is one here. Realistically, it is not always possible to have order quantities of one and economies of scale may dictate ordering in batches. (Q, r) model addresses this need by providing a method for calculating both the order quantity and the reorder point.

We first look at the Base Stock model and then (Q, r) model.

5.3 The Base Stock Model

The Base Stock model uses a continuous time frame and makes the following assumptions:

1. *Products can be analyzed individually.* There are no product interactions.
2. *Demands occur one at a time.* There are no batch orders.
3. *Any demand not filled from stock is backordered.* There are no lost sales.
4. *Replenishment lead times are fixed and known.* There is no randomness in delivery lead times.
5. *Replenishments are ordered one at a time.* There is no setup cost associated with placing an order and no constraint on the number of orders that can be placed per year.

We make use of the following notations:

l = Replenishment lead time (in days)

x = Demand during replenishment lead time (in units), a random variable

G (x) = P (X<=x) = $\sum_{i=0}^{x} p(i)$, cumulative distribution function of demand during replenishment lead-time; we will allow G to be continuous or discrete.

θ = E [X] mean demand (in units) during lead time l

h = cost to carry one unit of inventory for one year (in dollars per unit per year)

b = cost to carry one unit of backorder for one year (in dollars per unit per year)

r = reorder point which represents the inventory level that triggers a replenishment order;

R = r + 1 base stock level

S = r - θ, safety stock level

G (r) or S (R) = Fill rate i.e., Fraction of demand filled from stock is equal to the probability that an order arrives before the demand for it has occurred.

We place an order when there are r units in stock and we expect a demand of θ units to occur while we are waiting for replenishment order to arrive. The inventory level is $r - \theta$ when the order arrives. If $s = r - \theta > 0$, then we call this the **safety stock** for the system. Since finding $r - \theta$ is equivalent to finding r (θ = constant), we can view this as the problem of finding the optimal base stock ($R = r + 1$), or reorder point r, or safety stock level ($s = r - \theta$).

We can approach the problem of finding an optimal base stock level in one or two ways. We can formulate a cost function and find a reorder point that minimizes this cost. Or we can simply specify the desired customer service level and find the smallest r that attains it. We will look at the second approach since customer satisfaction is one of the key goals of Lean philosophy.

We begin by analyzing the relationship between inventory, replenishment orders, and backorders under a base stock policy. We distinguish between **on-hand inventory**, which represents physical inventory in stock (cannot be negative), and **inventory position**, which represents the balance of on-hand inventory, backorders, and replenishment orders and is given by:

$$\text{Inventory position} = \text{on-hand inventory} - \text{backorders} + \text{orders} \quad (10)$$

Under the base stock policy we place a order every time a demand occurs. Hence, the following relationship holds true at all times:

$$\text{Inventory position} = R \quad (11)$$

Using equations (10) and (11), we can derive an expression for the performance metric for meeting a specified service level.

Since lead times are constant, we know that all the other $R - 1 = r$ items either in the inventory or on order will be available to fill new demand before the order in question arrives. Therefore, the only way the order can arrive after the demand for it has occurred is if demand during the replenishment lead time is greater than or equal to R (that is, $X \geq R$). Hence, the probability that the order arrives before its demand (i.e., does not result in backorder) is given by

$$P(X < R) = P(X \leq R - 1) = G(R - 1) = G(r) \quad (12)$$

Since all orders are alike, the fraction of the demand that are filled from stock is equal to the probability that an order arrives before the demand for it has occurred, or

$$S(R) = G(R - 1) = G(r) \quad (13)$$

Hence, G(r) or S(R) represents the fraction of the demand that will be filled from stock. This is known as the **fill rate** and represents a measure of customer satisfaction and hence its selection as a performance metric.

Base stock model is equivalent to the Japanese Kanban System (with kanban size of one) since, order quantity is one.

If h = annual cost to hold a unit of inventory and

b = annual cost of backorder

The condition for the optimal base stock level for this model is very similar to one for Newsboy model and has been derived by Johnson and Montgomery [57].

$$G(R^*) = \frac{b}{h+b} \tag{14}$$

Thus the optimal base stock level is the one for which the fill rate is given by equation (14). This result makes intuitive sense, since increasing the holding cost h will decrease R*, while increasing backorder cost b will increase R*. It should be noted that when backorder and holding costs are equal the resulting fill rate is 0.5 and $R^* = \theta$, the average demand during replenishment lead time, and therefore there are no safety stocks.

Cost Analysis:

We can formulate the quantitative cost analysis by first looking at the expression for average inventory level. For most of the cases, unless there is seasonal product demand, the average inventory position can be expressed as:

Inventory Position = Average Inventory + Safety Stock

Average Inventory = Q/2

Safety Stock = $s = r - \theta$

Therefore: Inventory Position = $\left\{\frac{Q}{2} + r - \theta\right\}$ and

Investment in inventory = $c \times \left\{\frac{Q}{2} + r - \theta\right\}$

Where c = unit cost of product in dollars

$$\text{Total Cost} = \text{Order Cost} + c\times\left\{\frac{Q}{2}+r-\theta\right\}$$

We will use these cost equations to compare the various cases later in chapter 6.

Primary Insights from the Model:

Base stock model has been widely researched in operations management literature, partly because it is simple to analyze and can be applied to a wide rage of situations. For instance, base stock can be used to control work releases in a multistage production line or multiechelon supply chain. In summary, the primary insights from base stock model are:

1. Reorder points control the probability of stockouts by establishing **safety stock.**
2. To achieve a given fill rate, the required base stock level (and hence safety stock) will be an increasing function of both mean and standard deviation of the demand during replenishment lead time.
3. Base stock levels in multistage production systems are very similar to kanban.

5.4 Application of Base Stock Model – An Example

We consider the example of an appliance store which sells various models of refrigerators. We know from past experiences that the mean demand for a certain model is 10 units per month, and replenishment lead time is one month. Therefore mean demand during the replenishment lead time is 10 units. Thus known quantities are:

Average Demand = D = 10 units per month

Replenishment lead time, l = 1 months

Average demand during replenishment lead time, $\theta = \frac{l}{Q}\times D = \frac{1}{1}\times 10$ = 10 units

This example was adapted from the book by Hoop and Spearman [20] and included here to illustrate the application of this model. Let us assume that the demand for refrigerators follows Poisson distribution.

$$p(r) = \text{Probability } \{\text{Demand during lead time} = r\} = \frac{\theta^r e^{-\theta}}{r!} = \frac{10^r e^{-10}}{r!}$$

$$\text{And } G(r) \text{ Cumulative Probability Distribution} = \sum_{k=0}^{r} p(k) = \sum_{k=0}^{r} \frac{10^k e^{-10}}{k!}$$

The Poisson distribution is a good modeling choice for supply chains where demands occur one by one and do not exhibit cyclic fluctuations. It is completely specified by only one parameter, the mean and is therefore convenient when one does not have information concerning the variability of demand. The standard deviation of the Poisson is equal to the square root of the mean.

r	p(r)	G(r)=S(R)	r	p(r)	G(r)=S(R)	
0	0	0	12	0.095	0.792	r* = 12
1	0	0	13	0.073	0.864	
2	0.002	0.003	14	0.052	0.917	r= 14
3	0.008	0.01	15	0.035	0.951	
4	0.019	0.029	16	0.022	0.973	
5	0.038	0.067	17	0.013	0.986	
6	0.063	0.13	18	0.007	0.993	
7	0.09	0.22	19	0.004	0.997	
8	0.113	0.333	20	0.002	0.998	
9	0.125	0.458	21	0.001	0.999	
10	0.125	0.583	22	0.000	0.999	
11	0.114	0.697	23	0.00	1.00	

Table 5. Fill Rates G(r) for Various Values of r

We need to calculate the base stock level and safety stock for a given fill rate. Table 5 is constructed using the above formulae. From this table, we find the value of r that will satisfy a given fill rate. For example, if we want a fill rate G(r) of 90%, the closest number above 0.9 is 0.917 which corresponds to a value of r = 14.

Hence safety stock $s = r - \theta = 14 - 10 = 4$

The optimal base stock level is the one for which the fill rate is given by equation (9) which was derived by Johnson and Montgomery [57] and give here again.

$$G(r^*) = \frac{b}{h+b} \qquad (15)$$

Where h = annual cost to hold a unit of inventory and

b = annual cost of backorder

If we assume the annual holding cost h to be \$15 and annual cost of a backorder b to be \$ 40, then the fill rate corresponding to optimal base stock level will be given by:

$$G(r^*) = \frac{b}{h+b} = \frac{40}{15+40} = 0.727$$

This fill rate corresponds to an optimal base stock level of $r^* = 12$ from table 4.

This example points out the utility of Base Stock Model. According to the model, if the manager of the appliance store desires a fill rate of 90% then he should maintain a base stock level of $R = r + 1 = 14 + 1 = 15$ refrigerators. However, if the manager's primary concern is to minimize the cost associated with inventory then he should carry a base stock level of $R^* = r^* + 1 = 12 + 1 = 13$. The corresponding fill rate will drop down as in this case to 72.7% leading to a lower customer satisfaction.

5.5 The (Q, r) model

The first formal publication of the (Q, r) model was done by Wilson in 1934 [66]. From the modeling perspective, the (Q, r) model is identical to the base stock model except that:

1. A fixed cost is associated with each replenishment order.
2. Orders may be batched.
3. A constraint on the number of replenishment orders per year exists.

Since there is some cost associated with a replenishment order, replenishment quantities greater than one may make sense. The model makes the following assumptions:

1. Any demand not filled from stock is backordered.
2. Replenishment lead times are fixed and known.
3. There is a fixed cost associated with a replenishment order.
4. There is a constraint on the number of replenishment orders that can be placed per year.

The basic mechanics of the (Q, r) model are illustrated in the Figure 14.

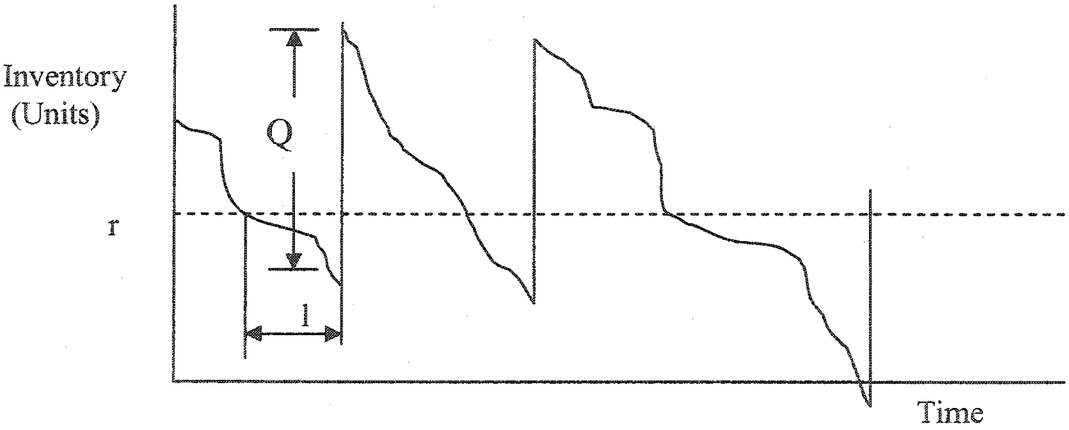


Figure 14. Inventory vs. Time in (Q, r) Model

When the inventory reaches the reorder point r, a replenishment order for quantity Q is placed. After a lead time of l, during which a stockout may occur, the order is received. Larger values of Q will result in fewer replenishment per year but **high average inventory levels**. Smaller values of Q will produce low average inventory but many replenishments per year. A high reorder point will result in **high inventory** but a **low probability of stockout**.

The replenishment quantity Q affects **cycle stock** i.e., inventory that is held to avoid excessive replenishment costs. The reorder point r affects **safety stock** i.e., inventory held to avoid stockouts. It should be noted that under these definitions, all inventory held in EOQ model is cycle stock and inventory held in base stock model is safety stock. In this sense, (Q, r) model is an integration of these two models. Depending upon how we define customer service, we can create two formulations of (Q, r) model. In both cases, we seek to choose values of Q and r to solve either (16) or (17).

$$\text{Min}_{(Q,\, r)} \ [\text{ fixed setup cost} + \text{holding cost} + \text{backorder cost }] \tag{16}$$

$$\text{Min}_{(Q,\, r)} \ [\text{ fixed setup cost} + \text{holding cost} + \text{stockout cost }] \tag{17}$$

We represent the customer service based upon the first formulation i.e., use cost of backorder in the analysis.

The following notations are used:

D = Expected demand per year (in units)

l = Replenishment lead time (in days) , assumed constant

X = Demand (random) during replenishment lead time (in units), a random variable.

$\theta = E[X] = Dl/365$ = Expected demand during replenishment lead time (in units)

σ = standard deviation of demand (in units) during lead time l (dollars per unit per year)

p(x) = P(X = x) = probability demand during replenishment lead time equals x (probability mass function). We are assuming demand is discrete (i.e., countable), but sometimes it is convenient to approximate demand with a continuous distribution. When we do this, we assume density function g(x) in place of the probability mass function.

G (x) = P (X<=x) = $\sum_{i=0}^{x} p(i)$, Cumulative distribution function of demand during replenishment lead-time; we will allow G to be continuous or discrete.

A = Setup or purchase order cost per replenishment (in dollars)

c = unit production cost (in dollars per unit)

h = annual unit holding cost (in dollars per unit per year)

k = cost per stockout (in dollars)

b = annual unit backorder cost (in dollars per unit of backorder per year); It should be noted that failure to have inventory available to fill a demand is penalized by using either k, or b but not both. This is same as choosing one of the formulations equation (8) or (9). We choose the first formulation and use cost of backorder.

Q = replenishment quantity (in units); this is a decision variable.

r = reorder point (in units) , this is the other decision variable

s = r - θ = safety stock implied by r (in units)

F(Q, r) = order frequency (replenishment orders per year) as a function of Q and r

S(Q, r) = $G(r)$= fill rate (fraction of orders filled from stock) as a function of Q and r (same fill rate as used in base stock model)

B(Q, r) = average number of outstanding backorders as a function of Q and r

I(Q, r) = average on-hand inventory level (in units) as a function of Q and r

B(r) = average number of backorders in a year as a function of r

n(r) = number of backorders during a replenishment cycle

The relationship between B(r) and n(r) is $B(r) = \frac{D}{Q} \times n(r)$

If the demand for product follows Poisson distribution then:

p(r) = Probability {Demand during lead time = r}= $\frac{\theta^r e^{-\theta}}{r!} = \frac{10^r e^{-10}}{r!}$

And G (r) Cumulative Probability Distribution = $\sum_{k=0}^{R} p(k) = \sum_{k=0}^{R} \frac{10^k e^{-10}}{k!}$

These are the same equations that we used in the case of base stock model.

The Poisson distribution is a good modeling choice for supply chains where demands occur one by one and do not exhibit cyclic fluctuations. It is completely specified by only one parameter, the mean and is therefore convenient when one does not have information concerning the variability of demand. The standard deviation of the Poisson is equal to the square root of the mean.

Now we construct a cost function based upon fixed setup cost, holding cost and backorder cost below:

a. Fixed setup cost

Since the number of replenishments per year is D/Q, the annual fixed set up cost can be written as

$$F(Q,r)\times A = \frac{D}{Q}\times A \tag{18}$$

b. Holding cost

The holding cost can be written as product of h, annual unit holding cost and I(Q, r) which is average on-hand inventory level. The exact expression for an average inventory has been calculated by Hadley and Whitin [70], but we can easily approximate the average inventory level I(Q, r) by looking at Figure 15.

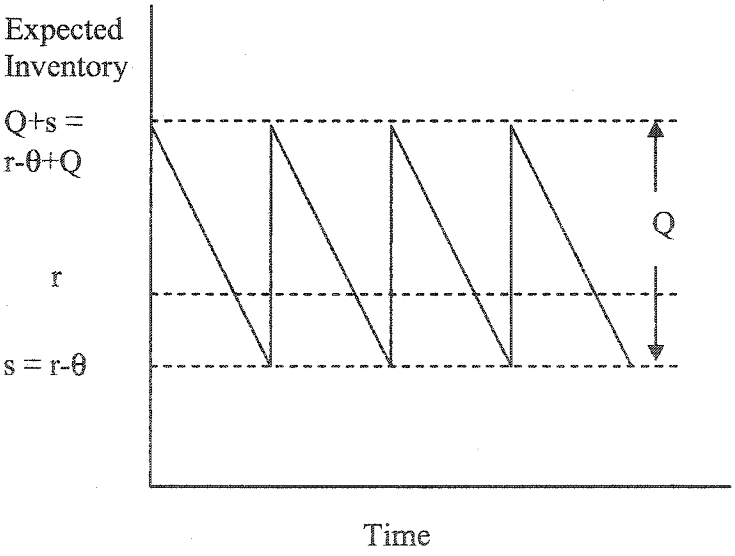


Figure 15. Expected Inventory vs. Time in the (Q,r) Model

It is clear that the expected inventory will decline from Q+s to s overreach replenishment cycle. Hence the average inventory is given by:

$$I(Q, r) \cong \frac{(Q+s)+s}{2} = \frac{Q}{2}+s = \frac{Q}{2}+r-\theta \tag{19}$$

(Assume s>0)

Using Equation (10) we can express the approximate holding cost per year as:

$$h \times I(Q,r) = h(\frac{Q}{2} + r - \theta) \tag{20}$$

c. Backorder cost:

The number of backorders in a cycle equals the number of backorders on the books when a replenishment order arrives. If the demand during the replenishment lead time is x, then the number of backorders can be expressed as

$$\text{Number of backorders} = \begin{cases} 0 & \text{if } x < r \\ x - r & \text{if } x \geq r \end{cases}$$

The expected number of backorders that will be placed during a cycle is indicated by n(r) which is integral of the

$$n(r) = \int_r^\infty (x - r) g(x) dx \tag{21}$$

Hence the expected number of backorders per year is obtained by multiplying n(r) by the expected number of cycles per year:

$$\text{Expected no of backorders per year} = B(r) = \frac{D}{Q} n(r) \tag{22}$$

$$\text{Therefore, total backorder cost will be} = b\frac{D}{Q} n(r) \tag{23}$$

Another approach to calculation of quantity B(Q, r) is to compute it similar to fill rate , by averaging the backorder level for the base stock model over all inventory positions between r + 1 and r + Q.

$$B(Q,r) = \frac{1}{Q} \sum_{x=r+1}^{r+Q} B(x) = \frac{1}{Q}[B(r+1) + \dots\dots + B(r+Q)] \tag{24}$$

To simplify our calculations, we can simply use the base stock backorder formula which was derived in a previous section in this chapter.

$$B(Q,r) \approx B(r)$$

The loss function B (r) which represents the average backorder level in a base stock model and was shown by Hopp and Spearman [20] to be:

$$n(r) = \theta\ p(r) + (\theta - r)(1 - G(r)) \tag{25}$$

Thus, $$B(r) = \frac{D}{Q} n(r) = \frac{D}{Q}\{\theta\ p(r) + (\theta - r)(1 - G(r))\} \tag{26}$$

Total Cost Formulation

Now substituting in Equation (8) , we get the (Q, r) model cost function

$$Y(Q,r) = \frac{D}{Q} A + h\left(\frac{Q}{2} + r - \theta\right) + b\frac{D}{Q} n(r) \tag{27}$$

We compute the values of Q and r that minimize this function. Differentiating Y (Q, r) with respect to Q and setting the result equal to zero yields

$$\frac{\partial Y(Q,r)}{\partial Q} = \frac{-DA}{Q^2} + \frac{h}{2} - \frac{bDn(r)}{Q^2} = 0 \tag{28}$$

This can be simplified as:

$$\frac{DA}{Q^2} + \frac{bDn(r)}{Q^2} = \frac{h}{2} \quad \text{or} \quad \frac{2D(A + bn(r))}{Q^2} = h \text{ and finally}$$

$$Q = \sqrt{\frac{2D(A + bn(r))}{h}} \tag{29}$$

Now, differentiating Y (Q, r) with respect to r and setting the result equal to zero yields

$$\frac{\partial Y(Q,r)}{\partial r} = h + \frac{bD}{Q}\frac{\partial n(r)}{\partial r} = 0 \tag{30}$$

Since

$$\frac{\partial n(r)}{\partial r} = \frac{\partial}{\partial r}\int_r^\infty (x - r) g(x) dx = -\int_r^\infty g(x) dx = -(1 - G(r))$$

Equation (30) becomes

$$h - \frac{bD}{Q}(1 - G(r)) = 0 \tag{31}$$

This can be further simplified and written as equation below:

$$G(r) = 1 - \frac{hQ}{bD} \tag{32}$$

The optimal replenishment quantity Q* and the reorder point r* can be found by simultaneously solving the following equations (33) and (34):

$$Q = \sqrt{\frac{2D(A+bn(r))}{h}} \qquad (33)$$

$$G(r) = 1 - \frac{hQ}{bD} \qquad (34)$$

Since these equations are coupled (i.e., Q depends on r and r depends on Q), we require an algorithm to solve these.

d. Algorithm for Solving Coupled Equations (Single product (Q, r) model)

Coupled equations like (33) and (34) can be solved by an iterative process which is described below:

Step 0 Given the known quantities like fixed setup cost A, annual unit holding cost h and annual demand in units D, we calculate an initial value of order quantity Q_0 using the EOQ model formula.

Then, we find an initial value of reorder point r_0 which will satisfy the desired fill rate calculated by equation (34). This value of r_0 is obtained from probability density function tables that we have already used in base stock model.

Step 1 Then, we compute optimal values for order quantity Q and reorder point r using equations (33) and (34) which were developed for backorder cost model.

Step 2 In step 2, we compare the results obtained in step 0 and step 1. If the difference between these values is less than one then these are the optimal values of Q and r. If the difference is larger than one, we repeat step 1. This is done until the solutions converge. It is observed that solutions converge quickly, generally within one or two iterations.

The above algorithm is described here in mathematical form.

Step 0

Set $Q_0 = \sqrt{2AD/h}$ and r_0 to be the value of r that satisfies

$$G(r) = 1 - \frac{hQ_0}{bD}$$

Let t = 1

Step 1

Compute

$$Q_t = \sqrt{\frac{2D(A + bn(r_{t-1}))}{h}}$$

and compute r_t as the value of r that satisfies

$$G(r) = 1 - \frac{hQ_t}{bD}$$

Step 2

If $|Q_t - Q_{t-1}| < 1$ and $|r_t - r_{t-1}| < 1$, stop and set $Q^* = Q_t$, $r^* = r_t$. Otherwise, set $t = t + 1$ and go to step (1).

This algorithm generally converges quickly.

e. Basic (Q, r) Insights

The basic insights behind the (Q, r) model are essentially those of EOQ and base stock model namely:

- Cycle stock increases as replenishment frequency decreases
- Safety stock provides a buffer against stockouts

(Q, r) model and base stock models (same a (Q, r) model except Q = 1) are historically early attempts to explicitly model variability in the supply chain and provide quantitative understanding of how safety stock affects the customer service level. This model suggests that the safety stock, service level and backorder levels are primarily affected by the reorder point r, while cycle stock and order frequency are essentially functions of order quantity Q.

The (Q, r) model offers some quantitative insights into the nature of the dependence of service on safety stock.

1. Increasing the annual average demand D during a replenishment lead time θ will tend to increase the optimal order quantity Q.
2. Increasing the variability of the demand process will tend to increase the optimal reorder point r. It should be noted that increasing either the annual demand D or the replenishment lead time l will serve to increase θ
3. Increasing the holding cost will tend to decrease the optimal replenishment quantity Q and reorder point r.

The basic (Q, r) model is premised on data that can be difficult to obtain in practice. The two potential trouble spots are:

1. The setup/purchase order cost A may not be known
2. The annual backorder cost b may be hard to estimate

However, we can still pursue the quantitative framework offered by the (Q,r) model to characterize the cost tradeoffs between inventory, replenishment frequency and customer service. To do this, we formulate the problem as follows:

We come up with a cost function for total inventory investment and minimize it with respect to constraints that are easy to estimate and are found in real world situations. For example, average replenishment frequency or customer service level. We can apply the following constraints to these two parameters:

$$\text{Average replenishment frequency} \leq F$$
$$\text{Average customer service level} \geq S$$

We have already developed an approximate expression for the average inventory level, namely $Q/2 + r - \theta$. Hence the total investment in inventory is

$$\text{Investment in inventory} = c \times \left\{ \frac{Q}{2} + r - \theta \right\}$$

The customer service or fill rate is given by

$$\text{Fill rate} = 1 - \frac{n(r)}{Q}$$

Hence, from the above discussion we can formulate the problem as follows:

$$Min \quad c \times \left\{ \frac{Q}{2} + r - \theta \right\} \quad \text{Subject to: } \frac{D}{Q} \le F \text{ and } 1 - \frac{n(r)}{Q} \ge S$$

After solving these equations we can rationally balance the frequency of replenishment and customer service with inventory investment.

5.6 Application of (Q, r) Model – An Example

We consider the example of an appliance store that sells various models of refrigerators. We know from past experiences that the mean demand for a certain model is 14 units per year, and replenishment lead time is 45 days. This example was adapted from a book by Hoop and Spearman [20] and included here to illustrate the application of this model.

Annual demand is D = 14 units/year

Unit cost of the part = \$150

Annual holding cost, h = \$15

Replenishment lead time, l = 45 days

Average demand during a replenishment lead time is

$$\theta = \frac{D}{365} \times l = \frac{14}{365} \times 45 = 1.726$$

The cost of each backorder, b = \$ 40

Let us model the demand using Poisson distribution.

p(r) = Probability {Demand during lead time = r } $= \frac{\theta^r e^{-\theta}}{r!} = \frac{10^r e^{-10}}{r!}$

And G (r) Cumulative Probability Distribution $= \sum_{r=0}^{r} p(r) = \sum_{r=0}^{r} \frac{10^r e^{-10}}{r!}$

Number of backorders in a replenishment cycle, $n(r) = \theta\, p(r) + (\theta - r)(1 - G(r))$

This above expression n(r) is same as that for the base stock model and justification for using this expression was presented by Hopp and Spearman [20] and explained in the previous section.

The Poisson distribution is a good modeling choice for supply chains where demands occur one by one and do not exhibit cyclic fluctuations. It is completely specified by only one parameter, the mean and is therefore convenient when one does not have information concerning the variability of demand. The standard deviation of the Poisson is equal to the square root of the mean.

Table 6 is generated using the equations for probability and cumulative probability distribution function. Where:

p(r) = Probability of demand during lead time
G(r) = Fill rate
n(r) = Expected number of backorders during a replenishment cycle

r	p(r)	G(r)	n(r)
0	0.178	0.178	1.7260
1	0.3072	0.4852	0.9040
2	0.2651	0.7503	0.3892
3	0.1525	0.9029	0.1396
4	0.0658	0.9687	0.0424
5	0.0227	0.9914	0.0111
6	0.0065	0.998	0.0026
7	0.00016	0.9996	0.0005
8	0.0003	0.9999	0.0001
9	0.0001	1.000	1
10	0	1	0

$r_0 = 3$
$r_1 = 3$
$r^* = 3$

Table 6. p(r), G(r), n(r) Values for Various Values of r

We now test the algorithm for (Q, r) model which was developed in the previous section.

Step 0

$$Q_o = \sqrt{\frac{2AD}{h}} = \sqrt{\frac{2\times 10\times 14}{15}} = 4.32 \sim 4$$

Find the smallest r such that

$$G(r) \geq 1 - \frac{hQ_0}{bD} = 1 - \frac{15\times 4}{40\times 14} = 0.893$$

From table 6, we see that the next higher fill rate after0.893 is 0.903 which corresponds to a value of r = 3. Hence $r_0 = 3$

Step 1

Compute Q_1

$$Q_1 = \sqrt{\frac{2D(A + bn(r_0))}{h}} = \sqrt{\frac{2\times 14(10 + 40\times 0.1396)}{15}} = 5.393 = 5$$

Recalculate r_1 as the smallest r such that

$$G(r) \geq 1 - \frac{hQ_1}{bD} = 1 - \frac{15\times 5}{40\times 14} = 0.866$$

From the table $r_1 = 3$

Again if we calculate Q_2 and r_2 we will find the same values.

Hence $Q^* = 5$, $r^* = 3$

Safety stock level = $r - \theta = 3 - 1.726 = 1.274$

5.7. Summary

A number of models have tried to address the complexity of inventory systems and supply chains. We have discussed in this chapter two deterministic and three stochastic models. These models are compared in table 7. The table compares them with respect to various parameters and assumptions. The dashes indicate that the particular modeling decisions do not apply to them.

Modeling Decision	Model					
	EOQ	EPL	WW	NV	BS	(Q, r)
Continuous, C or discrete D, time	C	C	D	D	C	C
Single, S or multiple M, product	S	S	S	S	S	S
Single, S or multiple, M periods	-	-	M	S	-	-
Backorder, B or lost sales, L	-	-	-	L	B	B
Setup or order cost (Yes or No)	Y	Y	Y	N	N	Y
Deterministic, D or random, R demand	D	D	D	R	R	R
Deterministic, D or random,R production	D	D	D	D	D	D
Constant, C or dynamic, D demand	C	C	D	-	C	C
Finite, F or infinite, I production rate	I	F	I	-	I	I
Finite, F or infinite, I horizon	I	I	F	F	I	I
Single, S or multiple, M echelons	S	S	S	S	S	S

Table 7. Classification of Inventory Models
Adapted from Hopp and Spearman [20]

While some of the above models are simpler to implement (ECQ), others are harder to implement since they require data that is hard to obtain. Collectively as a group, they do offer following insights:

1. There is a tradeoff between setups (**replenishment frequency**) and **inventory**. The more frequently we replenish inventory, the less **cycle stock** we will carry.
2. There is tradeoff between **customer service** and **inventory**. When demand is random, higher levels of **customer service** require higher **safety stock**.
3. There is a tradeoff between **variability** and **inventory.** For a given customer service and replenishment frequency, higher the variability of demand, the more inventory must be carried.

Chapter - 6

APPLICATION OF BASE STOCK MODEL

In this chapter, we apply the base stock model to a serial three level multiechelon single product supply chain system as shown in Figure 16. Supply chain systems like these are very common in industry. Research literature includes several examples of two level supply chains. Hopp and Spearman [20] discuss a two level arborescent system. It is important to study this since, supply chain dynamics effects like bullwhip effect get more amplified in a three level serial system.

Decision Variable = Reorder Point Inventory- r

Fill rate = 0.9, Poisson distribution for demand, Vary replenishment lead time

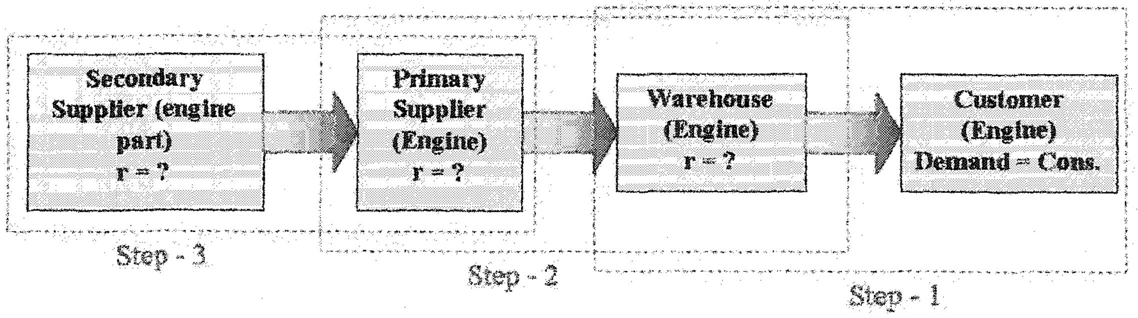


Figure 16. Base Stock Model Applied to Three Level Serial Supply Chain

Our goal is to study these supply chains by applying base stock (chapter 6) and (Q, r) models (chapter 7) and compare the results. We then, study these systems using physical simulations and validate the findings of mathematical models through physical simulations. Finally we, validate these models through the use of a computer based simulation model using ProModel software.

In this section we evaluate base stock model for five replenishment lead time, 12, 8, 6, 4, and 2 months and calculate reorder point for these cases. We start with the bottom of the supply chain and based upon customer demand calculate the inventory level that must be kept at the warehouse for a given fill rate (Step – 1 in Figure 16). For all these cases, the desirable fill rate is assumed to be 90%. Then, we move up the supply chain and calculate the quantity that must be stored at primary supplier to attain desired fill rate for orders received from the warehouse (Step – 2 in Figure 16). This is repeated until we have the r values for each entity in the supply chain.

Cost Analysis:

We can formulate the quantitative cost analysis by first looking at the expression for average inventory level. For most of the cases, unless there is seasonal product demand, the average inventory position can be expressed as:

Inventory Position = Average Inventory + Safety Stock

Average Inventory = Q/2

Safety Stock = s = r – θ

Therefore: Inventory Position = $\left\{\frac{Q}{2}+r-\theta\right\}$ and

Investment in inventory = $c\times\left\{\frac{Q}{2}+r-\theta\right\}$

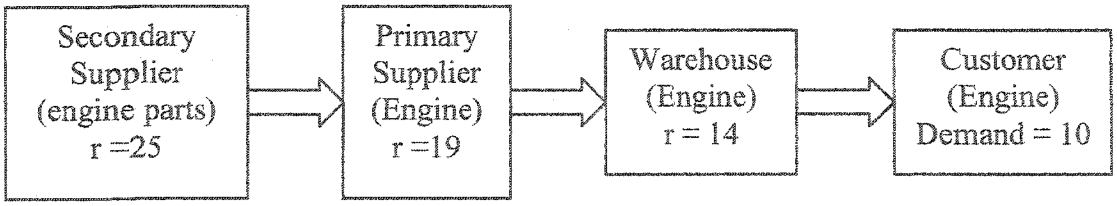
Where c = unit cost of product in dollars

Total Cost = Order Cost + $c\times\left\{\frac{Q}{2}+r-\theta\right\}$

We will use these cost equations to compare the various cases later in chapter 6.

The following pages include the analysis for five replenishment lead times.

6.1 Replenishment Lead Time = 12 months



Location - Warehouse

Average Demand = 10 units per year

Replenishment lead time, l = 12 months

Average demand during replenishment lead time, $\theta = \frac{1}{1} \times 10 = 10$ units

We model the demand based upon Poisson distribution:

p(r) = Probability {Demand during lead time = r}= $\frac{\theta^r e^{-\theta}}{r!} = \frac{10^r e^{-10}}{r!}$

And G (r) Cumulative Probability Distribution = $\sum_{k=0}^{r} p(k) = \sum_{k=0}^{r} \frac{10^k e^{-10}}{k!}$

The Poisson distribution is a good modeling choice for supply chains where demands occur one by one and do not exhibit cyclic fluctuations. It is completely specified by only one parameter, the mean and is therefore convenient when one does not have information concerning the variability of demand. The standard deviation of the Poisson is equal to the square root of the mean.

r	p(r)	G(r)	n(r)
0	0.00	0.00	10.00
1	0.00	0.00	9.00
2	0.00	0.00	8.00
3	0.01	0.01	7.00
4	0.02	0.03	6.01
5	0.04	0.07	5.04
6	0.06	0.13	4.11
7	0.09	0.22	3.24
8	0.11	0.33	2.46
9	0.13	0.46	1.79
10	0.13	0.58	1.25
11	0.11	0.70	0.83
12	0.09	0.79	0.53
13	0.07	0.86	0.32
14	0.05	0.92	0.19
15	0.03	0.95	0.10
16	0.02	0.97	0.05
17	0.01	0.99	0.03
18	0.01	0.99	0.01

r = 14

Table 8. Fill Rates for Various Values of r, l =12 months

For a fill rate of 90% { $G(r) \geq 0.9$}, we get a value of $r = 14$ from Table 8. Which means, at least 14 units must be stored at the warehouse to get a fill rate of 90%.

Location - Primary Supplier

Average Demand is 14 units per year from the ware house. We calculate the quantity that must be stored by the primary supplier to meet a fill rate of 90%, by constructing the table below for the demand that follows a Poisson distribution.

r	p(r)	G(r)
1	0.00	0.00
2	0.00	0.00
3	0.00	0.00
4	0.00	0.00
5	0.00	0.01
6	0.01	0.01
7	0.02	0.03
8	0.03	0.06
9	0.05	0.11
10	0.07	0.18
11	0.08	0.26
12	0.10	0.36
13	0.11	0.46
14	0.11	0.57
15	0.10	0.67
16	0.09	0.76
17	0.07	0.83
18	0.06	0.88
19	0.04	0.92
20	0.03	0.95
21	0.02	0.97
22	0.01	0.98
23	0.01	0.99

r = 19

Table 9. Fill Rates for Various Values of r, l = 12 months

In order to maintain the fill rate of 90%, we need r =19 at primary supplier

Thus, safety stock = 19-14 = 5

Location - Secondary Supplier

Average demand is 19 units per year from the primary supplier. We calculate the quantity that must be stored by the secondary supplier to meet a fill rate of 90%, by constructing the table below for the demand that follows a Poisson distribution.

r	p(r)	G(r)
1	0.00	0.00
2	0.00	0.00
3	0.00	0.00
4	0.00	0.00
5	0.00	0.00
6	0.00	0.00
7	0.00	0.00
8	0.00	0.00
9	0.00	0.01
10	0.01	0.02
11	0.02	0.03
12	0.03	0.06
13	0.04	0.10
14	0.05	0.15
15	0.07	0.21
16	0.08	0.29
17	0.09	0.38
18	0.09	0.47
19	0.09	0.56
20	0.09	0.65
21	0.08	0.73
22	0.07	0.79
23	0.06	0.85
24	0.04	0.89
25	0.03	0.93

r = 25

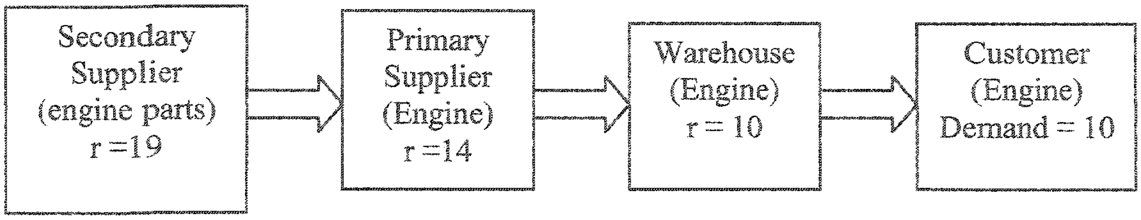
Table 10. Fill Rates for Various Values of r , l = 12 months

In order to maintain the fill rate of 90%, we need r = 25 at Secondary supplier

Safety stock = 25 -19 = 6

Thus when the inventory reaches to 25, replenishment is to be ordered.

6.2 Replenishment Lead Time = 8 months



Location – Warehouse

Average Demand = 10 units per year

Replenishment lead time, l = 8 months

Average demand during replenishment lead time, $\theta = \frac{l}{12} \times 10 = 6.67$ units

We model the demand based upon Poisson distribution:

p(r) = Probability {Demand during lead time = r}= $\frac{\theta^r e^{-\theta}}{r!} = \frac{10^r e^{-10}}{r!}$

And G (r) Cumulative Probability Distribution = $\sum_{k=0}^{r} p(k) = \sum_{k=0}^{r} \frac{10^k e^{-10}}{k!}$

r	p(r)	G(r)	n(r)
0	0.00	0.00	1.67
1	0.01	0.01	5.67
2	0.03	0.04	4.69
3	0.06	0.10	3.72
4	0.10	0.21	2.82
5	0.14	0.34	2.02
6	0.16	0.50	1.37
7	0.15	0.65	0.87
8	0.12	0.77	0.52
9	0.09	0.86	0.29
10	0.06	0.92	0.15
11	0.04	0.96	0.07
12	0.02	0.98	0.03
13	0.01	0.99	0.01
14	0.01	1.00	0.01
15	0.00	1.00	0.00

r = 10

Table 11. Fill Rates for Various Values of r, l = 8 months

Let the customer has average demand of 6.67 units (say engine).

For fill rate of 90% and referring Table 11

r = 10 units per 8 months to be stocked at warehouse.

Location - Primary Supplier

Average Demand = 10 units per 8 months We calculate the quantity that must be stored by the primary supplier to meet a fill rate of 90%, by constructing the table below for the demand that follows a Poisson distribution.

r	P(r)	G(r)
1	0.00	0.00
2	0.00	0.00
3	0.01	0.01
4	0.02	0.03
5	0.04	0.07
6	0.06	0.13
7	0.09	0.22
8	0.11	0.33
9	0.13	0.46
10	0.13	0.58
11	0.11	0.70
12	0.09	0.79
13	0.07	0.86
14	0.05	0.92
15	0.03	0.95
16	0.02	0.97
17	0.01	0.99
18	0.01	0.99

r = 14

Table 12. Fill Rates for Various Values of r, l = 8 months

In order to maintain the fill rate of 90%, we need r =14 at Primary supplier

Safety stock = 14-10 = 4

Location - Secondary Supplier

Average demand = 14 units per 8 month

r	p(r)	G(r)
0	0.00	0.00
1	0.00	0.00
2	0.00	0.00
3	0.00	0.00
4	0.00	0.00
5	0.00	0.01
6	0.01	0.01
7	0.02	0.03
8	0.03	0.06
9	0.05	0.11
10	0.07	0.18
11	0.08	0.26
12	0.10	0.36
13	0.11	0.46
14	0.11	0.57
15	0.10	0.67
16	0.09	0.76
17	0.07	0.83
18	0.06	0.88
19	0.04	0.92
20	0.03	0.95
21	0.02	0.97
22	0.01	0.98
23	0.01	0.99
24	0.00	0.99
25	0.00	1.00

r = 19

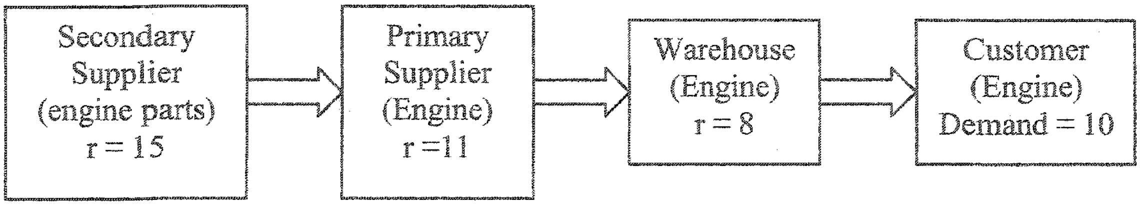
Table 13. Fill Rates for Various Values of r, l = 8 months

In order to maintain the fill rate of 90%, we need r =19 at Secondary supplier

Safety stock = 19-14 = 5

Thus when the inventory reaches to 19, replenishment is to be ordered.

6.3 Replenishment Lead Time = 6 months



Location - Warehouse

Average Demand = 10 units per year

Replenishment lead time, l = 6 months

Average demand during replenishment lead time, $\theta = \frac{l}{12} \times 10 = 5$ units

We model the demand based upon Poisson distribution:

p(r) = Probability {Demand during lead time = r}= $\frac{\theta^r e^{-\theta}}{r!} = \frac{10^r e^{-10}}{r!}$

And G (r) Cumulative Probability Distribution = $\sum_{k=0}^{r} p(k) = \sum_{k=0}^{r} \frac{10^k e^{-10}}{k!}$

r	p(r)	G(r)
0	0.01	0.01
1	0.03	0.04
2	0.08	0.12
3	0.14	0.27
4	0.18	0.44
5	0.18	0.62
6	0.15	0.76
7	0.10	0.87
8	0.07	0.93
9	0.04	0.97
10	0.02	0.99
11	0.01	0.99
12	0.00	1.00
13	0.00	1.00
14	0.00	1.00
15	0.00	1.00

r = 8

Table 14. Fill Rates for Various Values of r, l = 6 months

Let the customer has average demand of 5 units (say engine).

For fill rate of 90% and referring Table 14

r = 8 units per half year to be stocked at warehouse.

Location - Primary Supplier

r	p(r)	G(r)
0	0.00	0.00
1	0.00	0.00
2	0.01	0.01
3	0.03	0.04
4	0.06	0.10
5	0.09	0.19
6	0.12	0.31
7	0.14	0.45
8	0.14	0.59
9	0.12	0.72
10	0.10	0.82
11	0.07	0.89
12	0.05	0.94
13	0.03	0.97
14	0.02	0.98
15	0.01	0.99
16	0.00	1.00
17	0.00	1.00
18	0.00	1.00
19	0.00	1.00

r = 11

Table 15. Fill Rates for Various Values of r, l = 6 months

In order to maintain the fill rate of 90%, we need r =11 at Primary supplier

Safety stock = 11-8= 3

Location - Secondary Supplier

r	p(r)	G(r)
0	0.00	0.00
1	0.00	0.00
2	0.00	0.00
3	0.00	0.00
4	0.01	0.02
5	0.02	0.04
6	0.04	0.08
7	0.06	0.14
8	0.09	0.23
9	0.11	0.34
10	0.12	0.46
11	0.12	0.58
12	0.11	0.69
13	0.09	0.78
14	0.07	0.85
15	0.05	0.91
16	0.04	0.94
17	0.02	0.97
18	0.01	0.98
19	0.01	0.99
20	0.00	1.00

r = 15

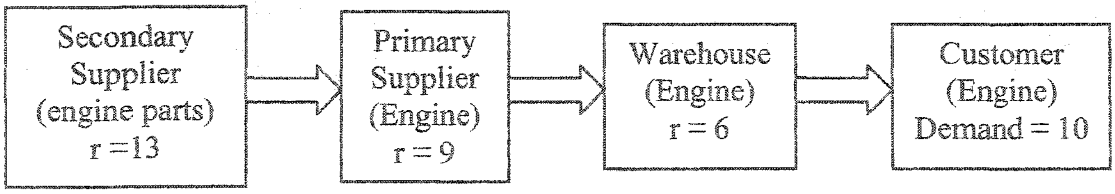
Table 16. Fill Rates for Various Values of r, l = 6 months

In order to maintain the fill rate of 90%, we need r =15 at Secondary supplier

Safety stock = 15-11=4

Thus when the inventory reaches to 11, replenishment is to be ordered.

6.4 Replenishment Lead Time = 4 months



Location – Warehouse

Average Demand = 10 units per year

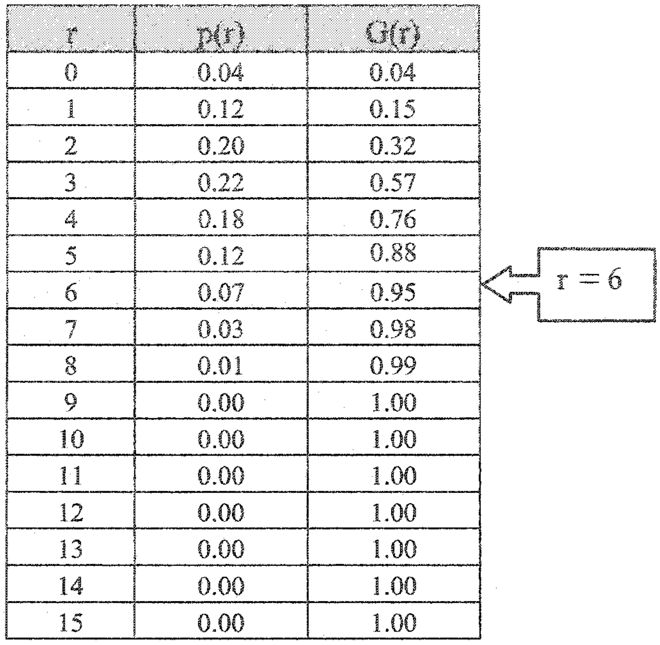
Replenishment lead time, l = 4 months

Average demand during replenishment lead time, $\theta = \frac{l}{12} \times 10 = 3.33$ units

We model the demand based upon Poisson distribution:

p(r) = Probability {Demand during lead time = r}= $\frac{\theta^r e^{-\theta}}{r!} = \frac{10^r e^{-10}}{r!}$

And G (r) Cumulative Probability Distribution = $\sum_{k=0}^{r} p(k) = \sum_{k=0}^{r} \frac{10^k e^{-10}}{k!}$



r	p(r)	G(r)
0	0.04	0.04
1	0.12	0.15
2	0.20	0.32
3	0.22	0.57
4	0.18	0.76
5	0.12	0.88
6	0.07	0.95
7	0.03	0.98
8	0.01	0.99
9	0.00	1.00
10	0.00	1.00
11	0.00	1.00
12	0.00	1.00
13	0.00	1.00
14	0.00	1.00
15	0.00	1.00

r = 6

Table 17. Fill Rates for Various Values of r, l = 4 months

Let the customer has average demand of 3.33 units (say engine).

For fill rate of 90% and referring Table 17

R = 6 units per 4 months to be stocked at warehouse.

Location – Primary Supplier

Average Demand =6 units per 4 months

r	P(r)	G(r)
0	0.00	0.00
1	0.01	0.02
2	0.04	0.06
3	0.09	0.15
4	0.13	0.29
5	0.16	0.45
6	0.16	0.61
7	0.14	0.74
8	0.10	0.85
9	0.07	0.92
10	0.04	0.96
11	0.02	0.98
12	0.01	0.99
13	0.01	1.00
14	0.00	1.00
15	0.00	1.00
16	0.00	1.00

r = 9

Table 18. Fill Rates for Various Values of r, l = 4 months

In order to maintain the fill rate of 90%, we need r = 9 at Primary supplier
Safety stock = 9-6 = 3 units

Location – Secondary Supplier

Average demand = 9 units per 4 months

r	p(r)	G(r)
0	0.00	0.00
1	0.00	0.00
2	0.00	0.01
3	0.01	0.02
4	0.03	0.05
5	0.06	0.12
6	0.09	0.21
7	0.12	0.32
8	0.13	0.46
9	0.13	0.59
10	0.12	0.71
11	0.10	0.80
12	0.07	0.88
13	0.05	0.93
14	0.03	0.96
15	0.02	0.98
16	0.01	0.99
17	0.01	0.99
18	0.00	1.00
19	0.00	1.00
20	0.00	1.00

r = 13

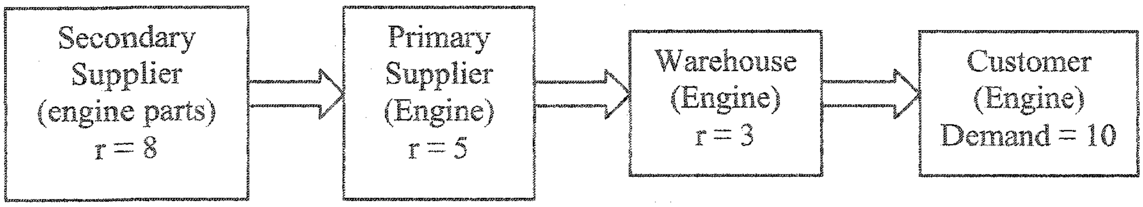
Table 19. Fill Rates for Various Values of r, l = 4 months

In order to maintain the fill rate of 90%, we need r =13 at Secondary supplier

Safety stock = 13 - 9 = 4

Thus when the inventory reaches to 13, replenishment is to be ordered.

6.5 Replenishment Lead Time = 2 months



Location – Warehouse

Average Demand = 10 units per year

Replenishment lead time, l = 2 months

Average demand during replenishment lead time, $\theta = \frac{l}{12} \times 10 = 1.67$ units

We model the demand based upon Poisson distribution:

p(r) = Probability {Demand during lead time = r}= $\frac{\theta^r e^{-\theta}}{r!} = \frac{10^r e^{-10}}{r!}$

And G (r) Cumulative Probability Distribution = $\sum_{k=0}^{r} p(k) = \sum_{k=0}^{r} \frac{10^k e^{-10}}{k!}$

r	p(r)	G(r)
0	0.19	0.19
1	0.31	0.50
2	0.26	0.58
3	0.15	0.91
4	0.06	0.97
5	0.02	0.99
6	0.01	1.00
7	0.00	1.00
8	0.00	1.00
9	0.00	1.00
10	0.00	1.00
11	0.00	1.00
12	0.00	1.00
13	0.00	1.00
14	0.00	1.00
15	0.00	1.00

$r = 3$

Table 20. Fill Rates for various values of r, l = 2 months

Let the customer has average demand of 1.67 units (say engine).
For fill rate of 90% and referring Table 20
r = 3 units per 2 months to be stocked at warehouse.

Location – Primary Supplier

Thus in order to fulfill the demand of 3 units per 2 months we require

r	p(r)	G(r)
0	0.05	0.05
1	0.15	0.20
2	0.22	0.37
3	0.22	0.65
4	0.17	0.82
5	0.10	0.92
6	0.05	0.97
7	0.02	0.99
8	0.01	1.00
9	0.00	1.00
10	0.00	1.00
11	0.00	1.00
12	0.00	1.00
13	0.00	1.00
14	0.00	1.00
15	0.00	1.00

r = 5

Table 21. Fill Rates for Various Values of r, l = 2 months

In order to maintain the fill rate of 90%, we need r =5 at Primary supplier

Safety stock = 5 - 3 = 2

Location – Secondary Supplier

Average demand = 5 per 2 months

r	p(r)	G(r)
0	0.01	0.01
1	0.03	0.04
2	0.08	0.12
3	0.14	0.27
4	0.18	0.44
5	0.18	0.62
6	0.15	0.76
7	0.10	0.87
8	0.07	0.93
9	0.04	0.97
10	0.02	0.99
11	0.01	0.99
12	0.00	1.00
13	0.00	1.00
14	0.00	1.00
15	0.00	1.00

r = 8

Table 22. Fill Rates for Various Values of r, l = 2 months

In order to maintain the fill rate of 90%, we need r = 8 at Secondary supplier.

6.6 Summary of Results for Base Stock Model:

To achieve a desirable customer satisfaction rate, we have assumed the fill rate to be 90%. The order cost is assumed to be \$ 25 per order and the unit product cost c = \$ 150. The expression for inventory investment was derived earlier. We need to add to that the cost of ordering products which will provide the total cost. The total cost is calculated as follows:

Total Cost = Order Cost + Inventory Cost

$$\text{Inventory Cost} = c\times\left\{\frac{Q}{2}+r-\theta\right\}$$

Order Cost = Cost per order x D

$$\text{Total Cost} = \text{Order Cost} + c\times\left\{\frac{Q}{2}+r-\theta\right\}\text{..........................}(35)$$

Table 23 summarizes all the results including the frequency of order, the order cost and the total cost of inventory. Total cost is shown in the last column. Sample cost calculation for the first case i.e. l = 12, D = 10 at warehouse is given here:

Total cost = \$25x10 + \$150 (1/2 + 14 -10) = \$ 250 + \$ 675 = \$ 925

Replenishment Lead Time	Demand	Reorder Point(r)	Q	Location	Frequency of order (F=D/Q)	Average Demand	Order Cost	Total Cost
12	10	14.00	1.00	Warehouse	10.00	10	250	925
	14	19.00		PS	14.00	14	350	1175
	19	25.00		SS	19.00	19	475	1450
8	6.67	10.00	1.00	Warehouse	6.67	6.67	166.75	741.25
	10	14.00		PS	10.00	10	250	925
	14	19.00		SS	14.00	14	350	1175
6	10	8.00	1.00	Warehouse	10.00	5	250	775
	16	11.00		PS	16.00	8	400	925
	22	15.00		SS	22.00	11	550	1225
4	10	6.00	1.00	Warehouse	10.00	3.33	250	725.5
	18	9.00		PS	18.00	6	450	975
	27	13.00		SS	27.00	9	675	1350
2	1.67	3.00	1.00	Warehouse	1.67	1.67	41.75	316.25
	3	5.00		PS	3.00	3	75	450
	5	8.00		SS	5.00	3	125	950

Table 23. Summary of Application Runs of Base Stock Model

Table 24 indicates the cost of replenishment for warehouse, primary supplier and secondary supplier.

Replenishment Lead Time (months)	Warehouse ($)	Primary Supplier ($)	Secondary Supplier ($)
12	925	1175	1450
8	741.25	925	1175
6	775	925	1225
4	725.5	975	1350
2	316.25	450	950

Table 24. Cost Results for Various Locations

The cost results can also be shown graphically in Figure 17.

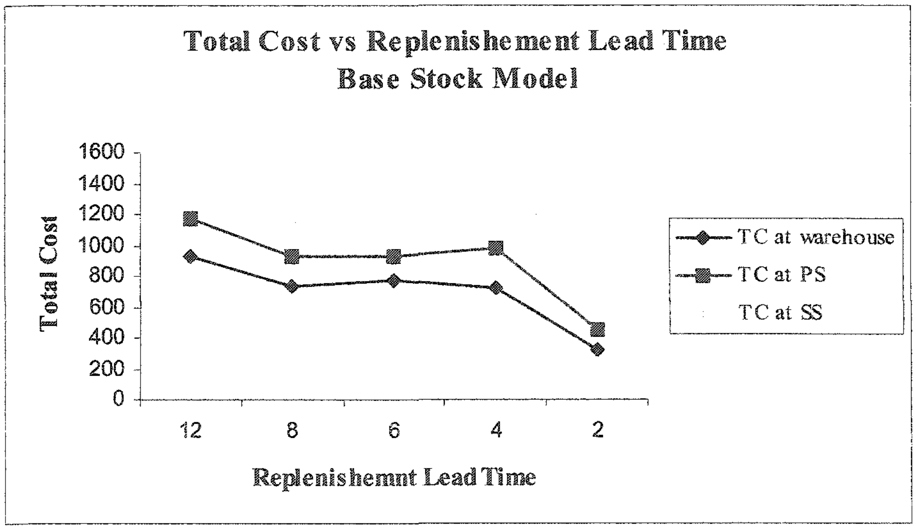


Figure 17. Total Cost vs. Replenishment Lead Time (Base Stock Model)

It is evident from the figure that as replenishment lead time decreases (frequency of delivery increases), the total cost of inventory goes down. It is possible to see slight increase in the cost of inventory at times. This is due to the fact that we are restricting to discrete reorder points and as replenishment times are reduced it is necessary to increase the reorder point, r to maintain the same customer satisfaction level.

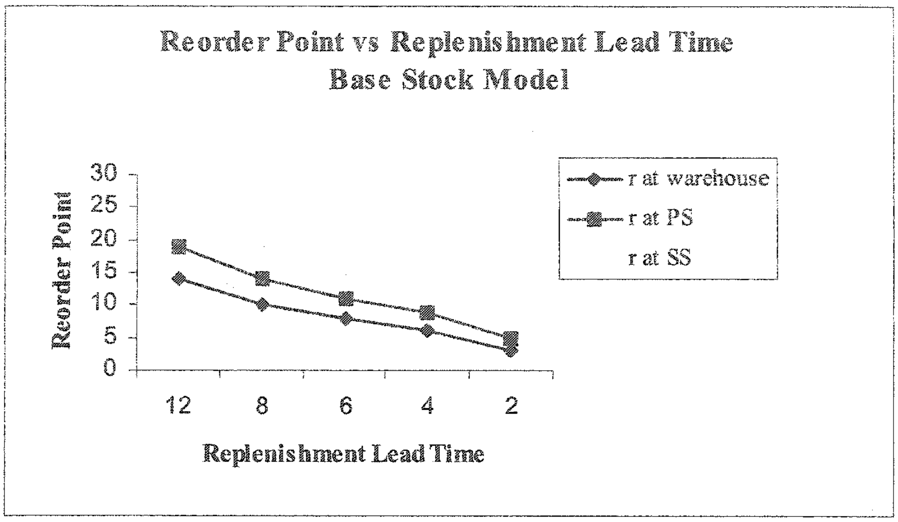


Figure 18. Reorder Point vs. Replenishment Lead Time (Base Stock Model)

Figure 18 shows the plot of reorder point at Warehouse, Primary Supplier and secondary supplier when Base Stock model is used for inventory control with different replenishment lead-time. We can see from Figure 18 that the reorder point decreases with reduction in replenishment lead time. This also leads to reduction in total cost as frequency of replenishment is increased.

Chapter - 7

APPLICATION OF (Q, r) MODEL

In this chapter, we apply the (Q, r) model to a serial three level multiechelon single product supply chain system as shown in Figure 19. Supply chain systems like these are very common in industry. Research literature includes several examples of two level supply chains. Hopp and Spearman [20] discuss a two level arborescent system. It is important to study this since supply chain dynamics effects like bullwhip effect get more amplified in a three level serial system.

Decision Variables = Order Quantity, Q and Reorder Point Inventory- r

Fill rate = 0.9, Poisson distribution for demand, Vary replenishment lead time

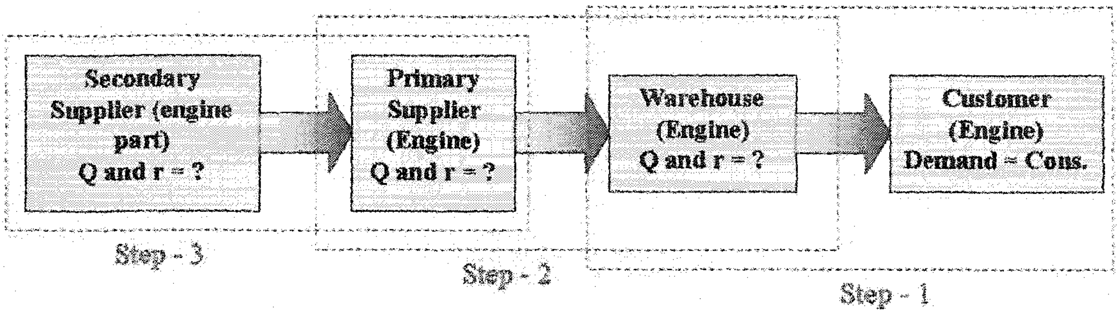


Figure 19. (Q, r) Model Applied to Three Level Serial Supply Chain

Our goal is to study these supply chains by applying base stock (chapter 6) and (Q, r) models (chapter 7) and compare the results. We then, study these systems using physical simulations and validate the findings of mathematical models through physical simulations. Finally, we validate these models through the use of a computer based simulation model using ProModel software.

In this section we evaluate base stock model for five replenishment lead time, 12, 8, 6, 4, and 2 months and calculate reorder point for these cases. We start with the bottom of the supply chain and based upon customer demand calculate the inventory level that must be kept at the warehouse for a given fill rate (Step - 1 in Figure 19). For all these cases, the desirable fill rate is assumed to be 90%. Then, we move up the supply chain and calculate the quantity that must be stored at primary supplier to attain desired fill rate for orders received from the warehouse (Step - 2 in Figure 19). This is repeated until we have the r values for each entity in the supply chain.

Cost Analysis:

We can formulate the quantitative cost analysis by first looking at the expression for average inventory level. For most of the cases, unless there is seasonal product demand, the average inventory position can be expressed as:

Inventory Position = Average Inventory + Safety Stock

Average Inventory = Q/2

Safety Stock = s = r – θ

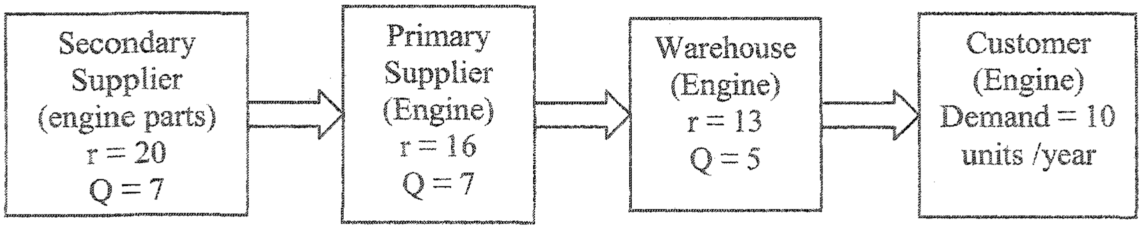
Therefore: Inventory Position = $\left\{\frac{Q}{2} + r - \theta\right\}$ and

Investment in inventory = $c \times \left\{\frac{Q}{2} + r - \theta\right\}$

Where c = unit cost of product in dollars

We will use these cost equations to compare the various cases later in the chapter.

7.1 Replenishment Lead Time = 12 months



Location - Warehouse

Replenishment Lead time = 12 months

Annual demand is D = 10 units/year

Unit cost of the part = \$150

Annual holding cost h = \$15

Average demand during a replenishment lead time is

$$\theta = \frac{D}{12\,months} \times l = \frac{10}{12} \times 12 = 10 \text{ units}$$

The cost of stockout = b = \$40

We model the demand based upon Poisson distribution:

p(r) = Probability {Demand during lead time = r}= $\dfrac{\theta^r e^{-\theta}}{r!} = \dfrac{10^r e^{-10}}{r!}$

And G (r) Cumulative Probability Distribution = $\sum_{k=0}^{r} p(k) = \sum_{k=0}^{r} \dfrac{10^k e^{-10}}{k!}$

Number of backorders in a replenishment cycle, $n(r) = \theta\, p(r) + (\theta - r)(1 - G(r))$

r	p(r)	G(r)	n(r)
0	0.0000	0.0000	10.00
1	0.0005	0.0005	9.00
2	0.0023	0.0027	8.00
3	0.0076	0.0103	7.00
4	0.0189	0.0293	6.01
5	0.0378	0.0671	5.04
6	0.0631	0.1301	4.11
7	0.0901	0.2202	3.24
8	0.1126	0.3328	2.46
9	0.1251	0.4579	1.79
10	0.1251	0.5830	1.25
11	0.1137	0.6968	0.83
12	0.0948	0.7916	0.53
13	0.0729	0.8645	0.32
14	0.0521	0.9165	0.19
15	0.0347	0.9513	0.10
16	0.0217	0.9730	0.05
17	0.0128	0.9857	0.03
18	0.0071	0.9928	0.01
19	0.0037	0.9965	0.01
20	0.0019	0.9984	0.00

$r_0 = 14$
$r_1 = 13$
$r^* = 13$

Table 25. p(r), G(r), n(r) Values for Various Values of r, l = 12 months

Step 0

$$Q_o = \sqrt{\frac{2AD}{h}} = \sqrt{\frac{2 \times 10 \times 10}{15}} = 3.65 \sim 3$$

Find the smallest r such that

$$G(r) \geq 1 - \frac{hQ_0}{bD} = 1 - \frac{15 \times 3}{40 \times 10} = 0.88$$

Hence $r_0 = 14$

Step1

Compute Q_1

$$Q_1 = \sqrt{\frac{2D(A + bn(r_0))}{h}} = \sqrt{\frac{2 \times 10(10 + 40 \times 0.19)}{15}} = 4.81 \sim 5$$

Recalculate r_1 as the smallest r such that

$$G(r) \geq 1 - \frac{hQ_1}{bD} = 1 - \frac{15 \times 5}{40 \times 10} = 0.82$$

From the table r_1=13

Step 2

Compute Q_2

$$Q_2 = \sqrt{\frac{2D(A + bn(r_1)}{h}} = \sqrt{\frac{2 \times 10(10 + 40 \times 0.32)}{15}} = 5.5 \sim 5$$

Recalculate r_2 as the smallest r such that

$$G(r) \geq 1 - \frac{hQ_1}{bD} = 1 - \frac{15 \times 5}{40 \times 10} = 0.82$$

Again if we calculate Q_2 and r_2 we will find the same values; Q_2=5 and R_2=13

Thus (Q, r) model suggests $Q^* = 5$ and $r^* = 13$ at Warehouse i.e. the engine should be replenished in a year with Q = 5 and should be replaced when the inventory level is at 13.

Safety stock level = r - θ

= 13 -10 = 3

Location - Primary Supplier.

r	p(r)	G(r)	n(r)
0	0.00	0.00	13.00
1	0.00	0.00	12.00
2	0.00	0.00	11.00
3	0.00	0.00	10.00
4	0.00	0.00	9.00
5	0.01	0.01	8.01
6	0.02	0.03	7.02
7	0.03	0.05	6.04
8	0.05	0.10	5.10
9	0.07	0.17	4.20
10	0.09	0.25	3.36
11	0.10	0.35	2.61
12	0.11	0.46	1.97
13	0.11	0.57	1.43
14	0.10	0.68	1.00
15	0.09	0.76	0.68
16	0.07	0.84	0.44
17	0.05	0.89	0.28
18	0.04	0.93	0.17
19	0.03	0.96	0.10

$r_0 = 16$
$r_1 = 16$
$r^* = 16$

Table 26. p(r), G(r), n(r) Values for Various Values of r, l = 12 months

Step 0

$$Q_o = \sqrt{\frac{2AD}{h}} = \sqrt{\frac{2.10.13}{15}} = 4.16 \sim 4$$

Find the smallest r such that

$$G(r) \geq 1 - \frac{hQ_0}{bD} = 1 - \frac{15.4}{40.13} = 0.83$$

Hence $r_0 = 16$

Step1

Compute Q_1

$$Q_1 = \sqrt{\frac{2D(A + bn(r_0))}{h}} = \sqrt{\frac{2 \times 13(10 + 40 \times 0.44)}{15}} = 6.9 \sim 7$$

Recalculate r_1 as the smallest r such that

$$G(r) \geq 1 - \frac{hQ_1}{bD} = 1 - \frac{15 \times 7}{40 \times 13} = 0.82$$

From the table $r_1 = 16$

Again if we calculate Q_2 and r_2 we will find the same values; $Q_2 = 7$ and $r_2 = 16$

Thus (Q, r) model suggests Q*=7 and r* =16 at Primary Supplier i.e. the engine should be replenished in a year with Q* = 7 and should be replaced when the inventory level is at 16.

Safety stock is 16 - 13 = 3

Location - Secondary Supplier.

r	p(r)	G(r)	n(r)
0	0.00	0.00	16.00
1	0.00	0.00	15.00
2	0.00	0.00	14.00
3	0.00	0.00	13.00
4	0.00	0.00	12.00
5	0.00	0.00	11.00
6	0.00	0.00	10.00
7	0.01	0.01	9.01
8	0.01	0.02	8.02
9	0.02	0.04	7.04
10	0.03	0.08	6.08
11	0.05	0.13	5.16
12	0.07	0.19	4.29
13	0.08	0.27	3.48
14	0.09	0.37	2.75
15	0.10	0.47	2.12
16	0.10	0.57	1.59
17	0.09	0.66	1.15
18	0.08	0.74	0.81
19	0.07	0.81	0.56
20	0.06	0.87	0.37
21	0.04	0.91	0.24
22	0.03	0.94	0.15
23	0.02	0.96	0.09
24	0.01	0.98	0.05
25	0.01	0.99	0.03

$r_0 = 21$
$r_1 = 21$
$r^* = 20$

Table 27. p(r), G(r), n(r) values for various values of r, l = 12 months

Step 0

$$Q_o = \sqrt{\frac{2AD}{h}} = \sqrt{\frac{2\times10\times16}{15}} = 4.6 \sim 5$$

Find the smallest r such that

$$G(r) \geq 1 - \frac{hQ_0}{bD} = 1 - \frac{15\times5}{40\times16} = 0.89$$

Hence $r_0 = 21$

Step1

Compute Q_1

$$Q_1 = \sqrt{\frac{2D(A+bn(r_0))}{h}} = \sqrt{\frac{2\times 16(10+40\times 0.24)}{15}} = 6.46 \sim 7$$

Recalculate r_1 as the smallest r such that

$$G(r) \geq 1 - \frac{hQ_1}{bD} = 1 - \frac{15\times 7}{40\times 16} = 0.84$$

From the table $r_1 = 20$

Step 2

$$Q_2 = \sqrt{\frac{2D(A+bn(r_1))}{h}} = \sqrt{\frac{2\times 16(10+40\times 0.37)}{15}} = 7.27 \sim 7$$

Recalculate r_1 as the smallest r such that

$$G(r) \geq 1 - \frac{hQ_2}{bD} = 1 - \frac{15\times 7}{40\times 16} = 0.84$$

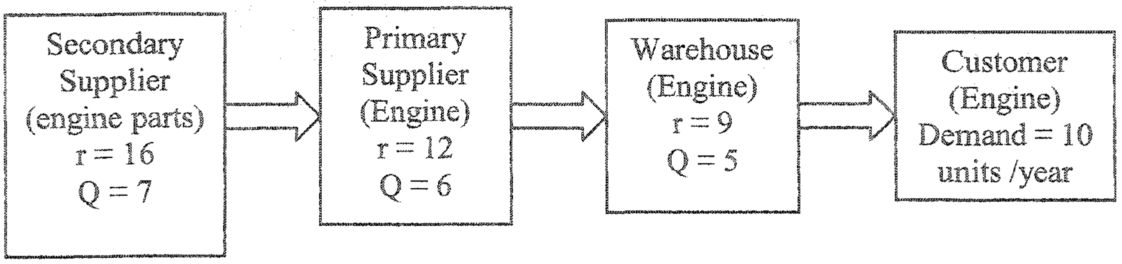
From the table $r_2 = 20$

Again if we calculate Q_3 and r_3 we will find the same values; $Q_3 = 7$ and $r_3 = 20$

Thus (Q, r) model suggests Q* =7 and r* =20 at warehouse i.e. the engine should be replenished in a year with Q* =7 and should be replaced when the inventory level reaches 20.

Safety stock is 20 -16 = 4

7.2 Replenishment Lead time is 8 months



Location - Warehouse

Annual demand is D = 10 units/year

Unit cost of the part = \$150

Annual holding cost h = \$15

Average demand during a replenishment lead time is

$$\theta = \frac{D}{12\, months} \times l = \frac{10}{12} \times 8 = 6.67 \text{ units}$$

The cost of stockout = b = \$40

Let us model the demand using Poisson distribution.

We model the demand based upon Poisson distribution:

p(r) = Probability {Demand during lead time = r}= $\frac{\theta^r e^{-\theta}}{r!} = \frac{10^r e^{-10}}{r!}$

And G (r) Cumulative Probability Distribution = $\sum_{k=0}^{r} p(k) = \sum_{k=0}^{r} \frac{10^k e^{-10}}{k!}$

Number of backorders in a replenishment cycle, $n(r) = \theta\ p(r) + (\theta - r)(1 - G(r))$

r	p(r)	G(r)	n(r)
0	0.00	0.00	6.67
1	0.01	0.01	5.67
2	0.03	0.04	4.69
3	0.06	0.10	3.72
4	0.10	0.21	2.82
5	0.14	0.34	2.02
6	0.16	0.50	1.37
7	0.15	0.65	0.87
8	0.12	0.77	0.52
9	0.09	0.86	0.29
10	0.06	0.92	0.15
11	0.04	0.96	0.07
12	0.02	0.98	0.03
13	0.01	0.99	0.01
14	0.01	1.00	0.01
15	0.00	1.00	0.00
16	0.00	1.00	0.00
17	0.00	1.00	0.00
18	0.00	1.00	0.00
19	0.00	1.00	0.00
20	0.00	1.00	0.00

$r_0 = 9$
$r_1 = 9$
$r^* = 9$

Table 28. p(r), G(r), n(r) Values for Various Values of r, l = 8 months

Step 0

$$Q_o = \sqrt{\frac{2AD}{h}} = \sqrt{\frac{2\times10\times10}{15}} = 3.65 \sim 4$$

Find the smallest r such that

$$G(r) \geq 1 - \frac{hQ_0}{bD} = 1 - \frac{15\times4}{40\times10} = 0.85$$

Hence $r_0 = 9$

Step1

Compute Q_1

$$Q_1 = \sqrt{\frac{2D(A + bn(r_0))}{h}} = \sqrt{\frac{2\times10(10 + 40\times0.29)}{15}} = 5.37 \sim 5$$

Recalculate r_1 as the smallest r such that

$$G(r) \geq 1 - \frac{hQ_1}{bD} = 1 - \frac{15\times5}{40\times10} = 0.81$$

From the table r_1=9

Again if we calculate Q_2 and r_2 we will find the same values; Q_2=5 and R_2=9

Thus, (Q, r) model suggests Q* = 5 and r* = 9 at Warehouse i.e. the engine should be replenished in a year with Q* = 5 and should be replaced when the inventory level is at 9.

Safety stock level = r - θ = 9-6.67 = 2.33

Location - Primary Supplier.

r	p(r)	G(r)	n(r)
0	0.00	0.00	9.00
1	0.00	0.00	8.00
2	0.00	0.01	7.00
3	0.01	0.02	6.01
4	0.03	0.05	5.03
5	0.06	0.12	4.08
6	0.09	0.21	3.20
7	0.12	0.32	2.41
8	0.13	0.46	1.73
9	0.13	0.59	1.19
10	0.12	0.71	0.77
11	0.10	0.80	0.48
12	0.07	0.88	0.28
13	0.05	0.93	0.16
14	0.03	0.96	0.08
15	0.02	0.98	0.04
16	0.01	0.99	0.02
17	0.01	0.99	0.01
18	0.00	1.00	0.00
19	0.00	1.00	0.00
20	0.00	1.00	0.00

$r_0 = 13$
$r_1 = 12$
$r^* = 12$

Table 29. p(r), G(r), n(r) Values for Various Values of r, l = 8 months

Step 0

$$Q_o = \sqrt{\frac{2AD}{h}} = \sqrt{\frac{2\times10\times13.5}{15}} = 4.24 \sim 4$$

Find the smallest r such that

$$G(r) \geq 1 - \frac{hQ_0}{bD} = 1 - \frac{15\times4}{40\times13.5} = 0.89\text{; hence } r_0 = 13$$

Step1

Compute Q_1

$$Q_1 = \sqrt{\frac{2D(A+bn(r_0)}{h}} = \sqrt{\frac{2\times 13.5(10+40\times 0.16)}{15}} = 5.43 \sim 5$$

Recalculate r_1 as the smallest r such that

$$G(r) \geq 1 - \frac{hQ_1}{bD} = 1 - \frac{15\times 5}{40\times 13.5} = 0.86$$

From the table $r_1=12$

Step 2

Compute Q_2

$$Q_2 = \sqrt{\frac{2D(A+bn(r_0)}{h}} = \sqrt{\frac{2\times 13.5(10+40\times 0.28)}{15}} = 6.18 \sim 6$$

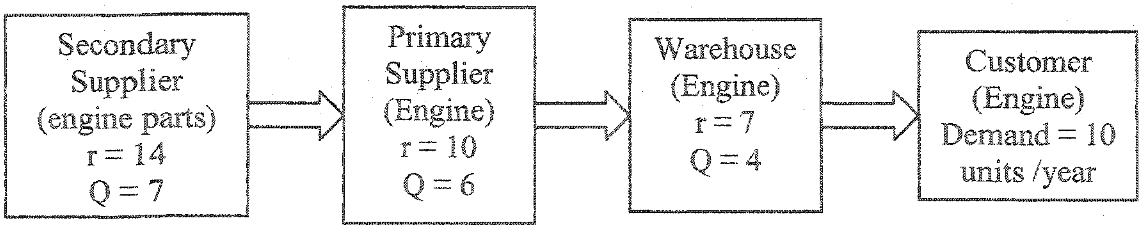
Again if we calculate Q_3 and r_3 we will find the same values.

Hence $Q^* = 6$, $r^* = 12$

Thus (Q, r) model suggests Q=6 and r =12 at warehouse i.e. the engine should be replenished in a year with Q = 6 and should be replaced when the inventory level reaches 12.

Safety stock is 12 - 9 = 3

7.3 Replenishment Lead time = 6 months



Location - Warehouse

Annual demand is D = 10 units/year

Unit cost of the part = $150

Annual holding cost h = $15

Average demand during a replenishment lead time is

$$\theta = \frac{D}{12\,months} \times l = \frac{10}{12} \times 6 = 5 \text{ units}$$

The cost of stockout = b = $40

Let us model the demand using Poisson distribution.

We model the demand based upon Poisson distribution:

p(r) = Probability {Demand during lead time = r}= $\dfrac{\theta^r e^{-\theta}}{r!} = \dfrac{10^r e^{-10}}{r!}$

And G (r) Cumulative Probability Distribution = $\sum_{k=0}^{r} p(k) = \sum_{k=0}^{r} \dfrac{10^k e^{-10}}{k!}$

Number of backorders in a replenishment cycle, $n(r) = \theta\ p(r) + (\theta - r)(1 - G(r))$

r	p(r)	G(r)	n(r)
0	0.01	0.01	5.00
1	0.03	0.04	4.01
2	0.08	0.12	3.07
3	0.14	0.27	2.17
4	0.18	0.44	1.44
5	0.18	0.62	0.88
6	0.15	0.76	0.49
7	0.10	0.87	0.26
8	0.07	0.93	0.12
9	0.04	0.97	0.05
10	0.02	0.99	0.02
11	0.01	0.99	0.01
12	0.00	1.00	0.00
13	0.00	1.00	0.00
14	0.00	1.00	0.00
15	0.00	1.00	0.00
16	0.00	1.00	0.00
17	0.00	1.00	0.00
18	0.00	1.00	0.00
19	0.00	1.00	0.00
20	0.00	1.00	0.00

$r_0 = 8$
$r_1 = 7$
$r^* = 7$

Table 30. p(r), G(r), n(r) Values for Various Values of r, l = 6 months

Step 0

$$Q_o = \sqrt{\frac{2AD}{h}} = \sqrt{\frac{2\times10\times10}{15}} = 3.65 \sim 3$$

Find the smallest r such that

$$G(r) \geq 1 - \frac{hQ_0}{bD} = 1 - \frac{15\times3}{40\times10} = 0.88$$

Hence $r_0 = 8$

Step1

Compute Q_1

$$Q_1 = \sqrt{\frac{2D(A+bn(r_0))}{h}} = \sqrt{\frac{2\times10(10+40\times0.12)}{15}} = 4.44 \sim 4$$

Recalculate r_1 as the smallest r such that

$$G(r) \geq 1 - \frac{hQ_1}{bD} = 1 - \frac{15 \times 4}{40 \times 10} = 0.85$$

From the table $r_1 = 7$

Step 2

$$Q_1 = \sqrt{\frac{2D(A + bn(r_0)}{h}} = \sqrt{\frac{2 \times 10(10 + 40 \times 0.12)}{15}} = 5.21 \sim 5$$

$$G(r) \geq 1 - \frac{hQ_1}{bD} = 1 - \frac{15 \times 5}{40 \times 10} = 0.82$$

From the table $r_2 = 7$

Again if we calculate Q_2 and r_2 we will find the same values, $Q_2 = 4$ and $r_2 = 7$.

Hence, (Q, r) model suggests $Q^* = 4$ and $r^* = 7$ at warehouse, the engine should be replenished in a year with $Q^* = 4$ and should be replaced when the inventory level reaches 7.

Safety stock level = r - θ

= 7 - 5 = 2

Location - Primary Supplier.

Primary supplier has to supply 7 items for 6 months and hence the demand for year is 14 items per year.

Total demand is 14 and the average demand is 7.

r	p(r)	G(r)	n(r)
0	0.00	0.00	7.00
1	0.01	0.01	6.00
2	0.02	0.03	5.01
3	0.05	0.08	4.04
4	0.09	0.17	3.12
5	0.13	0.30	2.29
6	0.15	0.45	1.59
7	0.15	0.60	1.04
8	0.13	0.73	0.64
9	0.10	0.83	0.37
10	0.07	0.90	0.20
11	0.05	0.95	0.10
12	0.03	0.97	0.05
13	0.01	0.99	0.02
14	0.01	0.99	0.01
15	0.00	1.00	0.00
16	0.00	1.00	0.00
17	0.00	1.00	0.00
18	0.00	1.00	0.00
19	0.00	1.00	0.00
20	0.00	1.00	0.00

$r_0 = 10$
$r_1 = 10$
$r^* = 10$

Table 31. p(r), G(r), n(r) Values for Various Values of r, l = 6 months

Step 0

$$Q_o = \sqrt{\frac{2AD}{h}} = \sqrt{\frac{2.10.14}{15}} = 4.32 \sim 4$$

Find the smallest r such that

$$G(r) \geq 1 - \frac{hQ_0}{bD} = 1 - \frac{15 \times 4}{40 \times 14} = 0.89$$

Hence $r_0 = 10$

Step1

Compute Q_1

$$Q_1 = \sqrt{\frac{2D(A + bn(r_0))}{h}} = \sqrt{\frac{2 \times 14(10 + 40 \times 0.20)}{15}} = 5.79 \sim 6$$

Recalculate r_1 as the smallest r such that

$$G(r) \ge 1 - \frac{hQ_1}{bD} = 1 - \frac{15 \times 6}{40 \times 14} = 0.84$$

From the table $r_1 = 10$

Again if we calculate Q_2 and r_2 we will find the same values.

Hence $Q^* = 6$, $r^* = 10$

Thus, (Q, r) model suggests $Q^* = 6$ and $r^* = 10$ at primary supplier i.e. the engine should be replenished in a year with $Q^* = 6$ and should be replaced when the inventory level reaches 10.

Safety stock is 10 -7 = 3

Location - Secondary Supplier.

r	p(r)	G(r)	n(r)
0	0.00	0.00	10.00
1	0.00	0.00	9.00
2	0.00	0.00	8.00
3	0.01	0.01	7.00
4	0.02	0.03	6.01
5	0.04	0.07	5.04
6	0.06	0.13	4.11
7	0.09	0.22	3.24
8	0.11	0.33	2.46
9	0.13	0.46	1.79
10	0.13	0.58	1.25
11	0.11	0.70	0.83
12	0.09	0.79	0.53
13	0.07	0.86	0.32
14	0.05	0.92	0.19
15	0.03	0.95	0.10
16	0.02	0.97	0.05
17	0.01	0.99	0.03
21	0.00	1.00	0.00
22	0.00	1.00	0.00
23	0.00	1.00	0.00

$r_0 = 14$
$r_1 = 14$
$r^* = 14$

Table 32. p(r), G(r), n(r) Values for Various Values of r, l = 6 months

Step 0

$$Q_o = \sqrt{\frac{2AD}{h}} = \sqrt{\frac{2\times 10\times 20}{15}} = 5.16 \sim 5$$

Find the smallest r such that

$$G(r) \geq 1 - \frac{hQ_0}{bD} = 1 - \frac{15\times 5}{40\times 20} = 0.91$$

Hence $r_0 = 14$

Step1

Compute Q_1

$$Q_1 = \sqrt{\frac{2D(A + bn(r_0))}{h}} = \sqrt{\frac{2\times 20(10 + 40\times 0.19)}{15}} = 6.85 \sim 7$$

Recalculate r_1 as the smallest r such that

$$G(r) \geq 1 - \frac{hQ_1}{bD} = 1 - \frac{15\times 7}{40\times 20} = 0.87$$

From the table $r_1=14$

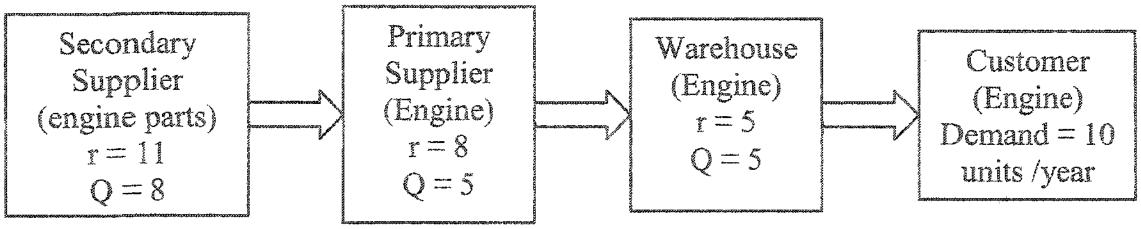
Step 2

After recalculating $Q_2 = 7$ and $r_2 = 14$

Thus, (Q, r) model suggests $Q^* = 7$ and $r^* = 14$ at Secondary Supplier i.e. the engine should be replenished in a year with $Q^* = 7$ and should be replaced when the inventory level reaches 14.

Safety stock is 14 - 10 = 4

7.4 Replenishment Lead time = 4 months



Location Warehouse

Annual demand is D = 10 units/year

Unit cost of the part = $150

Annual holding cost h = $15

Average demand during a replenishment lead time is

$$\theta = \frac{D}{12\,months} \times l = \frac{10}{12} \times 4 = 3.33 \text{ units}$$

The cost of stockout = b = $40

Let us model the demand using Poisson distribution.

We model the demand based upon Poisson distribution:

p(r) = Probability {Demand during lead time = r}= $\frac{\theta^r e^{-\theta}}{r!} = \frac{10^r e^{-10}}{r!}$

And G (r) Cumulative Probability Distribution = $\sum_{k=0}^{r} p(k) = \sum_{k=0}^{r} \frac{10^k e^{-10}}{k!}$

Number of backorders in a replenishment cycle, $n(r) = \theta\, p(r) + (\theta - r)(1 - G(r))$

r	p(r)	G(r)	n(r)
0	0.04	0.04	3.33
1	0.12	0.15	2.37
2	0.20	0.32	1.57
3	0.22	0.57	0.87
4	0.18	0.76	0.45
5	0.12	0.88	0.21
6	0.07	0.95	0.08
7	0.03	0.98	0.03
8	0.01	0.99	0.01
9	0.00	1.00	0.00
10	0.00	1.00	0.00
11	0.00	1.00	0.00
12	0.00	1.00	0.00
13	0.00	1.00	0.00
14	0.00	1.00	0.00
15	0.00	1.00	0.00

$r_0 = 5$
$r_1 = 5$
$r^* = 5$

Table 33. p(r), G(r), n(r) Values for Various Values of r, l = 4 months

Step 0

$$Q_o = \sqrt{\frac{2AD}{h}} = \sqrt{\frac{2\times 10\times 10}{15}} = 3.65 \sim 4$$

Find the smallest r such that

$$G(r) \geq 1 - \frac{hQ_0}{bD} = 1 - \frac{15\times 4}{40\times 10} = 0.85$$

Hence $r_0 = 5$

Step 1

Compute Q_1

$$Q_1 = \sqrt{\frac{2D(A+bn(r_0))}{h}} = \sqrt{\frac{2\times 10(10+40\times 0.21)}{15}} = 4.95 \sim 5$$

Recalculate r_1 as the smallest r such that

$$G(r) \geq 1 - \frac{hQ_1}{bD} = 1 - \frac{15\times 5}{40\times 10} = 0.81$$

From the table r_1=5

Again if we calculate Q_2 and r_2 we will find the same values; $Q_2=5$ and $R_2=5$

Thus, (Q, r) model suggests $Q^* = 5$ and $r^* = 5$ at Warehouse i.e. the engine should be replenished in a year with $Q^* = 5$ and should be replaced when the inventory level reaches 5.

Safety stock level = $r - \theta = 5 - 3.33 = 1.67$

Location - Primary Supplier.

r	p(r)	G(r)	n(r)
0	0.01	0.01	5.00
1	0.03	0.04	4.01
2	0.08	0.12	3.07
3	0.14	0.27	2.17
4	0.18	0.44	1.44
5	0.18	0.62	0.88
6	0.15	0.76	0.49
7	0.10	0.87	0.26
8	0.07	0.93	0.12
9	0.04	0.97	0.05
10	0.02	0.99	0.02
11	0.01	0.99	0.01
12	0.00	1.00	0.00
13	0.00	1.00	0.00
14	0.00	1.00	0.00
15	0.00	1.00	0.00

$r_0 = 8$
$r_1 = 8$
$r^* = 8$

Table 34. p(r), G(r), n(r) Values for Various Values of r, l = 4 months

Step 0

$$Q_o = \sqrt{\frac{2AD}{h}} = \sqrt{\frac{2\times 10\times 15}{15}} = 4.47 \sim 4$$

Find the smallest r such that

$$G(r) \geq 1 - \frac{hQ_0}{bD} = 1 - \frac{15\times 4}{40\times 13.5} = 0.9$$

Hence $r_0 = 8$

Step1

Compute Q_1

$$Q_1 = \sqrt{\frac{2D(A+bn(r_0)}{h}} = \sqrt{\frac{2\times 13.5(10+40\times 0.12)}{15}} = 5.44 \sim 5$$

Recalculate r_1 as the smallest r such that

$$G(r) \geq 1 - \frac{hQ_1}{bD} = 1 - \frac{15\times 5}{40\times 15} = 0.88$$

From the table $r_1=8$

Step 2

Again if we calculate Q_2 and r_2 we will find the same values.

Hence Q* =5, r* =8

Thus (Q, r) model suggests Q* = 5 and r* = 8 at Primary Supplier i.e. the engine should be replenished in a year with Q* = 5 and should be replaced when the inventory level reaches 8.

Safety stock is 8 -5 = 3

Location - Secondary Supplier.

r	p(r)	G(r)	n(r)
0	0.00	0.00	8.00
1	0.00	0.00	7.00
2	0.01	0.01	6.01
3	0.03	0.04	5.02
4	0.06	0.10	4.06
5	0.09	0.19	3.16
6	0.12	0.31	2.35
7	0.14	0.45	1.66
8	0.14	0.59	1.12
9	0.12	0.72	0.71
10	0.10	0.82	0.43
11	0.07	0.89	0.24
12	0.05	0.94	0.13
13	0.03	0.97	0.07
14	0.02	0.98	0.03
15	0.01	0.99	0.01
23	0.00	1.00	0.00
24	0.00	1.00	0.00
25	0.00	1.00	0.00

$r_0 = 12$
$r_1 = 11$
$r^* = 11$

Table 35. p(r), G(r), n(r) Values for Various Values of r, l = 4 months

Step 0

$$Q_o = \sqrt{\frac{2AD}{h}} = \sqrt{\frac{2\times10\times24}{15}} = 5.66 \sim 6$$

Find the smallest r such that

$$G(r) \geq 1 - \frac{hQ_0}{bD} = 1 - \frac{15\times6}{40\times24} = 0.91$$

Hence $r_0 = 12$

Step1

Compute Q_1

$$Q_1 = \sqrt{\frac{2D(A+bn(r_0)}{h}} = \sqrt{\frac{2\times 24(10+40\times 0.12)}{15}} = 6.97 \sim 7$$

Recalculate r_1 as the smallest r such that

$$G(r) \geq 1 - \frac{hQ_1}{bD} = 1 - \frac{15\times 7}{40\times 24} = 0.89$$

From the table $r_1=11$

Step 2

Compute Q_2

$$Q_2 = \sqrt{\frac{2D(A+bn(r_1)}{h}} = \sqrt{\frac{2\times 24(10+40\times 0.24)}{15}} = 7.92 \sim 8$$

Recalculate r_1 as the smallest r such that

$$G(r) \geq 1 - \frac{hQ_1}{bD} = 1 - \frac{15\times 8}{40\times 24} = 0.88$$

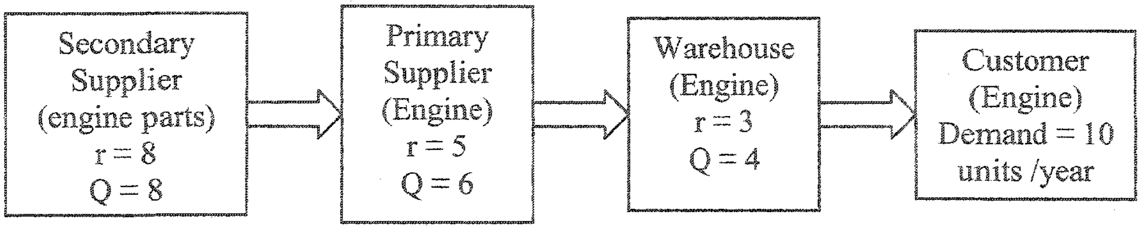
$r_2=11$

Thus $Q_2 = 8$ and $r_2 = 11$

Thus (Q, r) model suggests Q* = 8 and r* = 11 at Secondary Supplier i.e. the engine should be replenished in a year with Q* = 8 and should be replaced when the inventory level reaches 11.

Safety stock is 11- 8 = 3.

7.5 Replenishment lead time = 2 months



Location - Warehouse

Annual demand is D = 10 units/year

Unit cost of the part = \$150

Annual holding cost h = \$15

Average demand during a replenishment lead time is

$$\theta = \frac{D}{12\,months} \times l = \frac{10}{12} \times 2 = 1.67 \text{ units}$$

The cost of stockout = b = \$40

Let us model the demand using Poisson distribution.

We model the demand based upon Poisson distribution:

p(r) = Probability {Demand during lead time = r}= $\frac{\theta^r e^{-\theta}}{r!} = \frac{10^r e^{-10}}{r!}$

And G (r) Cumulative Probability Distribution = $\sum_{k=0}^{r} p(k) = \sum_{k=0}^{r} \frac{10^k e^{-10}}{k!}$

Number of backorders in a replenishment cycle, $n(r) = \theta\, p(r) + (\theta - r)(1 - G(r))$

r	p(r)	G(r)	n(r)
0	0.19	0.19	1.67
1	0.31	0.50	0.86
2	0.26	0.58	0.30
3	0.15	0.91	0.13
4	0.06	0.97	0.04
5	0.02	0.99	0.01
6	0.01	1.00	0.00
7	0.00	1.00	0.00
8	0.00	1.00	0.00
9	0.00	1.00	0.00
10	0.00	1.00	0.00
11	0.00	1.00	0.00
12	0.00	1.00	0.00
13	0.00	1.00	0.00
14	0.00	1.00	0.00
15	0.00	1.00	0.00

$r_0 = 3$
$r_1 = 3$
$r^* = 3$

Table 36. p(r), G(r), n(r) Values for Various Values of r, l = 2 months

Step 0

$$Q_o = \sqrt{\frac{2AD}{h}} = \sqrt{\frac{2\times10\times10}{15}} = 3.65 \sim 3$$

Find the smallest r such that

$$G(r) \geq 1 - \frac{hQ_0}{bD} = 1 - \frac{15\times3}{40\times10} = 0.88$$

Hence $r_0 = 3$

Step1

Compute Q_1

$$Q_1 = \sqrt{\frac{2D(A + bn(r_0))}{h}} = \sqrt{\frac{2\times10(10 + 40\times0.13)}{15}} = 4.5 \sim 4$$

Recalculate r_1 as the smallest r such that

$$G(r) \geq 1 - \frac{hQ_1}{bD} = 1 - \frac{15\times4}{40\times10} = 0.85$$

From the table r_1=3

Again if we calculate Q_2 and r_2 we will find the same values; Q2=4 and R2=3

Thus (Q, r) model suggests Q* = 4 and r* = 3 at Warehouse i.e. the engine should be replenished in a year with Q* = 4 and should be replaced when the inventory level reaches 3.

Safety stock level = r - θ

= 3 -1.67 = 1.33

Location - Primary Supplier.

r	p(r)	G(r)	n(r)
0	0.05	0.05	3.00
1	0.15	0.20	2.05
2	0.22	0.37	1.30
3	0.22	0.65	0.67
4	0.17	0.82	0.32
5	0.10	0.92	0.13
6	0.05	0.97	0.05
7	0.02	0.99	0.02
8	0.01	1.00	0.01
9	0.00	1.00	0.00
10	0.00	1.00	0.00
11	0.00	1.00	0.00
12	0.00	1.00	0.00
13	0.00	1.00	0.00
14	0.00	1.00	0.00
15	0.00	1.00	0.00

$r_0 = 5$
$r_1 = 5$
$r^* = 5$

Table 37. p(r), G(r), n(r) Values for Various Values of r, l = 2 months

Step 0

$$Q_o = \sqrt{\frac{2AD}{h}} = \sqrt{\frac{2\times10\times18}{15}} = 4.9 \sim 5$$

Find the smallest r such that

$$G(r) \geq 1 - \frac{hQ_0}{bD} = 1 - \frac{15\times5}{40\times18} = 0.90$$

Hence $r_0 = 5$

Step1

Compute Q_1

$$Q_1 = \sqrt{\frac{2D(A+bn(r_0)}{h}} = \sqrt{\frac{2\times18(10+40\times0.13)}{15}} = 6.04 \sim 6$$

Recalculate r_1 as the smallest r such that

$$G(r) \geq 1 - \frac{hQ_1}{bD} = 1 - \frac{15\times6}{40\times18} = 0.88$$

From the table r_1=5

Again if we calculate Q_2 and r_2 we will find the same values.

Hence Q* =6, r* =5

Thus (Q, r) model suggests Q* = 6 and r* = 5 at Primary Supplier i.e. the engine should be replenished in a year with Q* = 6 and should be replaced when the inventory level reaches 5.

Safety stock is 5 - 3 = 2

Location - Secondary Supplier.

r	p(r)	G(r)	n(r)
0	0.00	0.00	12.00
1	0.00	0.00	11.00
2	0.00	0.00	10.00
3	0.00	0.00	9.00
4	0.01	0.01	8.00
5	0.01	0.02	7.01
6	0.03	0.05	6.03
7	0.04	0.09	5.08
8	0.07	0.16	4.17
9	0.09	0.24	3.32
10	0.10	0.35	2.56
11	0.11	0.46	1.91
12	0.11	0.58	1.37
13	0.11	0.68	0.95
14	0.09	0.77	0.63
15	0.07	0.84	0.40
16	0.05	0.90	0.25
17	0.04	0.94	0.15
18	0.03	0.96	0.08
19	0.02	0.98	0.04
20	0.01	0.99	0.02

$r_0 = 16$
$r_1 = 16$
$r^* = 16$

Table 38. p(r), G(r), n(r) Values for Various Values of r, l = 2 months

Step 0

$$Q_o = \sqrt{\frac{2AD}{h}} = \sqrt{\frac{2\times10\times18}{15}} = 4.8 \sim 5$$

Find the smallest r such that

$$G(r) \geq 1 - \frac{hQ_0}{bD} = 1 - \frac{15\times5}{40\times18} = 0.90$$

Hence $r_0 = 16$

Step1

Compute Q_1

$$Q_1 = \sqrt{\frac{2D(A + bn(r_0))}{h}} = \sqrt{\frac{2\times18(10+40\times0.25)}{15}} = 6.93 \sim 7$$

Recalculate r_1 as the smallest r such that

$$G(r) \geq 1 - \frac{hQ_1}{bD} = 1 - \frac{15 \times 7}{40 \times 18} = 0.85$$

From the table r_1=16

Step 2

After recalculating Q_2 =7 and r_2 = 16

Thus (Q, r) model suggests Q* = 7 and r* = 16 at Secondary Supplier i.e. the engine should be replenished in a year with Q* = 7 and should be replaced when the inventory level reaches 16.

Safety stock is 16 -12 = 4

7.6 Summary of Results for (Q, r) Model:

We summarize the result by comparing the total cost associated with inventory for each of the above five cases. The order cost is assumed to be \$ 25 per order, backorder cost is \$ 40 per order and the unit product cost c = \$ 150. The total cost function was derived earlier for the (Q, r) model in chapter 5 and the final cost equation was shown in equation (27). We go through a quick cost formulation here again. The total cost associated with carrying an inventory has three components; Cost for ordering the inventory (setup cost), Inventory holding cost and backorder cost. Thus, the total cost can be calculated as follows:

Total Cost = Order Cost + Inventory Holding Cost + Backorder Cost

$$\text{Inventory Holding Cost} = c \times \left\{ \frac{Q}{2} + r - \theta \right\}$$

Order Cost = Cost per order x Frequency = A x F

$$\text{Backorder Cost} = b \times \frac{D}{Q} \times n(r)$$

$$\text{Total Cost} = A \times F \ + c \times \left\{ \frac{Q}{2} + r - \theta \right\} + b \times \frac{D}{Q} \times n(r)$$

Table 39 summarizes all the results including the frequency of order, the order cost and the total cost of inventory. Total cost is shown in the last column. Sample cost calculation for the first case i.e. l = 12, D = 10 at warehouse is given here:

Total cost = \$25x2 + \$150 (5/2 + 13 -10) = \$ 50 + \$ 825 +25.6 = \$ 900.60

Lead time	Location	n(r)	r*	Q*	Fill Rate G(r)	Freq. - F	Average Demand	Holding Cost $	Backorder Cost $	Order Cost $	Total Cost $
12	WH	0.32	13.00	5.00	0.94	2.00	10	825	25.6	50.00	900.60
	PS	0.44	16.00	7.00	0.94	1.86	13	975	32.7	46.43	1054.10
	SS	0.37	20.00	7.00	0.95	2.29	16	1125	33.8	57.14	1216.00
6	WH	0.26	7.00	4.00	0.94	2.50	5	600	26	62.50	688.50
	PS	0.20	10.00	6.00	0.97	2.33	7	900	18.7	58.33	977.00
	SS	0.19	14.00	7.00	0.97	2.86	10	1125	21.7	71.43	1218.10
2	WH	0.13	3.00	4.00	0.97	2.50	1.67	499.5	13	62.50	575.00
	PS	0.13	5.00	6.00	0.98	3.00	3	750	15.6	75.00	840.60
	SS	0.12	8.00	8.00	0.99	3.75	5	1050	18	93.75	1161.80
8	WH	0.29	9.00	5.00	0.94	2.00	6.67	724.5	23.2	50.00	797.70
	PS	0.28	12.00	6.00	0.95	2.25	9	900	25.2	56.25	981.50
	SS	0.25	16.00	7.00	0.96	2.57	12	1125	25.7	64.29	1215.00
4	WH	0.21	5.00	5.00	0.96	2.00	3.33	625.5	16.8	50.00	692.30
	PS	0.12	8.00	5.00	0.98	3.00	5	825	14.4	75.00	914.40
	SS	0.24	11.00	8.00	0.97	3.00	8	1050	28.8	75.00	1153.80

Table 39. Summary of Application Runs for (Q, r) Model

Replenishment Lead Time (months)	Warehouse Storage Cost ($)	Primary Supplier Storage Cost ($)	Secondary Supplier Storage Cost ($)
12	900.60	1054.10	1216.00
8	797.70	981.50	1215.00
6	688.50	977.00	1218.10
4	692.30	914.40	1153.80
2	575.00	840.60	1161.80

Table 40. Cost Values for Various Replenishment Lead Times

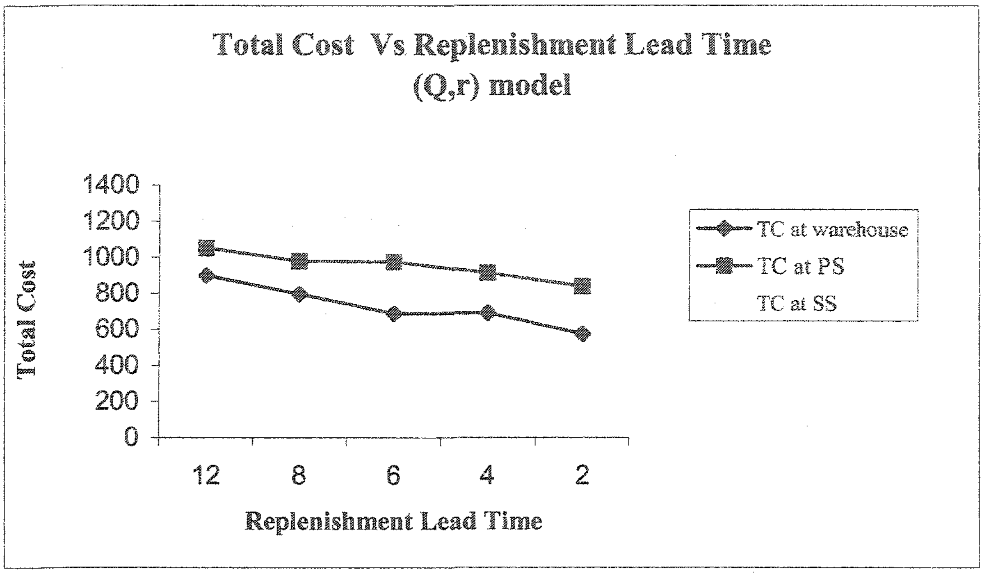


Figure 20. Total Cost vs. Replenishment Lead Time ((Q, r) model)

Different results of (Q, r) model are summarized in Table 41. The values at different stages of algorithm are also noted in the table. Table 40 compares Cost at Warehouse, Primary Supplier and secondary supplier when (Q, r) model is used for inventory control. These values are plotted in Figure 20.

Replenishment Lead Time (months)	Reorder Point at Warehouse	Reorder Point at Primary Supplier	Reorder Point at Secondary Supplier
12	13	16	20
8	9	12	16
6	7	10	14
4	5	8	11
2	3	5	8

Table 41. Reorder Point for Various Replenishment Lead Time (Q,r) Model

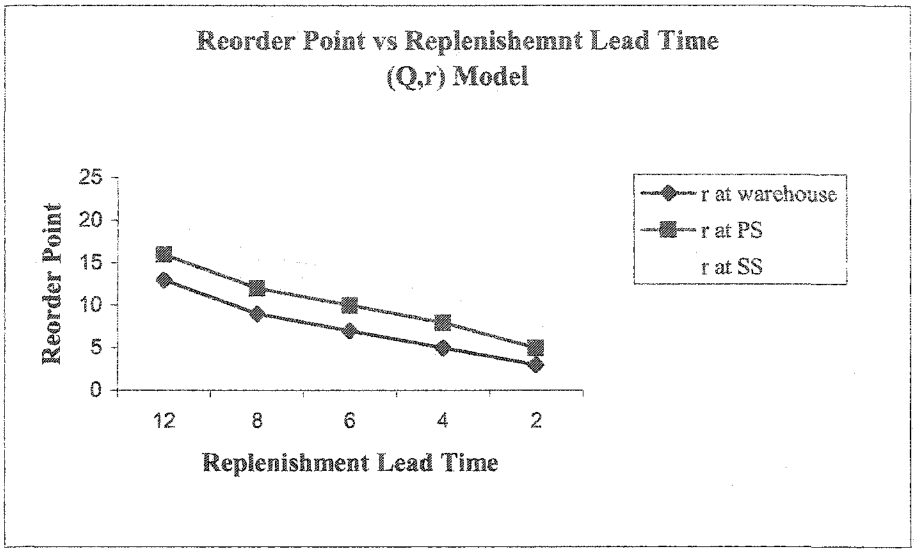


Figure 21. Reorder Point vs. Replenishment Lead Time ((Q, r) model)

Table 41 compares reorder point at Warehouse, Primary Supplier and secondary supplier when (Q, r) model is used for inventory control with different replenishment lead-time. We can see from Figure 21 that the reorder point is increasing with increase in replenishment lead time.

Replenishment Lead Time	Q at Warehouse	Q at Primary Supplier	Q at Secondary Supplier
12	5	7	7
8	5	6	7
6	4	6	7
4	5	5	8
2	4	6	8

Table 42. Q for Various Replenishment Lead Times

Chapter – 8

PHYSICAL SIMULATION OF BASE STOCK MODEL

8.1 Goals of Physical Simulation

Primary goal of conducting the physical simulation is to validate the results obtained from the mathematical models. Simulation was run to confirm that optimum inventory levels i.e. reorder point at warehouse, primary supplier and secondary supplier are realistic values. Physical simulations are being used very effectively as a teaching tool for Lean training. Physical simulations can quickly and effectively demonstrate the effect of organizational and process change to participants. These simulations can be used to model stochastic systems like organizational supply chains.

8.2 Simulation Activity for Base Stock Model

This physical simulation models a three-tier single-product supply chain. ABC company uses a certain type of engine for their product. Final assembly department of the company withdraws these engines from the warehouse as needed. The **Warehouse** receives engines from **Primary Supplier. Primary Supplier** receives the engine parts like cylinders from **Secondary Supplier**. We will make the assumption that only one cylinder is needed per engine. We are interested in inventory levels at **Warehouse, Primary Supplier** and **Secondary Supplier**. Excessive inventory results in increased holding costs while inadequate inventory results in backorders. Thus it is necessary to keep the optimum level of inventory at **Warehouse, Primary Supplier and Secondary Supplier**.

8.3 Simulation Layout

Customer, Warehouse, Primary Supplier and **Secondary Supplier** are 4 departments in the simulation. The movement of the parts is as shown in the Figure 22 below. The Secondary Supplier provides cylinders to Primary Supplier. The Primary Supplier assembles the cylinders in the Engine Block and sends the Engine to the Warehouse. Engines are pulled from warehouse based upon a demand that follows Poisson distribution.

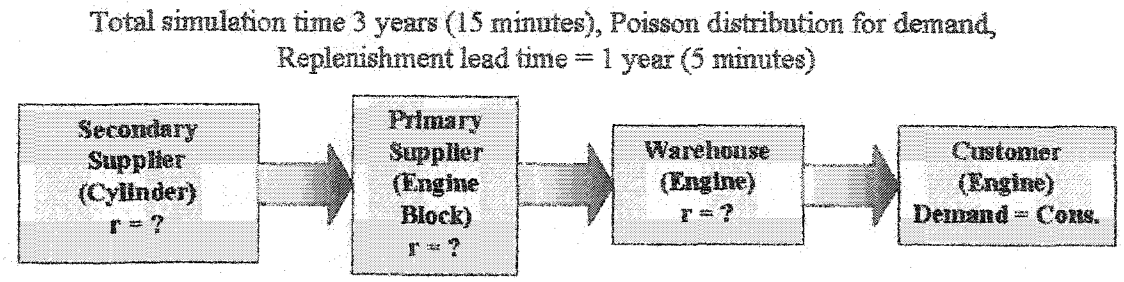


Figure 22. Layout of Supply Chain for Physical Simulation

8.4 Departments

a. Customer

Customer sends the Order Requirement Form to the **Warehouse** of company ABC.

b. Warehouse

This department receives the Order Requirement **Form** from the **Customer** and sends the parts to the **Customer** as per the schedule.

c. Primary Supplier:

Primary Supplier receives the Order Requirement Form from the **Warehouse** and sends the parts to the **Warehouse** as per the schedule. **Primary Supplier** sends the Order Requirement Form to **Secondary Supplier** and receives the parts from it.

d. **Secondary Supplier**

Secondary Supplier receives the Order Requirement Form from **Primary Supplier** and sends the parts to the **Primary Supplier** as per the schedule.

8.5 Simulation Activity Time Frame

The total duration of simulation for each phase is 15 minutes (3 years). Customer sends the Order Requirement Form to the **Warehouse** at the start of simulation. Inventory at **Warehouse** goes below reorder point when the customer demands parts from **Warehouse** (at 1st min). **Warehouse** then sends Order Requirement Form to **Primary Supplier**. This triggers production activity at **Primary Supplier** which has a replenishment lead time of one year. Replenishment lead time at **Secondary Supplier** is also one year. **Warehouse** has initial inventory (equal to reorder point). Demand at **Customer** is satisfied with this initial inventory.

In second year **Primary Supplier** sends the parts to **Warehouse** as per the schedule provided by **Warehouse**. Demand at **Warehouse** also follows Poisson distribution. When inventory level at **Primary Supplier** goes below reorder point (at 6th min), it sends Order Requirement Form to **Secondary Supplier**. This initiates production at **Secondary Supplier**. **Secondary Supplier** takes one year to replenish the items at **Primary Supplier**. **Customer** sends second order at 6th minute to the warehouse and subsequently **Warehouse** sends Order Requirement Form to **Primary Supplier**. Thus the production for third year starts at **Primary Supplier**.

In third year, **Secondary Supplier** starts sending parts to **Primary Supplier** (11th min). **Primary supplier** sends engine to **Warehouse** as per the schedule received in second year. **Warehouse** fulfills the **Customer** demand as per the Order Requirement Form provided by **Customer** in third year.

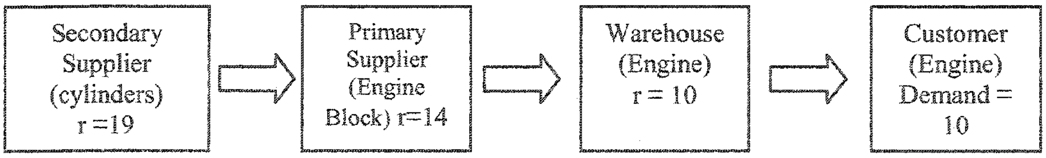
8.6 Phase-I

During phase-I, amount of initial inventory is same as reorder point calculated but lower than the quantities predicted by the mathematical model. The level of inventory is 10 items at **Warehouse**, 14 items at **Primary Supplier** and 19 items at **Secondary Supplier**. **Customer** demand is 10 units per year. These values are intentionally kept lower than the ideal values of inventory predicted by mathematical model.

Any demand not filled from stock is backordered. The number of backorders during this phase is noted in the form provided at each department. Simulation activity takes place and data is collected.

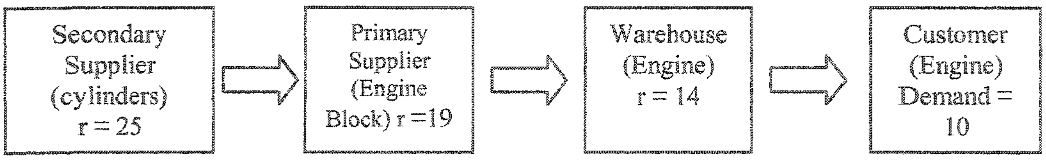
Base Stock model assumes replenishment quantity of one unit. Hence there is **Single Piece Flow** in supply chain.

Inventory at the end of simulation at **Warehouse, Primary Supplier** and **Secondary Supplier** is documented. The ideal values calculated by mathematical model are **Warehouse** =14, **Primary Supplier** = 19. **Secondary Supplier** = 25. Total number of backorders is documented and results are shown in spreadsheet.



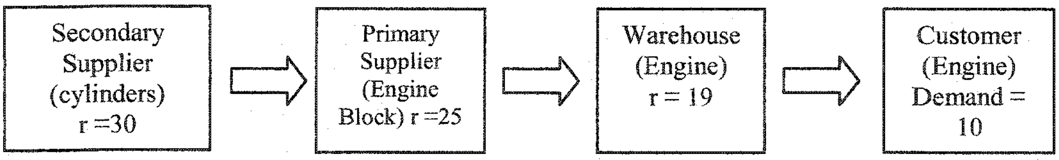
8.7 Phase-II

During phase-II, the inventory levels are kept at the optimum values predicted by the mathematical model. The inventory levels are same as reorder points in this phase also. With optimum levels of inventory, no backorders were documented in this phase confirming the results predicted by mathematical models.



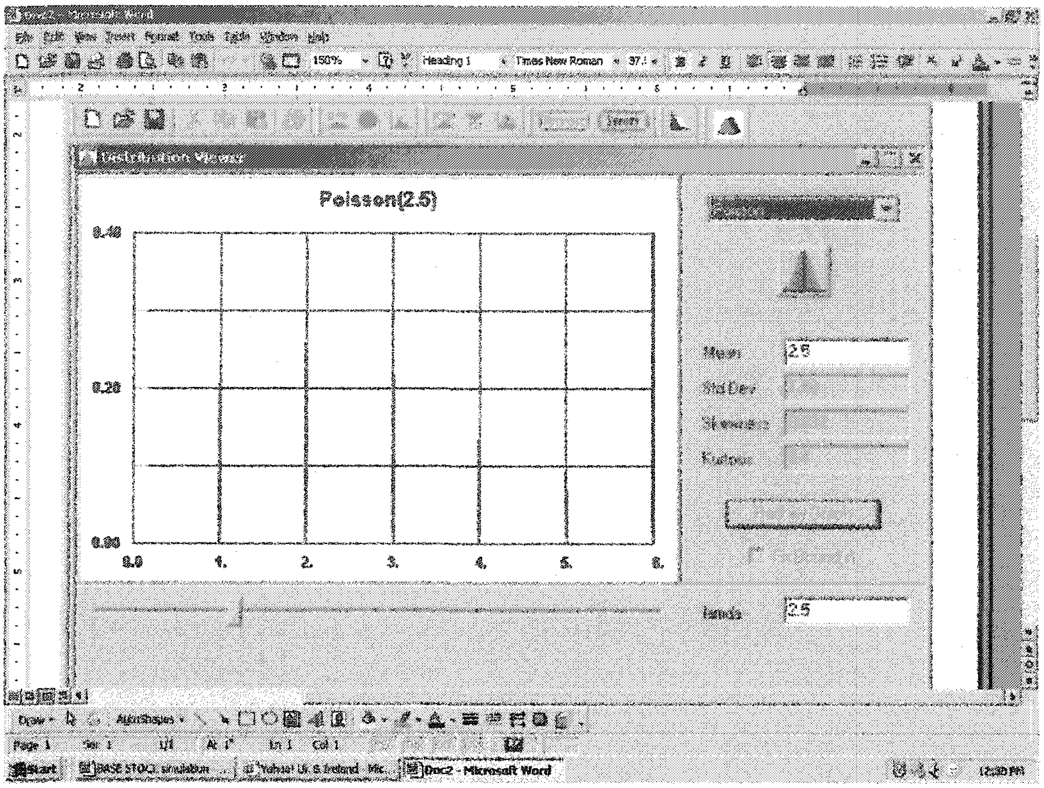
8.8 Phase-III

During phase-III, the inventory levels are kept intentionally higher than the optimum levels and the reorder points are as shown in the figure below. No backorders were observed in this phase due to high inventory levels but inventory costs were high due to large inventory level.



8.9 Distribution of Demand

We ensure that the demand at **Warehouse, Primary Supplier** and **Secondary Supplier** follows Poisson distribution as in the case of mathematical models. This is done by using Stat-Fit software to calculate demand quantities for **Customer, Primary Supplier and Secondary Supplier**. Figure 23 shows the Stat-Fit screen for demand calculation for a typical year.



Mean 2.5

lambda 2.5

Figure 23. Stat-Fit Screen Showing Poisson Distribution

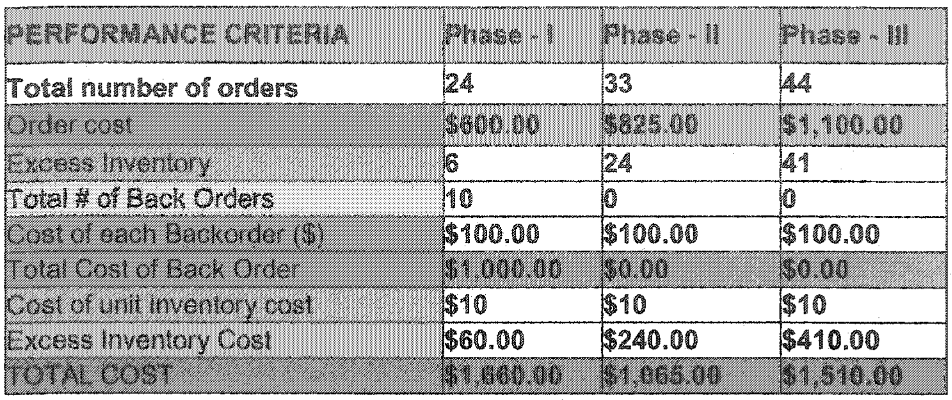
The values obtained are shown in Table 43.

Demand at Customer	Demand at Primary Supplier	Demand at Secondary Supplier
2	3	4
3	4	5
2	3	4
2	2	3
1	2	3
10	**14**	**19**

Table 43. Order Quantity vs. Replenishment Lead Time

8.10 Performance Metrics

The assumptions about backorder cost and inventory holding costs match with the mathematical models. It is assumed that each backorder costs \$100 and unit inventory holding cost is \$20. The order cost is assumed to be \$25 per order. In Base Stock model, the order quantity is one therefore, total numbers of orders are same as order quantity. Following spreadsheet is used to collect the data:



PERFORMANCE CRITERIA	Phase - I	Phase - II	Phase - III
Total number of orders	24	33	44
Order cost	$600.00	$825.00	$1,100.00
Excess Inventory	6	24	41
Total # of Back Orders	10	0	0
Cost of each Backorder ($)	$100.00	$100.00	$100.00
Total Cost of Back Order	$1,000.00	$0.00	$0.00
Cost of unit inventory cost	$10	$10	$10
Excess Inventory Cost	$60.00	$240.00	$410.00
TOTAL COST	$1,660.00	$1,065.00	$1,510.00

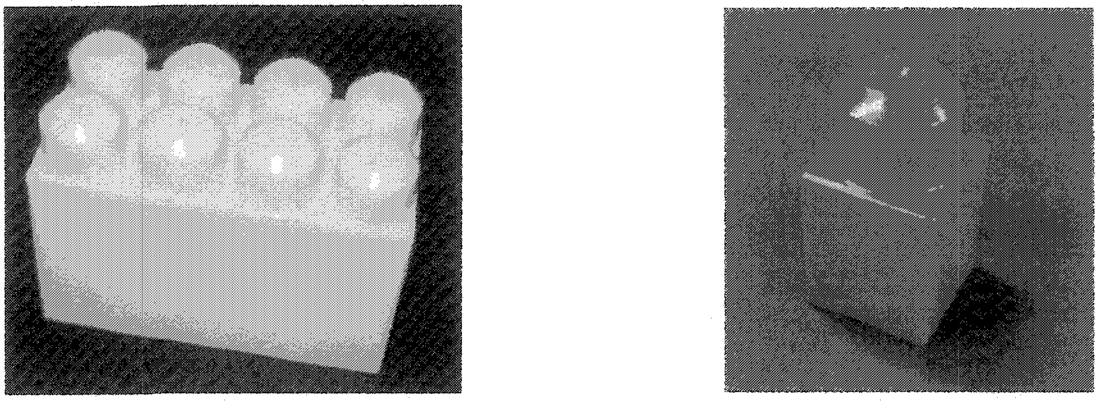
Table 44. Performance Metric Spreadsheet

8.11 Summary

Excess inventory and number of backorders is documented at the end of each phase. The inventory holding cost and backorder cost are calculated in each phase. Ten backorders were observed during phase-I because of inadequate inventory at Warehouse. Therefore, total backorder cost is $1000 in phase-I. During phase-III, excess inventory exists and cost associated with this inventory is $410.

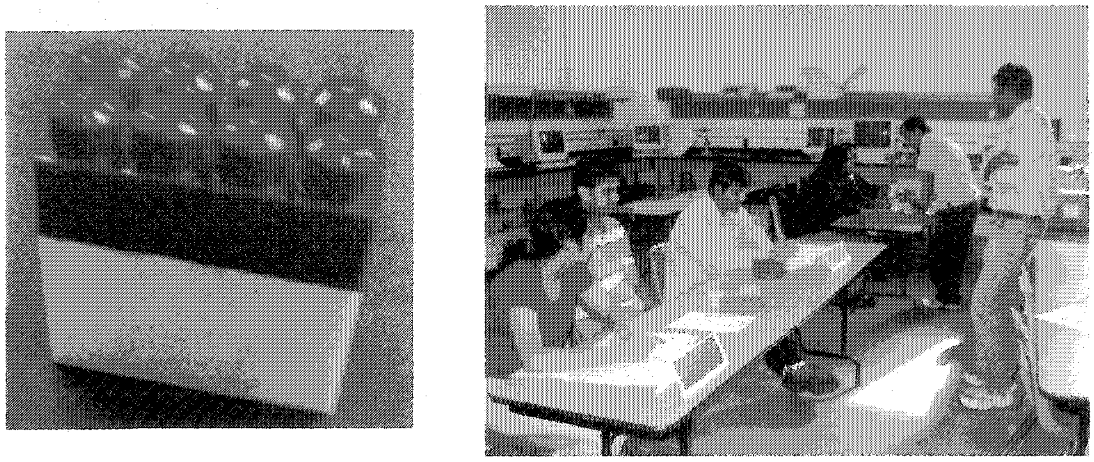
Phase-II, includes the optimum level of inventory as predicted by mathematical models. In this case, backorder cost is zero and excess inventory cost is higher than phase-I but lower compared with phase-III. Total cost of inventory is the lowest in Phase-II as predicted by the mathematical models. Figure 24 shows the blocks used during simulation for engine blocks, cylinders and assembled engines. Figures 25 and 26 show the forms used during physical simulation.

Parts used in Physical Simulation:



Engine Block

Cylinder



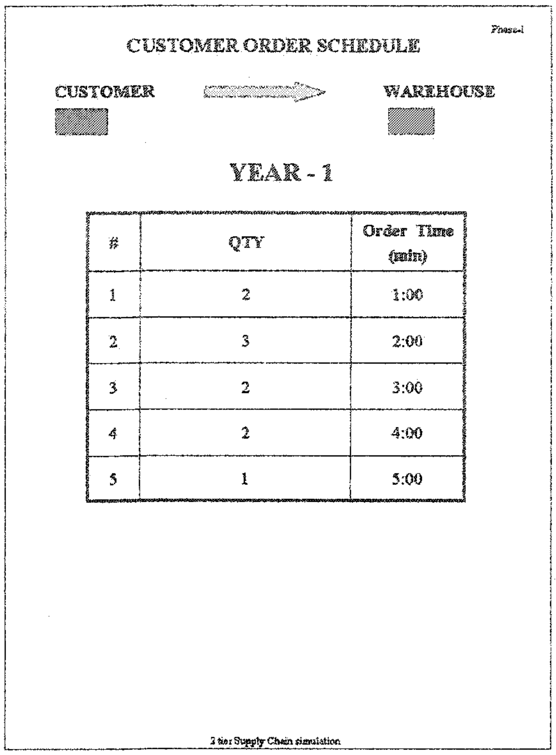
Assembled Engine

Physical Simulation of Two-Tier Supply Chain

Figure 24. Parts Used in Simulation

8.12 Forms Used

Forms used in the simulation during phase-I are shown below. Similar forms were used for phase-II and phase-III but not shown here. The forms are color coded. Rectangles on top indicate the origin workstation and destination workstation. The simulation is run for 15 minutes. Each year is equivalent to 5 minutes of simulation. The demand quantities follow a Poisson distribution and were calculated with Stat-Fit. Total customer demand for the year 1, 2 and 3 are same at 10.



Phase-I

CUSTOMER ORDER SCHEDULE

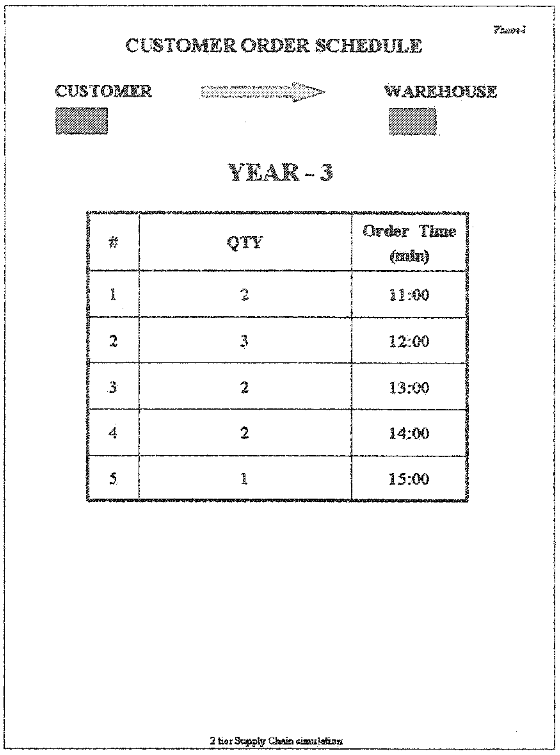
CUSTOMER → **WAREHOUSE**

▨ ▨

YEAR - 1

#	QTY	Order Time (min)
1	2	1:00
2	3	2:00
3	2	3:00
4	2	4:00
5	1	5:00

3 tier Supply Chain simulation



Phase-I

CUSTOMER ORDER SCHEDULE

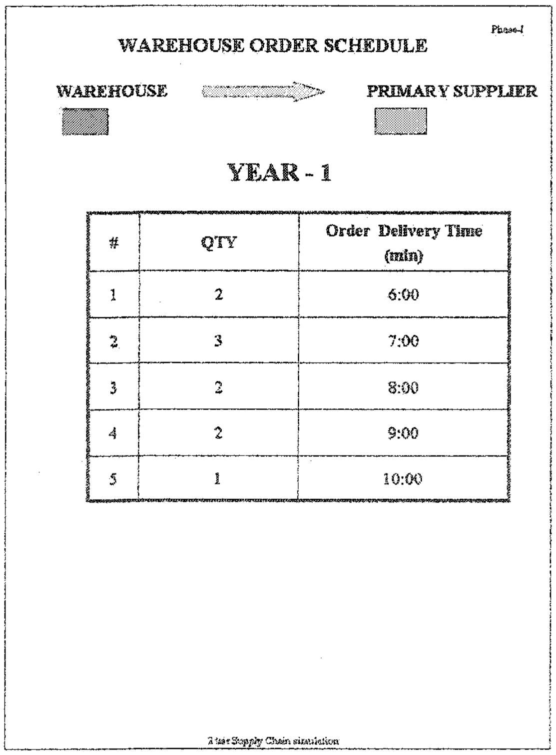
CUSTOMER → **WAREHOUSE**

▨ ▨

YEAR - 3

#	QTY	Order Time (min)
1	2	11:00
2	3	12:00
3	2	13:00
4	2	14:00
5	1	15:00

3 tier Supply Chain simulation



Phase-I

WAREHOUSE ORDER SCHEDULE

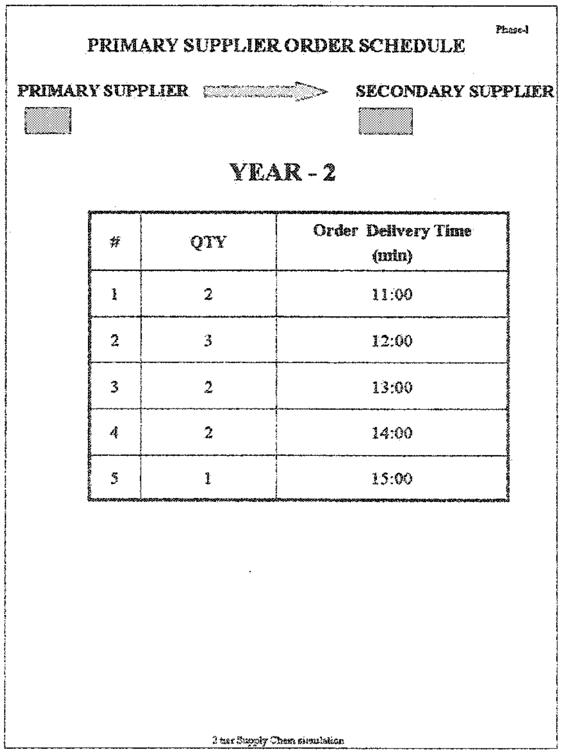
WAREHOUSE → **PRIMARY SUPPLIER**

▨ ▨

YEAR - 1

#	QTY	Order Delivery Time (min)
1	2	6:00
2	3	7:00
3	2	8:00
4	2	9:00
5	1	10:00

3 tier Supply Chain simulation



Phase-I

PRIMARY SUPPLIER ORDER SCHEDULE

PRIMARY SUPPLIER → **SECONDARY SUPPLIER**

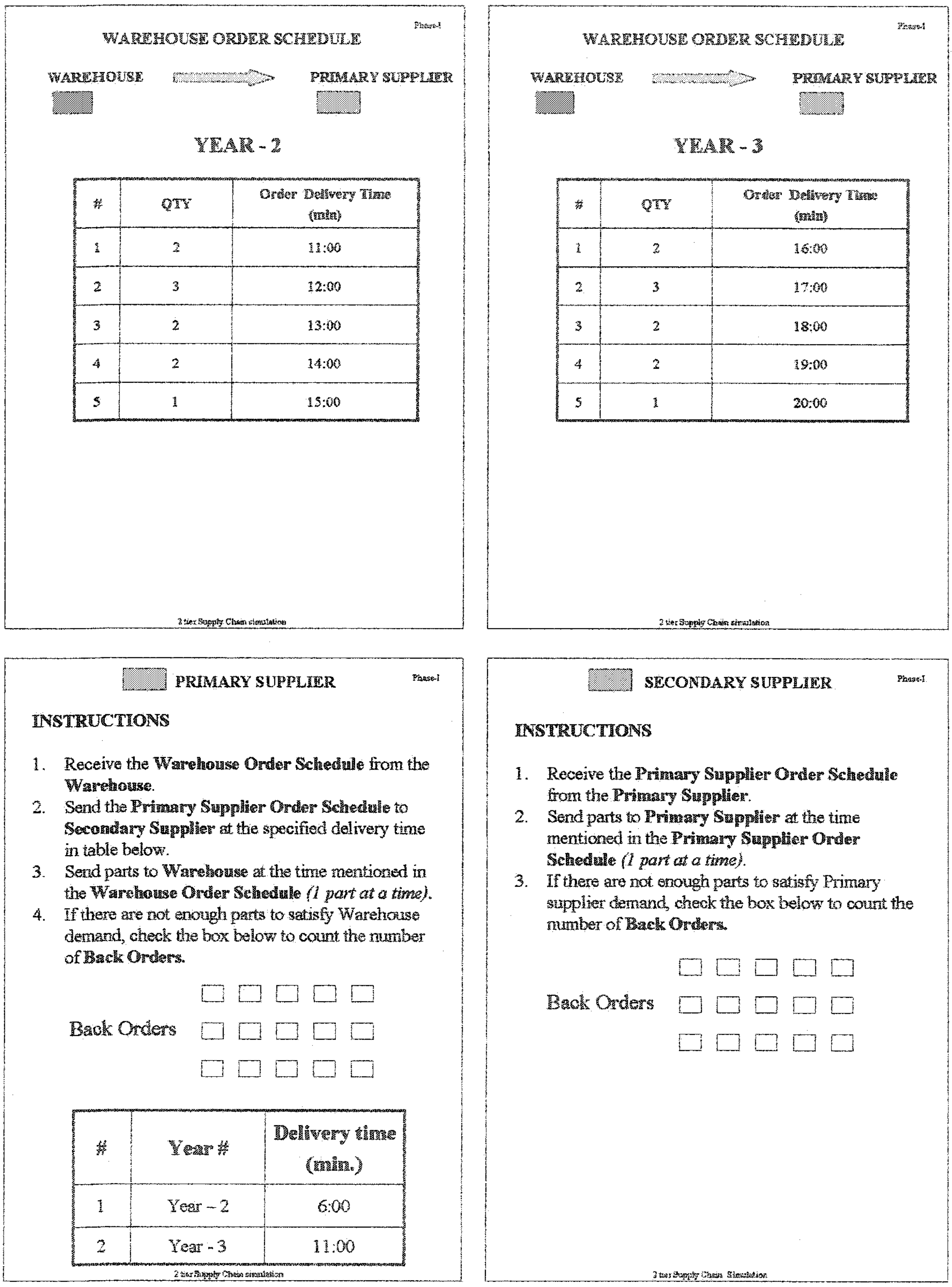
▨ ▨

YEAR - 2

#	QTY	Order Delivery Time (min)
1	2	11:00
2	3	12:00
3	2	13:00
4	2	14:00
5	1	15:00

3 tier Supply Chain simulation

Figure 25. Forms Used in Simulation



Phase-I

WAREHOUSE ORDER SCHEDULE

WAREHOUSE ▨ ⇨ PRIMARY SUPPLIER ▨

YEAR - 2

#	QTY	Order Delivery Time (min)
1	2	11:00
2	3	12:00
3	2	13:00
4	2	14:00
5	1	15:00

2 tier Supply Chain simulation

Phase-I

WAREHOUSE ORDER SCHEDULE

WAREHOUSE ▨ ⇨ PRIMARY SUPPLIER ▨

YEAR - 3

#	QTY	Order Delivery Time (min)
1	2	16:00
2	3	17:00
3	2	18:00
4	2	19:00
5	1	20:00

2 tier Supply Chain simulation

▨ PRIMARY SUPPLIER

Phase-I

INSTRUCTIONS

1. Receive the **Warehouse Order Schedule** from the **Warehouse**.
2. Send the **Primary Supplier Order Schedule** to **Secondary Supplier** at the specified delivery time in table below.
3. Send parts to **Warehouse** at the time mentioned in the **Warehouse Order Schedule** *(1 part at a time)*.
4. If there are not enough parts to satisfy Warehouse demand, check the box below to count the number of **Back Orders**.

☐ ☐ ☐ ☐ ☐

Back Orders ☐ ☐ ☐ ☐ ☐

☐ ☐ ☐ ☐ ☐

#	Year #	Delivery time (min.)
1	Year - 2	6:00
2	Year - 3	11:00

2 tier Supply Chain simulation

▨ SECONDARY SUPPLIER

Phase-I

INSTRUCTIONS

1. Receive the **Primary Supplier Order Schedule** from the **Primary Supplier**.
2. Send parts to **Primary Supplier** at the time mentioned in the **Primary Supplier Order Schedule** *(1 part at a time)*.
3. If there are not enough parts to satisfy Primary supplier demand, check the box below to count the number of **Back Orders**.

☐ ☐ ☐ ☐ ☐

Back Orders ☐ ☐ ☐ ☐ ☐

☐ ☐ ☐ ☐ ☐

2 tier Supply Chain Simulation

Figure 26. Forms Used in Simulation

Chapter – 9

PHYSICAL SIMULATION OF SUPPLY CHAIN WITH LEAN PRINCIPLES

9.1 Goals of Physical Simulation

A physical simulation model is presented here for addressing issues within a supply chain. These issues are addressed by applying Lean tools and measuring the impact of these tools on organizational productivity. This simulation was specifically developed for ship building industry but can be implemented for supply chains in other industries with some modifications. This simulation was developed specifically for the low volume and high variety environment of shipbuilding and repair companies.

Primary goal of this simulation is to demonstrate the benefits of supply chain integration and its impact on key performance metrics for a Lean enterprise. The simulation activity will utilize Lean tools to teach and demonstrate the effectiveness of Lean principles.

9.2 Introduction

Smooth operation of supply chain is very important for the success of any enterprise. A failure or delay in supply of a component can cause reduced productivity and increased waste. Unlike mass production industries, the shipbuilding and repair industry does not have a constant demand, so it becomes very important to have good communication between suppliers and the shipyards. Apart from the communication problem, there are other issues, which shipyards face, which are listed in Table 1 below.
The simulation is conducted in three phases, first being the traditional method. During the subsequent phases, lean tools will be implemented to show the participants benefits of Lean in improving the performance of supply chain and subsequently the entire enterprise.

9.3 Important Issues

The following table lists the issues related to supply chain that currently plague the shipbuilding and repair industry. The table below is a general list and is not ranked. Table 45 lists the Lean tools that could be used to reduce or eliminate the problem.

No	ISSUES	LEAN TOOLS
1	Scheduling Problem	Pull, Integrate Planning & Sourcing with suppliers, information sharing
2	Adversarial Relationship with Supplier	Team - Sharing information, long-term commitment, communication
3	No Involvement of Supplier in Design.	Co-location
4	Long Lead-Time	Pull, Group technology
5	High Costs	Batch size reduction.
6	High Inventory	POUS, Pull, 5S, Batch reduction, TPM
7	Challenge in Synchronizing Flow with Suppliers.	Pull, Kanban, Takt time.
8	Vendors Furnishing Information Late	Map information flow, (reduce paperwork, improve scheduling)
9	Irregular Performance	Built in quality, mistake proofing.
10	Higher Price to US Shipyards	Co-designing, sharing information, long-term commitment
11	Shrinking Choice of Vendors	Vendor development
12	Many Engineering Changes	Concurrent Engineering, Co- location.

Table 45. Issues in Supply Chain and Lean Tools

9.4 Simulation Activity

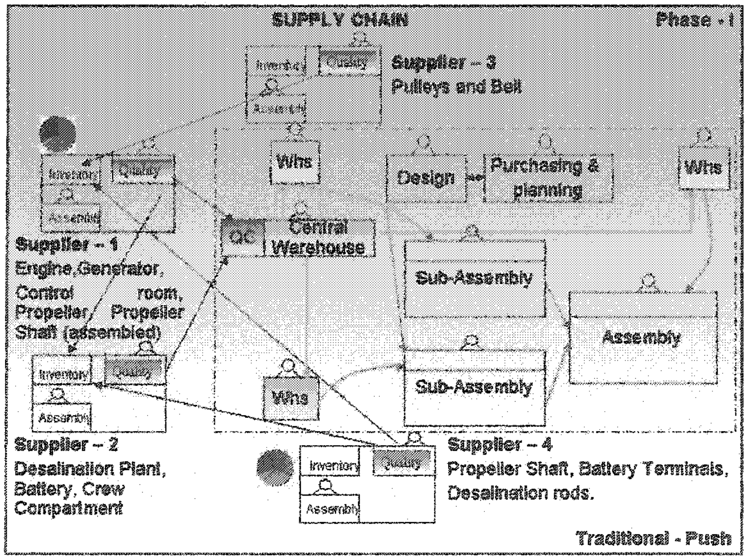


Figure 27. Room Layout for Phase –I

The simulation activity will be carried out in 3 phases, first being the traditional way a typical supply chain operates. Figure 27 above shows the room layout for the first phase. In the first phase, the participants will encounter the problems faced in a traditional supply chain like, frequent engineering changes, vendor furnishing information late, high inventory, material not being received on time, quality problems, communication problems, long lead times, etc. Problems like machine breakdown and weather conditions are difficult to show in a simulation, a variability wheel, as shown in Figure 28, is used at Supplier 1 and Supplier 4 to bring the simulation closer to reality.

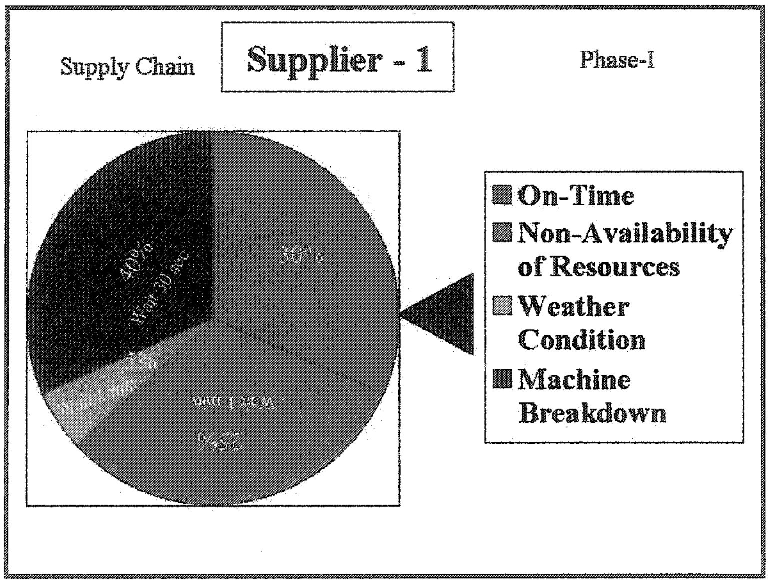


Figure 28. Variability Wheel

In the second phase, Lean is implemented only at the primary suppliers. Due to implementation of Lean, quality at source is built into the production system. This will reduce the quality checks on parts sent from primary suppliers to the shipyard. However, since the secondary suppliers are still not lean, quality check on incoming parts have to be done at primary suppliers. Additional Lean tools implemented during phase-II include Total Productive Maintenance and Co-location as shown in Figure 29.

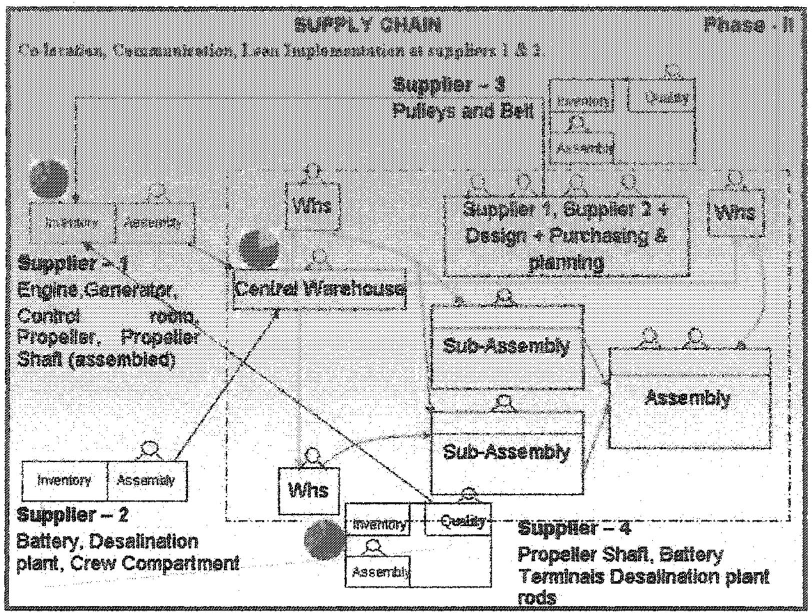


Figure 29. Room Layout for Phase –II

Primary suppliers, and design and planning departments are co-located at the shipyard, which aids in better communication between the shipyard and its suppliers. This is illustrated in the Figure 30 below.

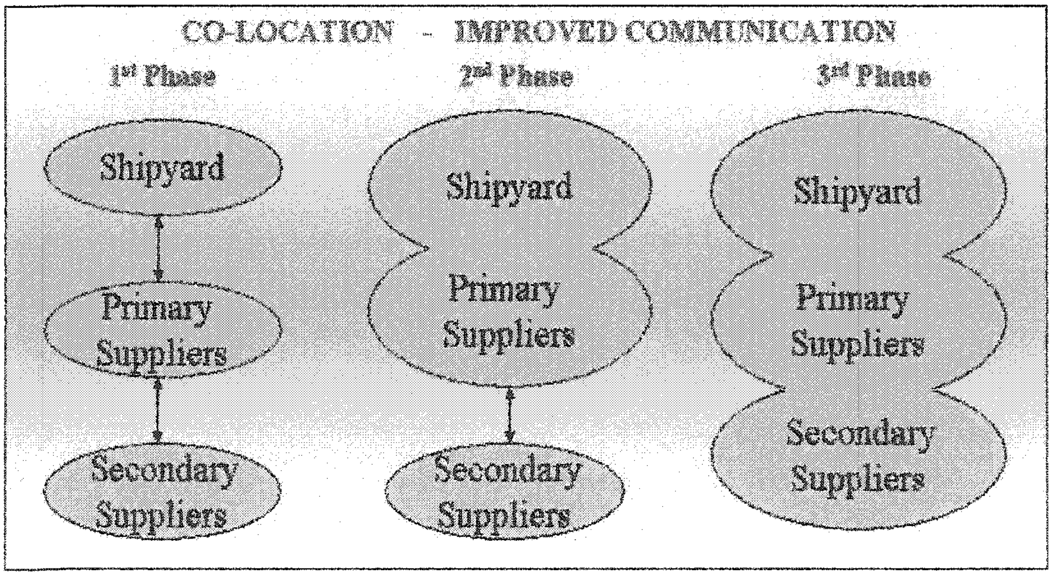


Figure 30. Communication through Three Phases

It is not unusual for Navy to require 100% inspection on some of the parts. Interview with NGNN personnel revealed that 20% of parts may require 100% inspection. To take this into account, we have introduced a 20/80 wheel at the central warehouse. 80% of the parts do not require quality checks while the remaining 20% require quality checks as shown below in Figure 31. The participant sitting at the central warehouse spins the wheel for each part, received from suppliers, and follows the instruction on the wheel (Figure 32).

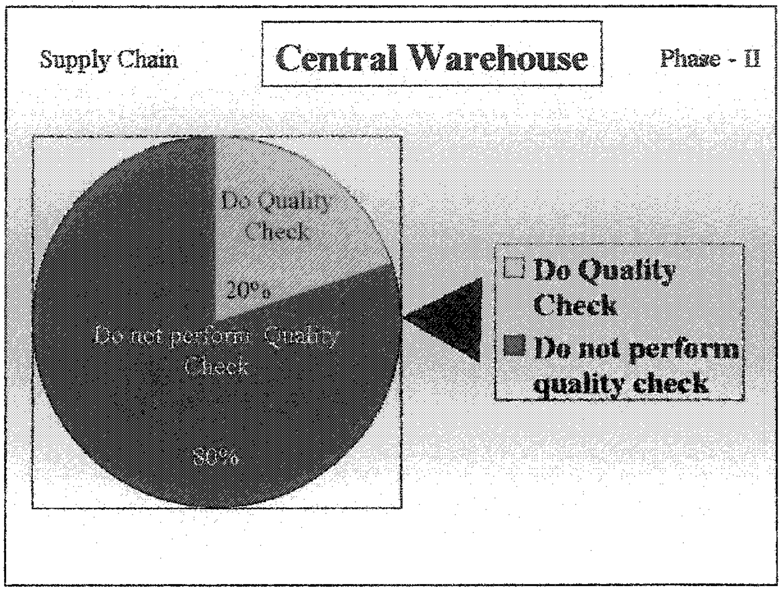


Figure 31. Quality Check Wheel

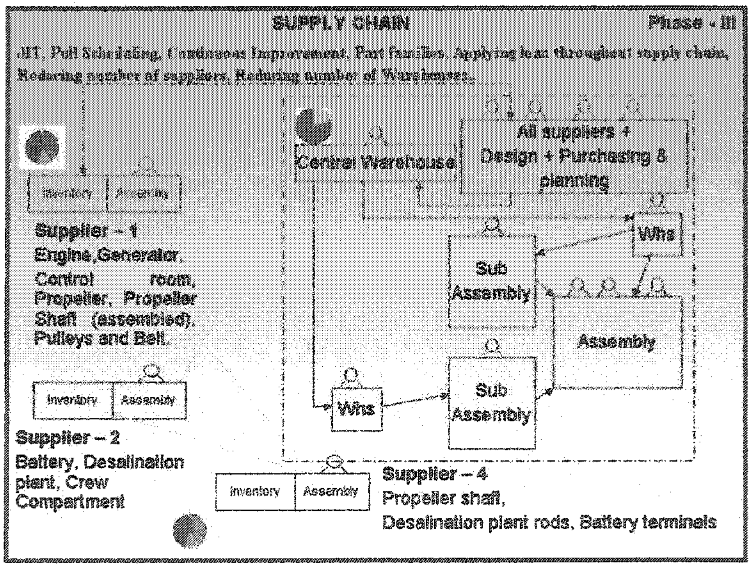


Figure 32. Room Layout for Phase –III

During the third phase, tools like just in time (JIT), and part families will be implemented, which will reduce the problems associated with high inventory and late deliveries. Number of suppliers is reduced by forming part families and Lean is applied throughout the supply chain.

9.5 Model for Simulation

The simulation uses the production and assembly of a submarine and its associated supply chain to demonstrate the impact of Lean principles. Figures 33-35 illustrate the submarine model and its various components. The model has been designed to replicate the details of construction of an actual submarine. The assembly sequence and construction activity closely mimic the actual process.

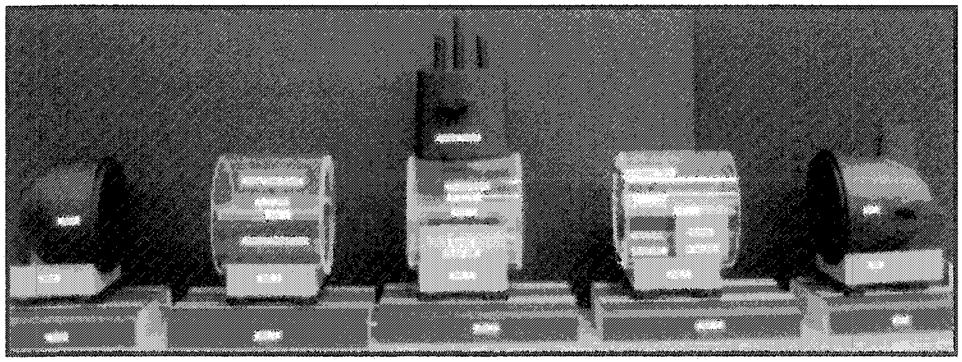


Figure 33. Submarine Model Components

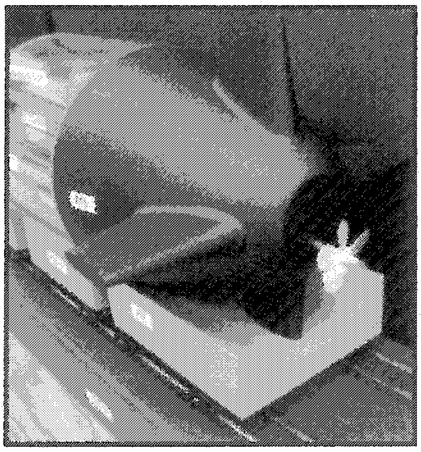


Figure 34. Submarine Aft Component

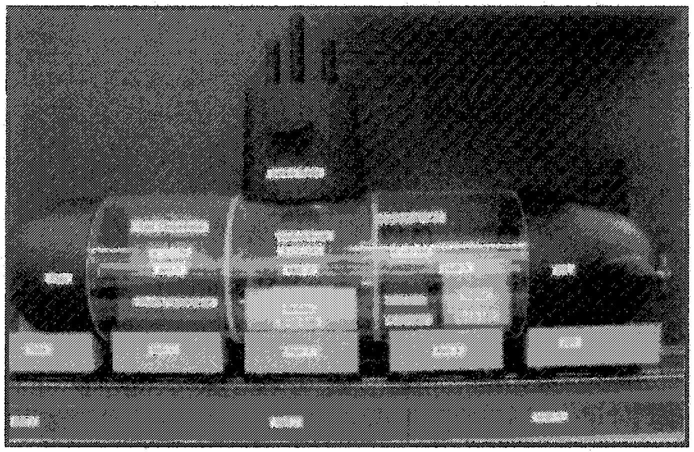


Figure 35. Assembled Submarine Model

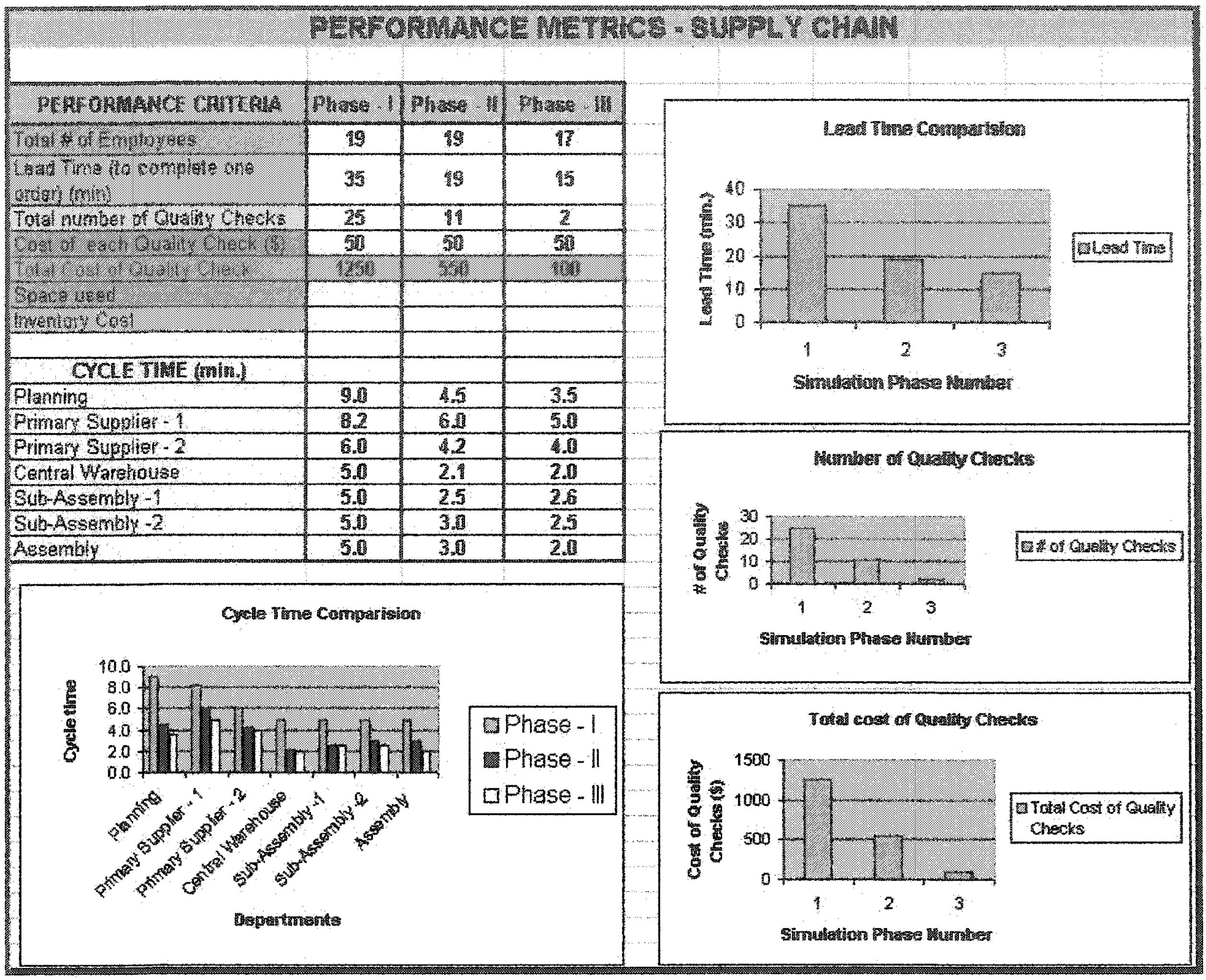
The model consists of 3 hulls, a nose, an aft and a conning tower forming the exterior of the submarine. The hull components can be seen in Figure 33 and the final assembly is shown in Figure 35. There are two sub-assembly stations where different components like engine, generator, control room, battery, crew compartment, desalination plant and torpedo compartment are assembled in the Hull. The participants will be provided with pictorial instructions to aid in assembly.

9.6 Implementation of Simulation Activity

The simulation activity requires approximately 18 participants with each person having a role to play in the supply chain simulation. The 3 phases are not time bound and the activity will continue until the first Submarine model is built. The time required during the first phase is higher compared to successive phases. At the end of each phase, participants are encouraged to discuss the problems encountered during simulation and these issues are noted down. During the following phase a set of Lean tools are implemented. The simulation demonstrates to participants, how application of simple Lean tools can benefit the enterprise. Participants observe that Lean when applied throughout the supply chain provides maximum benefit. Figure 35 is the performance metric spreadsheet obtained from pilot simulations run at ODU.

9.7 Performance Metrics

Performance metrics used in this simulation include total lead time, number of quality checks and cost of quality checks. It can be observed that the lead-time to assemble one submarine reduces as we implement Lean tools. The results from simulation are shown in the performance metric spreadsheet in Figure 36. The lead-time decreases by almost 46% during the first set of Lean implementation and by another 25% during phase-III. In addition, cost associated with quality checks go down too. One of the major reasons for long lead-time during phase-I is the amount of paper work between planning/buyer and suppliers.



PERFORMANCE METRICS - SUPPLY CHAIN

PERFORMANCE CRITERIA	Phase - I	Phase - II	Phase - III
Total # of Employees	19	19	17
Lead Time (to complete one order) (min)	35	19	15
Total number of Quality Checks	25	11	2
Cost of each Quality Check ($)	50	50	50
Total Cost of Quality Check	1250	550	100
Space used			
Inventory Cost			
CYCLE TIME (min.)			
Planning	9.0	4.5	3.5
Primary Supplier - 1	8.2	6.0	5.0
Primary Supplier - 2	6.0	4.2	4.0
Central Warehouse	5.0	2.1	2.0
Sub-Assembly -1	5.0	2.5	2.6
Sub-Assembly -2	5.0	3.0	2.5
Assembly	5.0	3.0	2.0

Figure 36. Performance Metrics Spreadsheet from Pilot Session

9.8 Summary

Physical simulations are powerful tools for demonstrating effectiveness of Lean principles and tools on the productivity of an organization. The results discussed in the previous section show a consistent decrease in the total lead time, cycle time at stations and cost of quality control. The simulation also demonstrated the effectiveness of Lean tools in streamlining the supply chain. This can be critical for a large organization with long supply chains involving multiple tiers. While the physical simulation in chapter was specifically designed to demonstrate the Base Stock model, this simulation shows the supply chain for submarine construction.

Results shown in Figure 36 show that lead-time reduces as we go from phase-I to phase-III. This happens due to implementation of different lean tools. The drastic reduction in cycle time for buyer/planner is due to better communication in the second phase, which is brought about by co-locating the suppliers with the shipyard. Number of quality checks decrease and correspondingly the cost of quality checks also goes down, due to implementation of quality at source at the primary and secondary suppliers.

Chapter – 10

COMPUTER BASED SIMULATION MODEL

Computer based simulation is the "*imitation of a dynamic system using a computer model in order to evaluate and improve system performance*" [64]. In practice, simulation is usually performed using commercial simulation software like ProModel that have modeling constructs specifically designed for capturing the dynamic behavior of system. Performance statistics are gathered during the simulation and automatically summarized for analysis. Modern simulation software provides a realistic, graphical animation of the system being modeled. During the simulation, the user can interactively adjust the speed and model parameter values to do a "what if" analysis. Some simulation software provide optimization technology also. Trial and error approaches are expensive, time consuming and disruptive. The power of simulation lies in the fact that it provides a method of analysis that is not only formal and predictive, but is capable of accurately predicting the performance of even the most complex systems.

The terms continuous and discrete applied to a system refer to the change of state of the system with respect to time. A system whose changes in state occur in finite quanta or jumps are known as discrete systems [65]. Supply chains are discrete systems since a customer order triggers the change of state in these systems.

A discrete event simulation model is created using ProModel software to assess the performance of a two tier supply chain. Base stock Model and (Q, r) Model were applied to this supply chain in the previous sections.

10.1 Goals of Computer Based Simulation

Primary goal of this computer based simulation is to demonstrate that Base Stock Model can effectively predict the level of inventory at reorder point. Another goal is to compare the results obtained here with those of mathematical model and physical simulation model.

10.2 Software Used

Pro-Model is a computer simulation program that allows its user to evaluate the effectiveness of a given process. Pro-Model utilizes the Windows graphical interface to make programming more user-friendly [62, 63]. Components of this process can be rearranged to optimize productivity. This allows for many changes in the simulation before anything is installed or moved physically. To create this simulation several parameters need to be specified. Locations, entities, processes, resources, and arrivals must be specified for the program. Entities are the items being processed. Locations are defined as the various areas where work is being done to the entities or the entities are being stored. Processing is the route in which the entities travel and the logic behind that travel path. Resources are the personnel and equipment used for the process, and arrivals are the number and frequencies of additional entities to the process. The finished model can then be simulated using animation.

After the initial conditions are specified, more detail is needed to make the simulation realistic. This software has the capability of simulating work done in shifts, which also encompasses breaks for the employees and down times for the equipment. A few additional capabilities of ProModel include programmable times, distributions and cost analysis.

10.3 Simulation Layout

Discrete event simulation is a pedagogical tool that uses computer models to study a production system with the goal of optimizing its performance. ProModel simulation software is used for analyzing and assessing the flow of parts through a two tier supply chain system. A computer model of a two tier supply chain was build using ProModel software. The model uses four locations to indicate the key players in the supply chain namely Customer, Ware House, primary Supplier and Secondary Supplier. The layout of the model is shown in Figure 37.

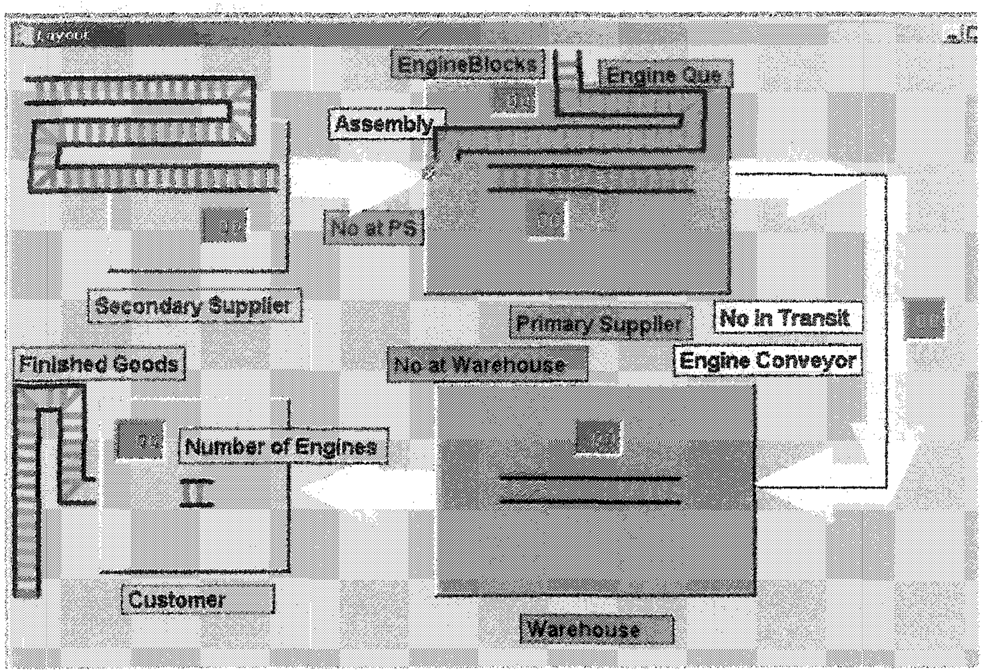


Figure 37. Layout of the Supply Chain in ProModel

The model uses real time counters and global variables to define and display the number of parts as they go through the supply chain. The conveyors are designed long enough to display all parts as they are waiting to be processed. A specified number of cylinders arrive at the secondary supplier with a Poisson distribution. Engine blocks arrive at the primary supplier with another Poisson distribution. One cylinder is assembled with the engine block at the assembly station. Engine block icon is initially grey in color. After assembly of cylinder, the color of the engine block changes to blue indicating an assembled engine. The assembled engine proceeds to the warehouse via engine conveyor and then on to customer. The replenishment lead time is simulated by the travel delay between these stations. For example, if the replenishment lead time is 2 months, transportation between these stations takes 2 months.

10.4 Simulation Results

The goal behind building the computer based simulation model is to see if the results produced by the mathematical models can be replicated. This can be done easily by first running the simulation without any inventory in the supply chain. This will produce stockouts and backorders. If we then run the model with the inventory positions predicted by the base stock model and can show that customer demands are met without any backorders that will be an indication that the results from mathematical models are validated. The simulation model was run first with no inventory positions in the supply chain. The screen display for this case is produced in Figure 38. The counter located at the customer box (green) indicates the total number of engines delivered to the customer. In this case, seven engines were delivered to customer with three backorders. The mean demand is assumed to be the same as in previous runs of mathematical models, i.e. 10.

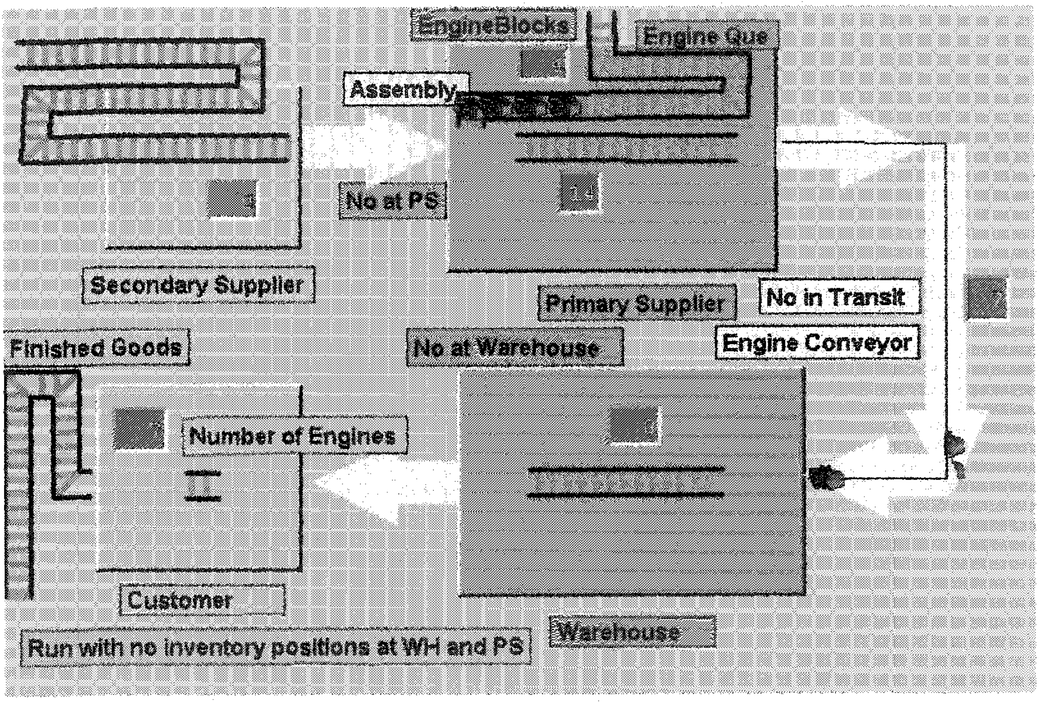


Figure 38. Screen Display for Case with Zero Inventory Positions

Next we run the simulation with the values of r predicted by the base stock model. For example, the base stock model predicted that to obtain a fill rate of 90%, following inventory levels must be maintained; warehouse-3, primary supplier-5 and secondary supplier-8 for a customer demand of 10 units/yr and replenishment lead time of 2 months. Screen display for this case is shown in Figure 39. The part counter in this case indicates that 10 engines were delivered to the customer without any backorder. These results are summarized in Table 46.

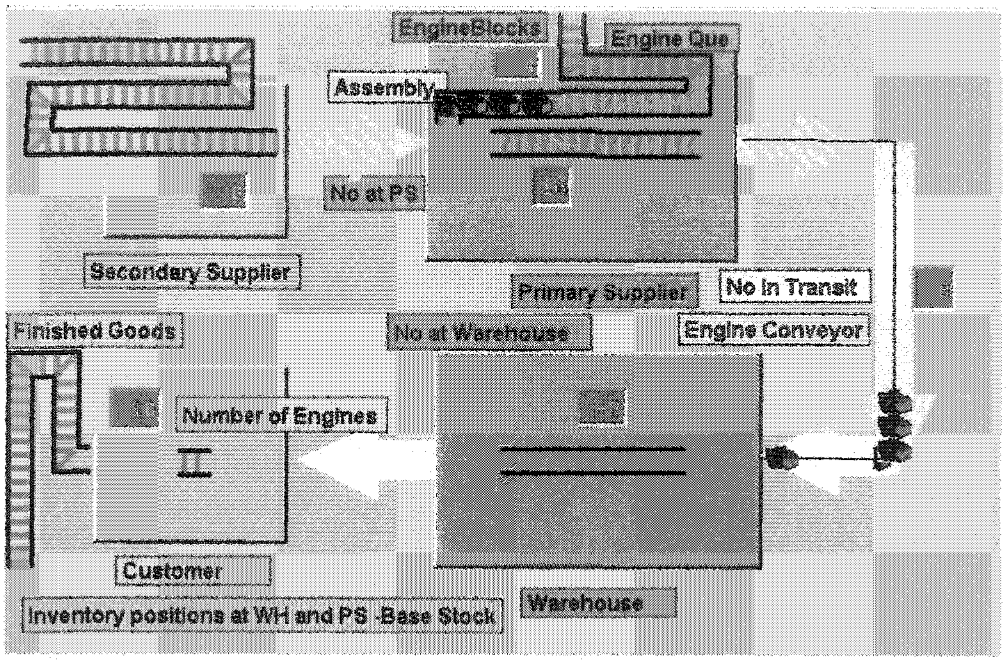


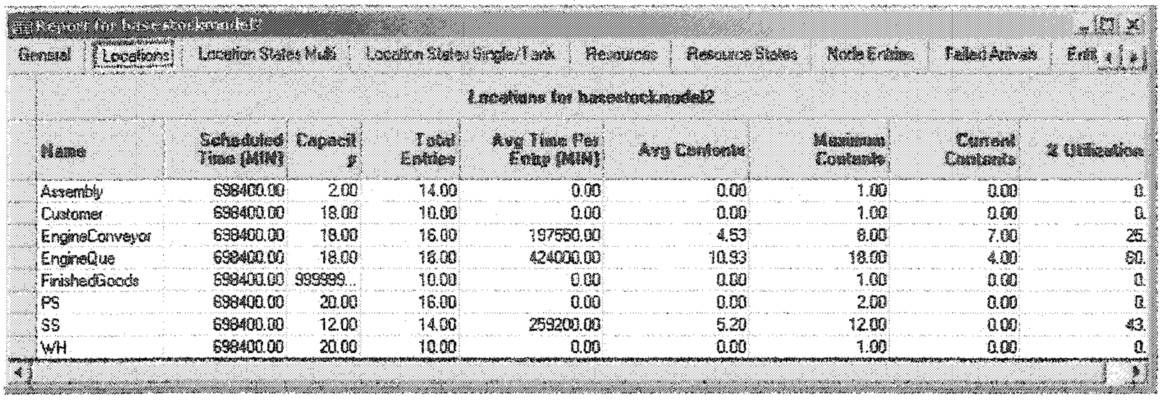
Figure 39. Screen Display for Case with Inventory Positions per Base Stock Model

Case	Inventory at PS	Inventory at WH	Lead time	Engines to Customer	Number of Backorders
1	0	0	60 days	7	3
2	5	3	60 days	10	0

Table 46. Results from ProModel

Table 46 shows the inventory levels and number of engines produced during the two cases for lead time of 60 days. Customer demands are met with no backorders when predicted values of inventory position are used.

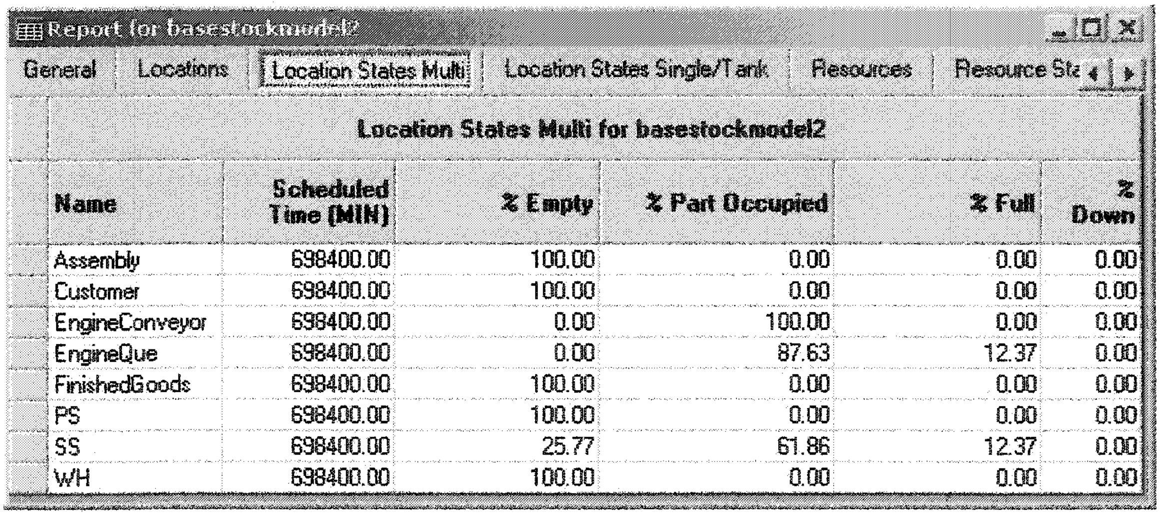
ProModel software can generate a number of tables and charts to analyze a simulation model. A few of these tables and charts are discussed here. Table 47 shows all the locations defined within the model and their state. It also indicates average content, maximum content and % utilization at those locations. Table 58 shows the percentage utilization of multi capacity locations. This is used to determine % empty, % occupied and % full state of these locations.



Locations for basestockmodel2

Name	Scheduled Time (MIN)	Capacity	Total Entries	Avg Time Per Entry (MIN)	Avg Contents	Maximum Contents	Current Contents	% Utilization
Assembly	698400.00	2.00	14.00	0.00	0.00	1.00	0.00	0.
Customer	698400.00	18.00	10.00	0.00	0.00	1.00	0.00	0.
EngineConveyor	698400.00	18.00	16.00	197550.00	4.53	8.00	7.00	25.
EngineQue	698400.00	18.00	18.00	424000.00	10.93	18.00	4.00	60.
FinishedGoods	698400.00	999999...	10.00	0.00	0.00	1.00	0.00	0.
PS	698400.00	20.00	16.00	0.00	0.00	2.00	0.00	0.
SS	698400.00	12.00	14.00	259200.00	5.20	12.00	0.00	43.
WH	698400.00	20.00	10.00	0.00	0.00	1.00	0.00	0.

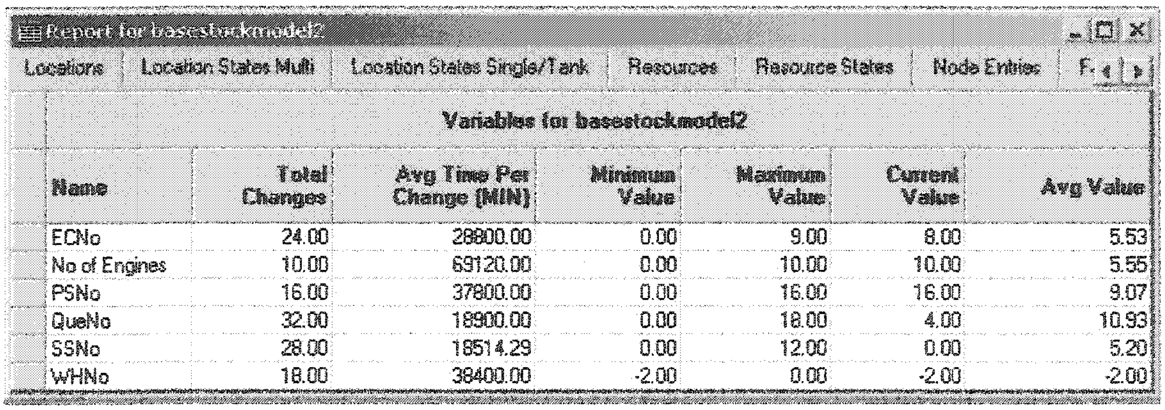
Table 47. Locations and their State



Location States Multi for basestockmodel2

Name	Scheduled Time (MIN)	% Empty	% Part Occupied	% Full	% Down
Assembly	698400.00	100.00	0.00	0.00	0.00
Customer	698400.00	100.00	0.00	0.00	0.00
EngineConveyor	698400.00	0.00	100.00	0.00	0.00
EngineQue	698400.00	0.00	87.63	12.37	0.00
FinishedGoods	698400.00	100.00	0.00	0.00	0.00
PS	698400.00	100.00	0.00	0.00	0.00
SS	698400.00	25.77	61.86	12.37	0.00
WH	698400.00	100.00	0.00	0.00	0.00

Table 48. Multiple Capacity Locations and their State



Variables for basestockmodel2

Name	Total Changes	Avg Time Per Change (MIN)	Minimum Value	Maximum Value	Current Value	Avg Value
ECNo	24.00	28800.00	0.00	9.00	8.00	5.53
No of Engines	10.00	69120.00	0.00	10.00	10.00	5.55
PSNo	16.00	37800.00	0.00	16.00	16.00	9.07
QueNo	32.00	18900.00	0.00	18.00	4.00	10.93
SSNo	28.00	18514.29	0.00	12.00	0.00	5.20
WHNo	18.00	38400.00	-2.00	0.00	-2.00	-2.00

Table 49. Variables Defined within the Model

Table 49 shows the data for all variables used within the model. This table is used to obtain the minimum, maximum, average and current value of a variable. Figure 40 and 41 show the time plot of these variables throughout the entire simulation time period. These charts help us debug the simulation by charting the simulation progress.

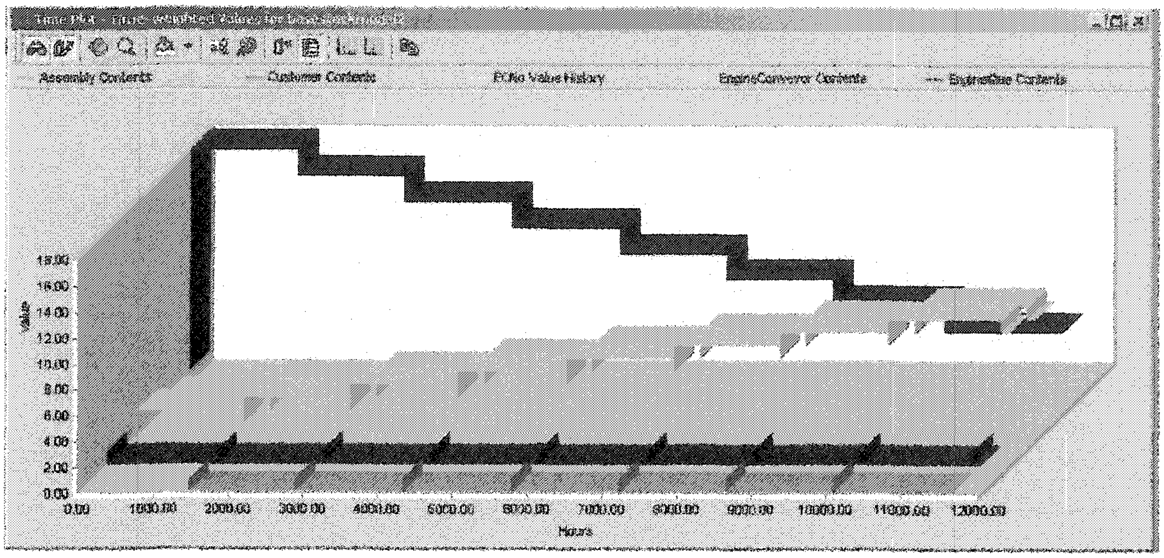


Figure 40. Time Line for Various Variables

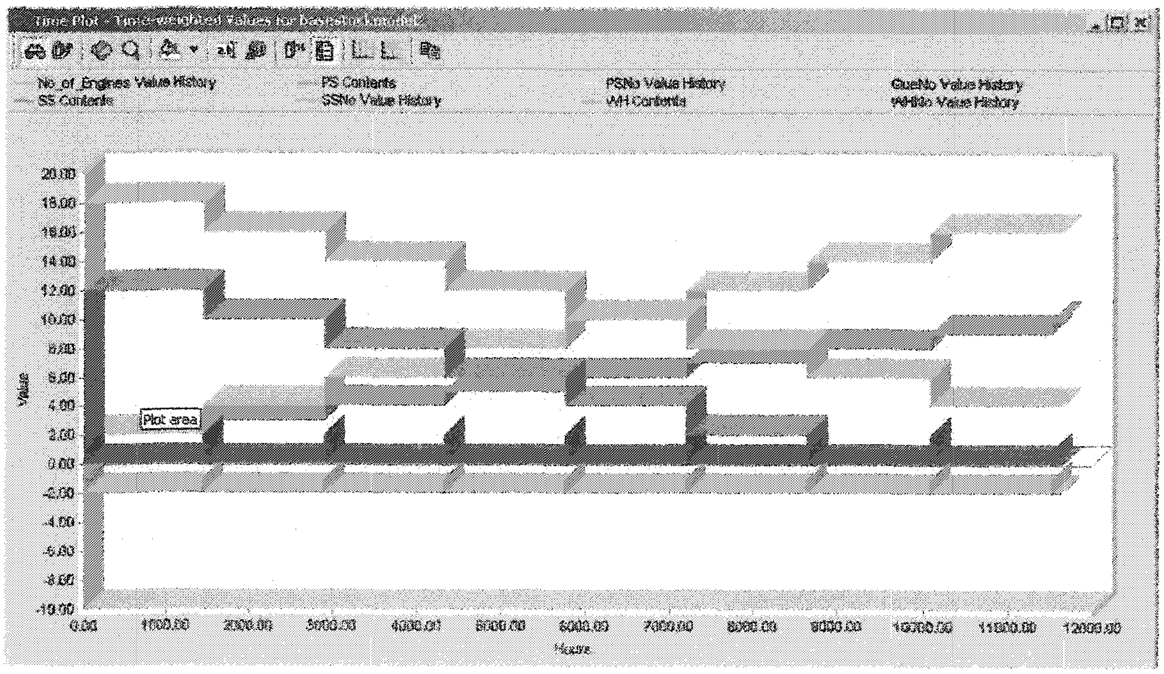


Figure 41. Time Line for Various Variables

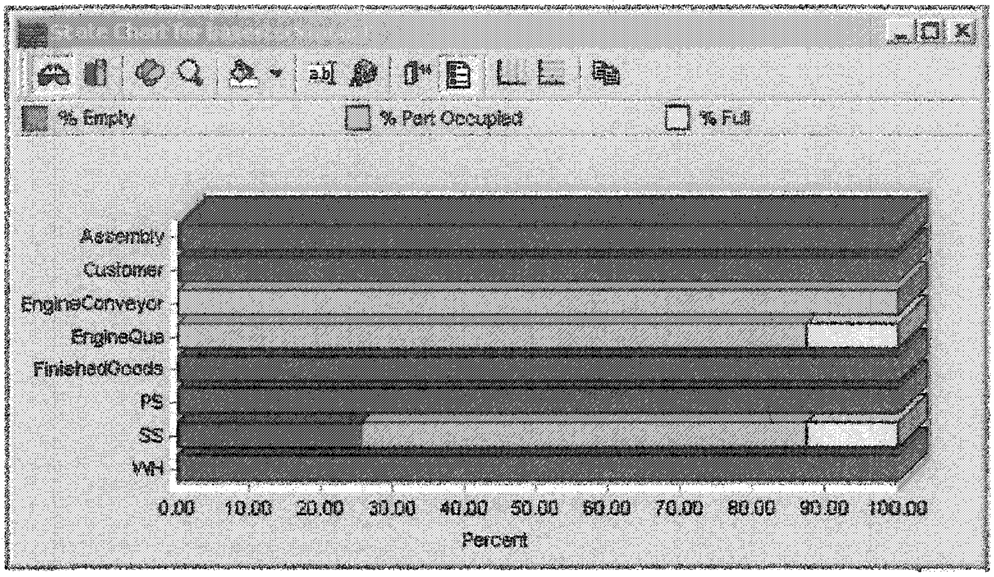


Figure 42. State Chart for Locations

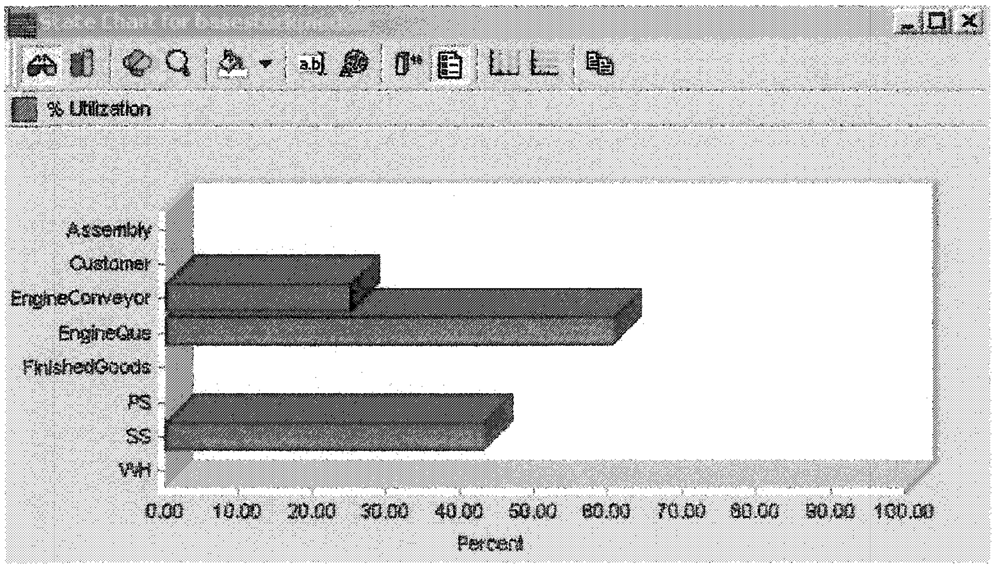


Figure 43. Percent Utilization Chart

Figure 42 shows the state chart for all locations defined within the simulation. This chart indicates % full, % empty and % occupied status of all locations. Figure 43 shows the % utilization of a few specific locations. Figure 44 is similar to Figure 42 except it is for entities.

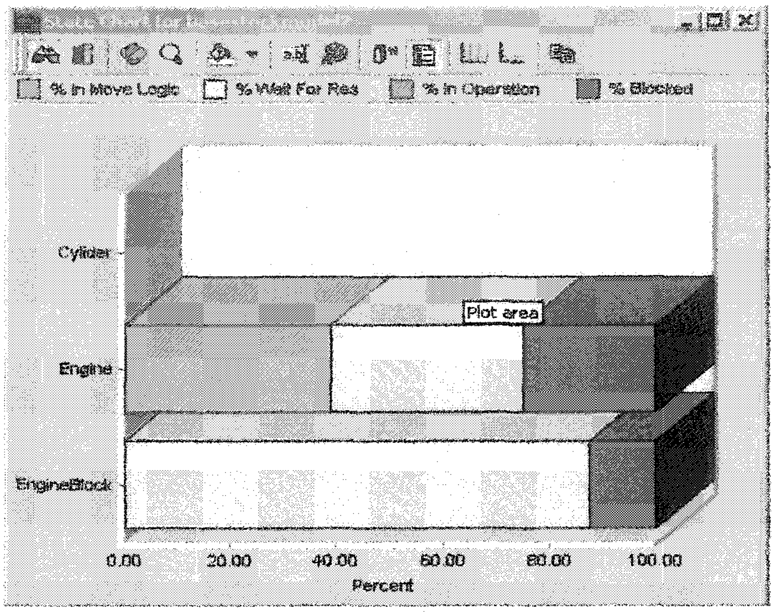


Figure 44. Entity States of Engine and Engine Block

10.5 Summary

Computer based simulation model is created using ProModel software to assess the values of inventory levels predicted by base stock model. Creation of a simulation model requires a detailed understanding of the process. Common elements of a simulation model are locations, entities, processing, arrival, variables and attributes etc. Once a model is built using these elements, its validity is checked by running a few trial cases. Results from the computer simulation model validate the results predicted by base stock model. This was done by first running the simulation with no inventory positions either at the primary supplier or the warehouse. This resulted in backorders. Then the primary supplier and warehouse were populated with inventory positions predicted by the base stock model. The simulation model showed that all 10 engines were delivered to the customer without any backorders.

Chapter – 11

DISCUSSION ON RESULTS

Published work in the area of supply chain covers a plethora of topics which are outlined in chapter 5. Specific issues related to supply chains of shipbuilding and repair industry are discussed in section 3.1 of chapter 3. Mathematical models clearly show that the total cost of inventory can be brought down by reducing replenishment times and increasing the frequency of replenishments. The cost associated with ordering is more than compensated by benefits due to added flexibility from a reduction in replenishment lead times.

Physical simulations models discussed in chapter 10 clearly indicates the benefits of implementing lean through reduction of the lead time and increased flow through the supply chain. This simulation is brought closer to the stochastic and dynamic nature of a supply chain by introducing variability due to weather, machine breakdown, non-availability of resources etc. During phase II, Lean is implemented only at the first tier of the supply chain. This is extended to second tier in phase III. Principles of concurrent engineering are incorporated in phase II by requiring the suppliers to meet with buyer/planner of the company during phase II and III. The results of these implementation lead to a consistent reduction in cycle time for all seven workstations. Total lead time goes down from 35 to 19 to 15 minutes. Total cost of quality checks goes down from $1250 to $550 to $100.

The physical simulation model for Base Stock discussed in chapter 9 was used to validate the inventory levels for reorder point as predicted by the mathematical model. The optimum level of inventory when used with the simulation did not result in any backorder. When these levels were reduced, backorders were observed confirming the results of the mathematical model. The results of the mathematical models are discussed below.

The Base Stock and (Q, r) inventory control models are compared for different replenishment lead times. If we compare the results from table 23 (Base Stock Model) and table 39 ((Q, r) model), there is a significant decrease in the frequency of order in (Q, r) model as compared to Base Stock model. The two tables are reproduced here for convenience. The frequency of order plays an important role here, as there is cost associated with placing the order. Replenishment at higher frequency however, may be beneficial from the point of customer satisfaction and Lean implementation. Higher frequency of replenishments also helps the organization become more agile in meeting customer demand.

Replenishment Lead Time	Demand	Reorder Point(r)	Q	Location	Frequency of order (F=D/Q)	Average Demand	Order Cost	Total Cost
12	10	14.00	1.00	Warehouse	10.00	10	250	925
	14	19.00		PS	14.00	14	350	1175
	19	25.00		SS	19.00	19	475	1450
8	6.67	10.00	1.00	Warehouse	6.67	6.67	166.75	741.25
	10	14.00		PS	10.00	10	250	925
	14	19.00		SS	14.00	14	350	1175
6	10	8.00	1.00	Warehouse	10.00	5	250	775
	16	11.00		PS	16.00	8	400	925
	22	15.00		SS	22.00	11	550	1225
4	10	6.00	1.00	Warehouse	10.00	3.33	250	725.5
	18	9.00		PS	18.00	6	450	975
	27	13.00		SS	27.00	9	675	1350
2	1.67	3.00	1.00	Warehouse	1.67	1.67	41.75	316.25
	3	5.00		PS	3.00	3	75	450
	5	8.00		SS	5.00	3	125	950

Table 23. Summary of Results Application Runs of Base Stock Model

The Base Stock model emphasizes on replenishment quantity of 1 and therefore has higher frequency of order. On the other hand, the (Q, r) model provides a lower total cost, since the frequency of order is less. The service factor obtained for (Q, r) model is in the range of 0.94 - 0.98, which falls within an acceptable range for most organizations. The service factor for Base Stock model was assumed to be 90%.

Lead time	Location	n(r)	r*	Q*	Fill Rate G(r)	Freq. - F	Average Demand	Holding Cost $	Backorder Cost $	Order Cost $	Total Cost $
12	WH	0.32	13.00	5.00	0.94	2.00	10	825	25.6	50.00	900.60
	PS	0.44	16.00	7.00	0.94	1.86	13	975	32.7	46.43	1054.10
	SS	0.37	20.00	7.00	0.95	2.29	16	1125	33.8	57.14	1216.00
6	WH	0.26	7.00	4.00	0.94	2.50	5	600	26	62.50	688.50
	PS	0.20	10.00	6.00	0.97	2.33	7	900	18.7	58.33	977.00
	SS	0.19	14.00	7.00	0.97	2.86	10	1125	21.7	71.43	1218.10
2	WH	0.13	3.00	4.00	0.97	2.50	1.67	499.5	13	62.50	575.00
	PS	0.13	5.00	6.00	0.98	3.00	3	750	15.6	75.00	840.60
	SS	0.12	8.00	8.00	0.99	3.75	5	1050	18	93.75	1161.80
8	WH	0.29	9.00	5.00	0.94	2.00	6.67	724.5	23.2	50.00	797.70
	PS	0.28	12.00	6.00	0.95	2.25	9	900	25.2	56.25	981.50
	SS	0.25	16.00	7.00	0.96	2.57	12	1125	25.7	64.29	1215.00
4	WH	0.21	5.00	5.00	0.96	2.00	3.33	625.5	16.8	50.00	692.30
	PS	0.12	8.00	5.00	0.98	3.00	5	825	14.4	75.00	914.40
	SS	0.24	11.00	8.00	0.97	3.00	8	1050	28.8	75.00	1153.80

Table 39. Summary of Application Runs for (Q, r) Model

Chapter – 12

CONCLUSIONS

An efficient supply chain is one which can deliver the right amount of product at the required place at the right time in spite of the variability and supply chain dynamics. Deterministic models fail to take into account system variability and thus are inadequate for modeling complex supply chain systems. Deterministic models however, are certainly useful in cases where demand is relatively well known and fixed.

The Base Stock model has been widely studied in the operations management literature and it is simple to analyze. This model assumes that demand occurs one at a time in quantity of one. It also assumes that lead times are known and fixed and there are no setup costs associated with orders. This model provides us with a value of inventory level r for a certain customer satisfaction level or fill rate. In general, the higher the mean demand during the replenishment lead time the higher the value of r to achieve a particular fill rate. In addition, the variability of the demand also affects the value of r. The higher the standard deviation of demand , the larger the value of r. In this model, reorder point controls the probability of stockouts by establishing a safety stock.

In (Q, r) model, the replenishment quantity Q affects the tradeoff between order frequency and inventory. Large values of Q will result in fewer replenishments per year but will produce higher level of average inventory. Smaller values will produce low average inventory but higher frequency of replenishments. The reorder point r, affects the probability of a stockout. A high value of r will produce higher average inventory but lower probability of stockouts. A lower value of r will produce higher probability of stockouts. Thus, these two variables generate two different kinds of inventory. Q affects the **cycle stock**: inventory held to avoid excessive replenishment costs. The reorder point r affects the **safety stock**: inventory held to avoid stockouts.

In summary, the two mathematical models discussed here adequately capture the variability in the supply chain. However, they have limitations due to the assumptions they make. Some of these assumptions provide a scope for future developments in modeling.

Physical simulations also capture system variability for a complex system and often provide a simple method for demonstrating complex ideas. Two physical simulations were designed and developed. One to specifically simulate the Base Stock model and validate results obtained. The second one to simulate a two tier supply chain system for submarine construction. The second model also demonstrated the impact of Lean tools on supply chain integration.

The computer based simulation model using ProModel software validated the results from the base stock model by indicating that if quantities of base stock level are selected correctly, it can enhance the flow through a supply chain and maximize customer satisfaction. This can be a formidable tool in the hands of inventory managers who constantly struggle to find the right compromise between minimizing inventory and maximizing customer satisfaction.

In summary this dissertation aims at demonstrating the validity of two mathematical models, namely Base stock and (Q, r) through the applications of physical simulation and computer based simulation models. It also generates a number of practical recommendations for the inventory control managers. These recommendations are:

1. Use computer simulations to explore the dynamics of a supply chain. This recommendation is particularly relevant when the supply chain is very complex and the user desires to explore many 'what – if' scenarios.
2. Use physical simulations to explore the impact of implementing lean. This approach requires some initial investment in capital and time but the benefits derived in convincing the management and long term benefits from implementation will far outweigh the initial investment.
3. Given the validity as provided by both physical and computer simulations, the simple Base stock and (Q, r) models should be used as a first-hand

approach to determine the order quantity (Q) and reorder point (r) and the safety stock.

Chapter - 13

CONTRIBUTIONS OF PRESENT RESEARCH WORK

Scope of Research

- A survey of existing deterministic and stochastic models for inventory control was conducted.
- Two stochastic mathematical models were implemented for a two tiered supply chain.
- Design and development of physical simulation model to simulate Base Stock model.
- Design and development of a physical simulation to demonstrate the effect of Lean principles on supply chain integration.
- Design and development of a discrete event simulation model for two tiered supply chain using ProModel software.
- Comparative analysis of results from the above three types of models.
- Demonstrate the effect of lean tools using physical simulation on the effectiveness of supply chain in shipbuilding and repair companies.
- Use of all three types of tools to study the supply chain integration problem.

Future Work

- Application of these models to multi-product supply chains.
- Design and development of physical simulation model to simulate (Q, r) model.
- Design and development of a discrete event simulation model using ProModel software to study (Q, r) model.
- Comparative analysis of results from the above two models for a three tiered supply chain.

- (Q, r) model makes the assumption that replenishment lead times are fixed and known, demands occur one at a time and that each replenishment order has a fixed cost. In reality these assumptions are not true and a model should capture these sources of variability.

- A software tool can be developed for inventory managers which will provide the optimum values for reorder point and order quantity for a given lead time and customer satisfaction level.

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APPENDIX – A

Glossary of Lean Terms

5S System: A system designed to organize and standardize a workplace and consisting of five component parts: Sort, Set in Order, Shine, Standardize, and Sustain.

7 Wastes: Wastes addressed by lean manufacturing that include : overproduction, transportation, excess inventory, waiting, defects, excess motion, underutilized people. Bottleneck: A resource whose capacity is less than the demand put on it.

Cycle Time: How frequently an item or product is actually completed by a process, as timed by direct observation. Also the time it takes an operator to go through all of his or her work elements before repeating them.

Flow: A main objective of the entire Lean production effort, and one of the key concepts that passed directly from Henry Ford to Taiichi Ohno. Ford recognized that, ideally, production should flow continuously all the way from raw material to the customer and envisioned realizing that ideal through a production system that acted as one long conveyer.

Kaizen: Continuously improving in incremental steps.

Kanban: A signaling device that gives instruction for production and conveyance of items in a pull system.

Lead Time: The time required for one piece to move all the way through a process or value stream, from start to finish. Envision timing a marked item as it moves from beginning to end.

Non- Value Added: Any activity that does not add market form or function or is not necessary. These activities should be eliminated, simplified, reduced or integrated.

Point of Use Storage (POUS): Raw material stored at the workstation where it is used.

Pull System: A method of controlling the flow of resources by replacing only what has been consumed.

Queue Time: The tome a product spends waiting in line for the next processing step.

Six Sigma: It is a business-driven, multi-faceted approach to process improvement, reduced costs, and increased profits. With a fundamental principle to improve customer satisfaction by reducing defects, its ultimate performance target is virtually defect-free processes and products (3.4 or fewer defective parts per million (ppm)).

Takt time: The rate of customer demand: How often the customer requires one finished item. Takt Time is used to design assembly and pacemaker processes, to develop material handling containerization and routes to determine problem-response requirements and so on. Takt is heartbeat of a lean system. Takt time is calculated by dividing production time by the quantity the customer requires in that time.

Total Productive Maintenance (TPM): A systematic approach to the elimination of equipment downtime as a waste factor.

Value Stream: All activities, both value added and non-value added, required to bring a product from raw material into the hands of the customer, a customer requirement from order to delivery, and a design from concept to launch. Value stream improvement usually begins at the door-to-door level within a facility, and then expands outward to eventually encompass the full value stream.

Work Standardization: Operations safely carried out with all tasks organized in best-known sequence and using the most effective combination of resources (people, material, methods and machines).

APPENDIX - B

```
************************************************************************
*
*
*                        Formatted Listing of Model:
*
*                     D:\PhDResearch\BaseStockModel2.MOD
*
*
*
************************************************************************

  Time Units:                         day
  Distance Units:                     Feet


************************************************************************
*                                 Locations
*
************************************************************************

  Name           Cap      Units Stats       Rules          Cost
  -------------- -------- ----- ----------- -------------- ------------
  PS             20       1     Time Series Oldest, FIFO,
  WH             20       1     Time Series Oldest, FIFO,
  Customer       18       1     Time Series Oldest, FIFO,
  EngineConveyor 18       1     Time Series Oldest, FIFO,
  EngineQue      18       1     Time Series Oldest, FIFO,
  Assembly       2        1     Time Series Oldest, ,
  FinishedGoods  INFINITE 1     Time Series Oldest, FIFO,
  SS             12       1     Time Series Oldest, FIFO,


************************************************************************
*                                 Entities
*
************************************************************************

  Name        Speed (fpm)  Stats       Cost
  ----------- ------------ ----------- ------------
  Cylider     150          Time Series
  Engine      150          Time Series
  EngineBlock 150          Time Series


************************************************************************
*                                Processing
*
************************************************************************

                                                  Process
Routing

 Entity  Location Operation Blk  Output Destination  Rule  Move Logic
```

```
 ------- -------- ---------  --- ------  ------------ ------  --------
 Cylider     SS

                              1 Cylider  Assembly  FIRST 1  DEC SSNo, 1

                                                            MOVE FOR 60
                                                            DAY


 Cylider  Assembly JOIN 1 EngineBlock

                              1 Engine     PS      FIRST 1

 EngineBlock EngineQue  Wait 0

                              1 EngineBlock Assembly JOIN 1 DEC QueNo,1

 Engine EngineConveyor Wait 0 1    Engine  WH FIRST 1  MOVE FOR 60 DAY

                                                            DEC ECNo, 1

                                                            INC WHNo, 1


Engine WH
                               1 Engine Customer  FIRST 1  DEC WHNo, 1

Engine  Customer INC No_of_Engines, 1
                 IF No_of_Engines=12 THEN
                 STOP
                               1  Engine FinishedGoods  FIRST 1

Engine  PS   Wait 0

                           1  Engine EngineConveyor FIRST 1 INC PSNo, 1

                                                            INC ECNo, 1

Engine FinishedGoods       1 Engine EXIT  FIRST 1  MOVE FOR 1000 DAY


***********************************************************************
*                                  Arrivals
*
***********************************************************************

  Entity      Location  Qty Each   First Time Occurrences Frequency
Logic
  ----------- --------- ---------- ---------- ----------- ---------- --
----------
  Cylider     SS        1                     P(30)
INC SSNo, 1
```

```
  EngineBlock EngineQue 1                    P(30)
INC QueNo, 1

  Engine      PS        1                    5
  Engine      WH        1                    3

*************************************************************************
*                              Variables (global)
*
*************************************************************************

  ID            Type         Initial value Stats
  ------------- ------------ ------------- -----------
  No_of_Engines Integer      0             Time Series
  PSNo          Integer      0             Time Series
  WHNo          Integer      0             Time Series
  SSNo          Integer      0             Time Series
  QueNo         Integer      0             Time Series
  ECNo          Integer      0             Time Series

*************************************************************************
*                                Arrival Cycles
*
*************************************************************************

  ID               Qty / %      Cumulative   Time (Hours) Value
  ---------------- ------------ ------------ ------------ ------------
  CylinderArrival  Quantity     No
```

APPENDIX - C

Author's Publications

IJAM International Journal of Agile Manufacturing

LEAN IMPLEMENTATION MODELS AND THEIR IMPACT ON PRODUCTIVITY IN LOW VOLUME - HIGH VARIETY ENVIRONMENT

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1 INTRODUCTION

Lean Manufacturing is quickly becoming a philosophy adopted by manufacturer's through out the world to cut out waste and improve productivity. Lean is a people-centric philosophy, which focuses on changing the work-culture within an organization and across the supply chain. Lean has been applied successfully to a variety of industries including aerospace, automotive, shipbuilding and consumer goods. A variety of implementation models have evolved during the last decade. The impact of lean philosophy in high production volume environment like automotive and consumer goods is well established and documented [17,18]. Its impact on low production volume and high variety environment however, is not as clearly documented. This paper presents a survey of recent efforts in this area and presents a generalized model for Lean implementation.

2 WHAT IS LEAN?

The term lean was first coined about 15 years ago at Massachusetts Institute of Technology and later published in a book called *Machine That Changed the World*, written by James Womack and his colleagues [18]. The generally accepted definition of lean in the industrial community is that it is:

"A systematic approach to identifying and eliminating waste (non-value-added activities) through continuous improvement by flowing the product at the pull of the customer in pursuit of perfection."

The lean principles have evolved from the works of Henry Ford and subsequent development of Toyota Production System in Japan. Lean manufacturing principles improve productivity by eliminating waste from the product's value stream and by making the product flow through the value stream without interruptions [14,17 & 18]. This system in essence shifts the focus from individual machines and their utilization to the flow of the product through processes .

In their book Lean Thinking, James Womack and Dan Jones [17] outline five steps for implementing lean:

1. Specify the value desired by the customer.
2. Identify the value stream for each product and challenge all waste.
3. Make the product flow through the value creating steps.
4. Introduce pull between all steps where continuous flow is possible.
5. Manage toward perfection by continuously improving the process.

When lean principles are applied not just to manufacturing but to business operations not only within the organization but also across all supply chains, a lean enterprise is created. The training program contains a module on lean enterprise which discuses the issues involved in the transition of a company to lean enterprise.

3 HIGH VOLUME – LOW VARIETY VS. LOW VOLUME – HIGH VARIETY

Lean was originally created in a manufacturing environment containing large volume and low variety products. The benefit derived from implementing Lean in this environment is well documented with large number of case studies. Implementing Lean in shipbuilding and aerospace industry created doubts in the minds of many for these production environments were substantially different. In fact, manufacturing environments in these industries contain low volume and high variety products.

During last decade, we have seen substantial success in the implementation of Lean in these industries. Job shop environment, which is characterized by low volume and high variety, is inherently different than consumer goods production environment. High product variety introduces unpredictability. This unpredictability requires a different implementation strategy. It requires more agility and flexibility in order to meet the higher demands of the system.

4 LEAN IMPLEMENTATION MODELS

4.1 Toyota Production System

The Toyota Production System (TPS) [10]was the first systematic implementation of lean principles. This system is depicted as a house as shown in Figure 1. Traditional mass production focused primarily on cost—cost reductions through individual efficiency gains within individual operations. We learned later from quality gurus like Edward Deming that in fact by focusing on quality—doing it right the first time—we could simultaneously reduce cost and improve quality. That is, building in quality leads to significant cost reductions. Toyota found that by focusing on eliminating the wastes that cause lead time to expand, quality improved as everyone got quick feedback on quality problems and cost was reduced as inefficiencies were driven out of the system. The focus of TPS is on total system costs by taking a value stream perspective.

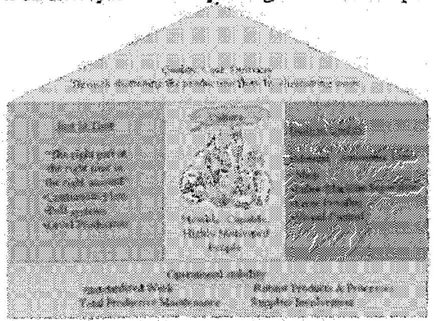

Figure-1, Toyota Production System

The reason for the house metaphor is that a house is a kind of system. Without a strong foundation, as well as strong pillars, as well as a good roof, the house will fail. The two main pillars of TPS are Just-In-Time and Built-in Quality. These are mutually reinforcing. Creating a JIT flow leads to increased quality. Without the inventory buffers of mass production, JIT systems will fail if there are frequent quality problems that interrupt the flow. The TPS house must sit on a foundation of extreme stability. For example, machine downtime in one operation will quickly propagate through the whole value stream because the inventory buffers are so small. Products that are not well designed to be manufactured will hang up the system at troublesome operations and prevent a well-orchestrated flow.

4.2 Lean Aerospace Initiative

Lean is a people centric system and thus any implementation must involve all employees. The tools used during Lean implementation must be viewed as a set of tools for accelerating transformation. The change of culture and transforming how everyone perceives their work is the real challenge of Lean.

A number of Lean Implementation models have been presented over the last decade. One of the early models was developed by the factory operations focus group of the Lean Aerospace Initiative [7]. This model was presented in the annual report of the group.

This model was later revised to include a more comprehensive model incorporating two feedback loops to emphasize the never-ending aspect of lean implementation. This model is presented in Figure 2.

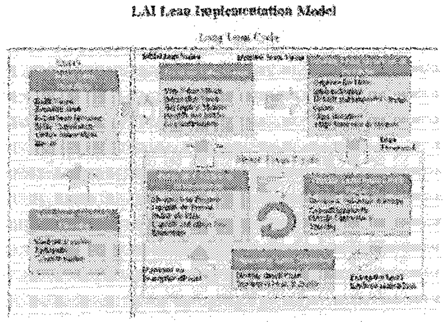

Figure-2, LAI - Lean Implementation Model

The box on the left represents the initial commitment to Lean paradigm and entry into the Lean implementation cycle. The box on the right includes two cycles, the long-term cycle, which focuses on the development of Lean structure and behavior and continuous assessment of progress made. In this loop, issues at a macro level are addressed. The short-term cycle focuses on the progress as a result of Lean initiatives and continuous improvement effort and thus, looks at the implementation at a micro level. The roadmap presented in this model specifies the flow of steps needed to initiate and institutionalize the continual drive toward excellence that exemplifies a Lean Enterprise.

4.3 Lean Enterprise Project at PSNS and Atlantic

The set of lean methods were implemented to minimize the cost and maximize the value added activities. The lean transformation plan formulated by these shipyards is shown in Figure 3.

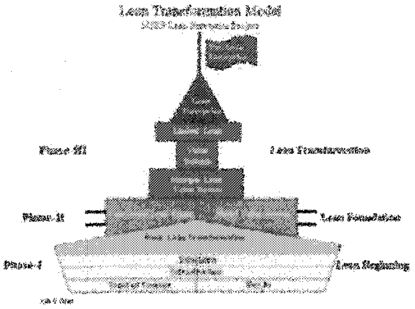

Figure-3, Transformation Model at PSNS and Atlantic Marine

The lean concepts such as 5S, visuals, Pull, Standardization of Process, Workflow, Value Stream Mapping are used in the above-mentioned departments.

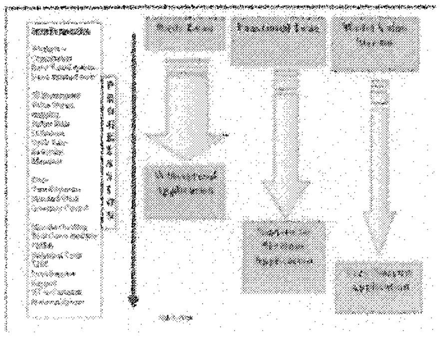

Figure-4, Lean Deployment Approaches

And the results show increase in throughput, reduction in travel cost, waste. Important lessons learnt through this experiments are – many lean concepts are counter-intuitive to conventional wisdom. Commitment and involvement of senior management determine the pace and extent of success of lean process. Employee participation is important factor in change process. Recognition of benefits is necessary for sustainment of lean process. Three deployment approaches to implementing Lean are shown in Figure 4.

4.4 Boeing Implementation Model

Boeing has developed a nine-step lean implementation plan as shown in figure 5 [20]. First step is a value stream mapping to identify not only the flow of material and information but also value added and non-value added processes. Spaghetti diagrams are used for value stream mapping. Second step is line balancing i.e. distributing the work evenly. In order to balance the lines TAKT times are calculated. Third step according to the plan is work standardization. Work standardization is the fastest way to perform the task at the lowest cost with highest quality every time task is performed. Then fourth step is putting visuals in place. Fifth step is point of use staging i.e. putting together all materials needed to complete the job. Next step is establishing the feeder lines. Seventh step is breaking through the process into small processes so that maximum work is done in shop and less work done in final assembly. Eighth step is converting the line to pulse line. And last step is converting line to a moving line

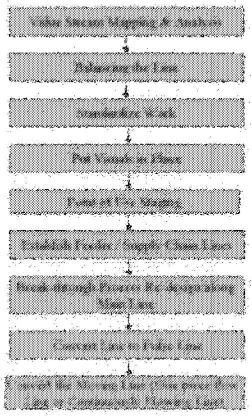

Figure-5, Boeing Implementation Model

4.5 Model In Aircraft Maintenance

At EL AL, Lean maintenance is a business strategy to increase the profits that requires tactics, careful planning, and commitment by executive management. It requires long-term commitment and employee participation. The primary lean maintenance tools used by El Al included– Value Stream Mapping, Accelerated Improvement Workshops, 5S,etc [6]. Lean maintenance model adopted by EL Al Airline is shown in Figure 6.

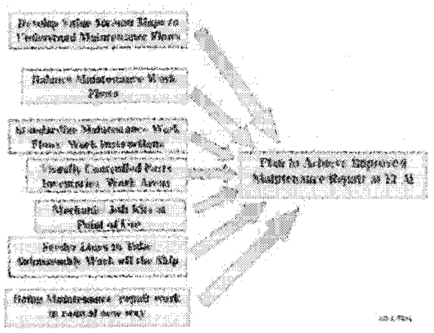

Figure-6, Lean Implementation Model at El Al

4.6 Lean Repair at Todd Pacific Shipyard

Todd is primarily a ship repair yard but a limited numbers of new ships are also built. Lean implementation in Todd [19]is aimed at reducing waste, sustaining gains, continuous improvement, and increasing profits while decreasing investment. With help of NSRP they developed and implemented lean implementation plan for ship repair. Lessons learnt during this project include:

- The People are the key.
- Must learn from all we do.
- Standardized Systems & Process Focus.
- Performance Measurement.
- Create greater opportunities for and through people.
- Wins for all.

Todd discovered that it's not kanban, cell, or 5S but it's people who are key in the implementation of lean. They also discovered that learning on the job was a key component of Lean implementation, namely use of Deming's plan, do, check, act (PDCA). At Todd, the Lean management philosophy is based upon a five-step process on the operations side along with an enterprise management strategy, on the corporate side as illustrated in Figure 7. It starts with workplace organization and ends with lean suppliers and customers.

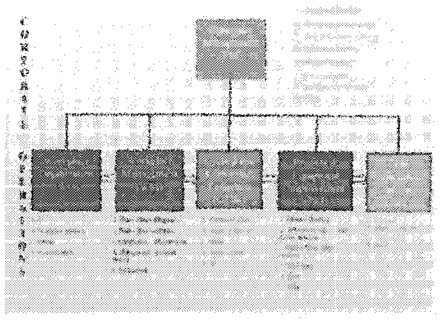

Figure-7, Lean Management Philosophy at Todd

5. IMPACT OF LEAN IMPLEMENTATIONS

At Boeing, lean implementation resulted in 50% increase in volume of flight deck panel. 99.5% times product was delivered on time and also quality acceptance was 99.0%. WIP airplanes per month were reduced from 29 (before implementation of lean) to 14. For 757 program lead time was reduced by more than 40%. Moving flow line was implemented in the production of 737 / 757 stowage beans. Benefits from this are – 23% reduction in hrs/part, 20% reduction in assembly stations, 1500 sq. feet reduction in floor space, and 66% reduction in work in process. Also predictability of output was increased and all line stoppages were logged and if possible fixed.

Lean improvements in fabrication division are – distance traveled by people reduced from 12,200 ft to 2,500 ft., distance traveled by product reduced from 5300 ft to 1000ft, product moves and flow days reduced from 21 and 75 to 4 and 18 respectively. Lean improvements in propulsion division are – 66 % reduction in inventory and 66% reduction in unit time flow.

Results of lean repair initiatives at Atlantic Marine are: over 30% increase in Throughput per Worker Rate in the Pontoon Fabrication Model Line, 33% of space available to enable a more continuous flow and additional area for value-added work added work, reduced travel cost, subsequent time studies have "indicated" that travel cost is reduced by 25-31% due to the workplace organization efforts.

Lean achievements in terms of dollars at El Al are – $ 2,55,000 worth reduction in work hours, $86600 worth inventory reduction and purchasing avoidance, $ 8,500 worth other savings, $10,000 worth work area improvements.

6. A GENERALIZED MODEL FOR LEAN IMPLEMENTATION

The proposed model for ship repair and maintenance incorporates issues related to Enterprise Resource Planning and Lean and Six Sigma implementation. It builds upon the model for new ship construction by Liker and Lamb (2000) and assimilates best practices found in the Japanese ship-repair industry.

The foundation for world-class fleet repair and maintenance starts with process stabilization, which includes Lean tools like 5S, standardization, TPM and Six Sigma tools for process control.

The second foundation element of the model relies upon value stream focus. Smooth flow of material and parts through the repair value stream and integration of the suppliers ensures timely delivery of product to the customer.

The third foundation element is the philosophy of continuous improvement. Any worker can make a suggestion to any manager at any time and it is followed through. Continuous improvement also involves revaluation of processes and procedures at regular intervals. Continuous improvement keeps an organization competitive. The proposed model is illustrated in Figure 8.

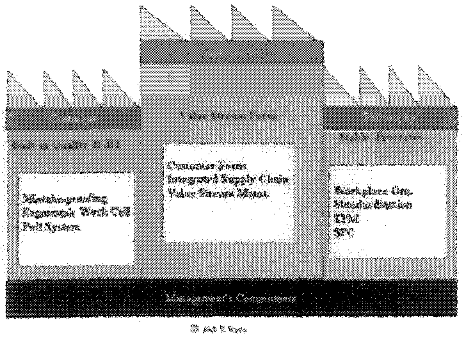

Figure-8, Generalized Implementation Model

7. CONCLUSIONS

The Lean implementation model presented here assimilates best practices found in industry today. The model builds upon a foundation of stable processes, value stream focus and a philosophy of continuous improvement. It is supported by just-in-time and built-in-quality principles.

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A Comparison of Stochastic Inventory Models (Base Stock and (Q, r)) in Two-Tier Supply Chain

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Abstract: We investigate two-stage serial supply chain with stochastic demand and fixed replenishment lead-time. Inventory holding costs are charged at each stage, and each stage may incur a consumer backorder penalty cost charged by primary supplier to secondary supplier. This paper deals with application of the stochastic inventory models to the two-tier supply chain. First we are implementing Base Stock Inventory Model at primary supplier and secondary supplier. The customer-demand follows Poisson distribution. Then we implement (Q, r) model for inventory control at both suppliers. Different cases are run by changing the replenishment lead-time and calculating the reorder point, safety stock at primary supplier, secondary supplier and warehouse for each case. We calculate the inventory holding cost for both Base Stock Model and (Q, r) Model and discuss the results.

Keywords: Bullwhip effect, Stochastic inventory models, Base Stock Model, (Q, r) Model, Two-tier supply chain, Fill rate

1. INTRODUCTION

For a number of reasons, many firms purchase parts from more than one supplier. The completion of order up to the customer depends upon on-time delivery of parts from the supplier. Inventory management throughout the supply chain is critical when the demand is not deterministic. Demand variability increases as one moves up the supply chain away from secondary suppliers and small changes in customer demand can result in large variation in orders upstream. This phenomenon is known as Bullwhip effect. Thus, it is necessary to study inventory models for uncertain demand.

We have considered News Vendor model, Base Stock model and (Q, r) Model. News Vendor model makes an assumption that there is no setup cost associated with producing an order. In reality there is always some cost associated with production of an order. Therefore, we are considering Base Stock and (Q, r) model only for our supply chain in this paper. Comparison of inventory models for two-tier supply chain where the demand follows a Poisson distribution is the primary subject of this paper.

We have considered the virtual company where there is a two-tier supply chain. In first scenario we applied Base Stock Inventory Model at primary supplier, secondary supplier and at warehouse. We calculated the fill rate, probability that the order has arrived before demand for each case and calculated reorder point at Primary Supplier, Secondary Supplier and Warehouse for five replenishment lead time (12,8,6,4 and 2 months)(Table no 2)

Similarly, we ran different cases for (Q, r) model and calculated the order quantity (Q) and reorder point (r) at primary supplier, secondary supplier and warehouse (Table 5a and 5b). We have calculated customer service level and order of frequency for each case.

2. LITERATURE REVIEW

Wilson (1934)[1, 2] has done major work on statistical modeling of production and inventory control. Wilson breaks the inventory control problem into two distinct parts: 1. Determining the order quantity, which is the amount of inventory that will be produced with each replenishment. 2. Determining the reorder point or the inventory level at which replenishment will be triggered. Yu-Sheng Zheng (1992)[3] studied the properties of stochastic inventory systems. He compared deterministic EOQ model and the stochastic (Q, r) model and performed sensitivity analysis, the results of which indicate that the stochastic model yields more accurate results.

Yu-Sheng Zheng and A. Feedergruen (1991)[14] worked on finding the algorithm for (s, S) i.e. (Q, r) policy for continuous Poisson demands. We are assuming that demand follows Poisson distribution in this paper.

We have discussed another model i.e. (Q, r) model where inventory is monitored continuously and demands occur randomly. Subrata Mitra, A.K. Chatterjee [4] have applied (Q, r) model for a multistage inventory system and application of continuous review (R, Q) model. Amy Hing Ling Lau and Hon-Shiang Lau [7] presented very effective procedure for determining the optimal lot size and reorder point for the popular Hadley-Within Continuous- Review Model. The procedure is more accurate for a wide range of parameter values and lead-time demand distributions.

A lot of research has been done in the area of application of (Q, r) model in two-tier supply chain for stochastic demand. Muckstadt, J A [10] and Chen F., Y.S.Zheng [12]. Graves S. [11] evaluated a two-echelon inventory system in which all locations follow continuous review (s, S) policies and emphasized on the continuous control of inventory according to the stochastic demand.

Wei-Shi Lim, Jihong OU, Chung-Piaw Teo [5] emphasized on reducing the inventory replenishment cost in multi-stage supply chain. Yingdong LU, Jing-Sheng Song, David D.[6] studied the base stock policies to control component inventories. They calculated the order fulfillment performance measures foe the system having Poisson demand. P Zipkin [8] emphasized on backorder policies in multistage supply chain where base stock inventory model is used. P. Zipkin and Svoronos [9] presented a simple algorithm for estimating the performance of multi-level inventory system.
In this paper we are trying to apply both base stock policies and (Q, r) policies to two-tier supply chain.

3. THE BASE STOCK MODEL

The modeling assumptions:

1. Demands occur one at a time.
2. Any demand not filled from stock is backordered.
3. Replenishment lead times are fixed and known.
4. Replenishments are ordered one at a time.
5. Products can be analyzed individually.

We make use of the following notations:
l = Replenishment lead time (in years)
x = Demand during replenishment lead time (in units) , a random variable
$G(x) = P(X <= x)$, cumulative distribution function of demand during replenishment lead-time; we will allow G to be continuous or discrete.
$\theta = E[X]$ = mean demand (in units) during lead time l
h = cost to carry one unit of inventory for one year
b = cost to carry one unit of backorder for one year
r = reorder point which represents the inventory level that triggers a replenishment order
$R = r + 1$ base stock level
$S = r - \theta$, safety stock level

The fraction of demands filled from stock (as opposed to backordered), which we call the service level or fill rate.

As the order is placed every time a demand occurs, the relationship

Inventory + orders = R

The probability that the order arrives before its demand (i.e. does not result in a backorder) is given by $P(X<R)$.
The fraction of demands that are filled from stock is equal to the probability that an order arrives before the demand it has occurred.

$P(X<R) = G(R)$ if demand is continuous
$G(r)$ if demand is discrete

Hence $G(R)$, $G(r)$ represents the fraction of demands that will be filled from stock (i.e. fill rate).
Base stock model is equivalent to the Japanese Kanban System.

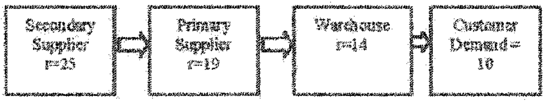
The primary insights from the model:

1. Reorder points control the probability of stockouts by establishing safety stock.
2. To achieve a given fill rate, the required base stock level (and hence safety stock) will be an increasing function of both mean and standard deviation of the demand during replenishment lead time.
3. Base stock levels in multistage production systems are very similar to kanban.

We have assumed Poisson distribution for demand and found out reorder point, order quantity and the safety stock in supply chain.

3.1 Application runs of Base Stock Model to Two- Tier Supply chain

Replenishment lead time = 12 months



At Warehouse

Demand during 12 months is 10 units /year
Average Demand = 10 units per year
$P(k)$ = Probability (Demand during lead time, k)

$$= \frac{\theta^k e^{-\theta}}{k!} = \frac{10^k e^{-10}}{k!}$$

$$G(r) = \sum_{k=0}^{r} p(k)$$

Let the customer has average demand of 10 units (say engine) per year.
For fill rate of 90% and referring Table 1,
r = 14 units per year to be stocked at warehouse.

Similarly we can find out r at Primary Supplier and Secondary Supplier and also for Replenishment lead time of 8 months, 6 months, 4 months and 2 months. (Table 2).

r	P(r)	G(r)
0	0.00	0.00
1	0.00	0.00
2	0.00	0.00
3	0.01	0.01
4	0.02	0.03
5	0.04	0.07
6	0.06	0.13
7	0.09	0.22
8	0.11	0.33
9	0.13	0.46
10	0.13	0.58
11	0.11	0.70
12	0.09	0.79
13	0.07	0.86
14	0.05	0.92
15	0.03	0.95
16	0.02	0.97
17	0.01	0.99
18	0.01	0.99

Table 1. Fill rate for various values of r

4. THE (Q, *r*) MODEL

The modeling assumptions:

1. Demands occur one at a time
2. Any demand not filled from stock is backordered.
3. Replenishment lead times are fixed and known.
4. There is fixed cost associated with a replenishment order.
5. There is a constraint on the number of replenishment orders that can be placed per year.

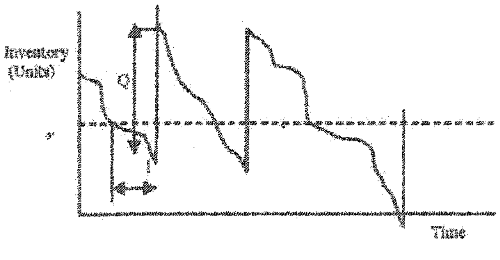


Figure 1. Inventory Vs time in the (Q, r) model

As there is cost associated with replenishment order, replenishment quantities greater than one may make sense.
The basic mechanics of the (Q, r) model are illustrated in the Figure 1.

When the inventory reaches the reorder point r, a replenishment order for quantity Q is placed. After a lead-time of l, during which a stockout may occur, the order is received. Larger values of Q will result in little replenishment per year but **high average inventory levels**. Smaller values will produce low average inventory but many replenishments per year.

A high reorder point will result in **high inventory** but a **low probability of stockout**. The replenishment quantity Q affects cycle stock, inventory that is held to avoid excessive replenishment costs. The reorder point r affects safety stock, inventory held to avoid stockouts. (Refer figure 2)

In basic (Q, *r*) model we seek to choose values of Q and r to solve

Min {fixed setup cost + holding cost + backorder cost)

Following notations are used:
D = Expected demand per year (in units)
l = Replenishment lead time (in years), assumed constant.
X = Demand (random) during replenishment lead time (in units)
$\theta = E[X]$ = Expected demand during replenishment lead time
$G(x) = P(X <= x)$ = Cumulative distribution function of demand during replenishment lead time; we allow G to be either a continuous or a discrete distribution.
$g(x) = \frac{d}{dx} G(x)$ = Density function of demand during replenishment lead time if G is a Continuous distribution
$P(x) = P(X = x)$ = Probability mass function of demand during Replenishment lead-time if G is a discrete distribution.
A = Setup or purchase order cost per replenishment
c = production cost of an item
h = annual unit holding cost (in dollars per unit per year)
b = cost per backorder (in dollars per stockout)
Q = Replenishment quantity (in units); this is a decision variable.
r = Reorder point (in units)
$s = r - \theta$ = safety stock implied by r (in units)

We require an algorithm for solving these equations:

Step 0

Set $Q_0 = \sqrt{2AD/h}$ and r_0 to be the value of r that satisfies

$$G(r) = 1 - \frac{hQ_0}{bD}$$

Let t = 1

Step 1
Compute

$$Q_t = \sqrt{\frac{2D(A + bn(r_{t-1}))}{h}}$$

And compute r_t as the value of r that satisfies

$$G(r) = 1 - \frac{hQ_t}{bD}$$

Step 2

If $|Q_t - Q_{t-1}| < 1$ and $|r_t - r_{t-1}| < 1$, stop and set $Q^* = Q_t$, $r^* = r_t$. Otherwise, set $t = t + 1$ and go to step (1).
This algorithm generally converges quickly.

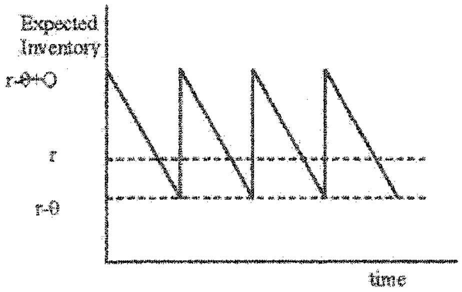
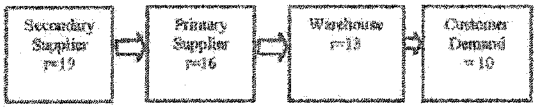


Figure 2. Expected inventory versus time in the (Q , r) Model

4.1 Application runs of (Q, r) Model to Two-Tier Supply chain:

Replenishment lead time = 12 months



P(r) = Probability of demand during lead time
G(r) = Fill rate
n(r) = the expected number of backorders that will be placed during a cycle

For warehouse
Replenishment Lead time = 12 months
Annual demand is D = 10 units/year
Unit cost of the part = $150
Annual holding cost h = $15
Average demand during a replenishment lead time is 10.

The cost of stockout = b = $40

Let us model the demand using Poisson distribution.

$$P(k) = \frac{\theta^k e^{-\theta}}{k!}$$

$$G(r) = \sum_{k=0}^{r} p(k)$$

$$n(r) = \theta p(r) + (\theta - r)(1 - G(r))$$

r	p(r)	G(r)	n(r)
0	0.0000	0.0000	10.00
1	0.0005	0.0005	9.00
2	0.0023	0.0027	8.00
3	0.0076	0.0103	7.00
4	0.0189	0.0293	6.01
5	0.0378	0.0671	5.04
6	0.0631	0.1301	4.11
7	0.0901	0.2202	3.24
8	0.1126	0.3328	2.46
9	0.1251	0.4579	1.79
10	0.1251	0.5830	1.25
11	0.1137	0.6968	0.83
12	0.0948	0.7916	0.53
13	0.0729	0.8645	0.32
14	0.0521	0.9165	0.19
15	0.0347	0.9513	0.10
16	0.0217	0.9730	0.05
17	0.0128	0.9857	0.03
18	0.0071	0.9928	0.01
19	0.0037	0.9965	0.01
20	0.0019	0.9984	0.00

Table 3. p(r), G(r), n(r) values for various values of r

P(r) = Probability of demand during lead time
G(r) = Fill rate
n = The expected number of backorders that will be placed during a cycle
Step 0

$$Q_0 = \sqrt{\frac{2AD}{h}} = \sqrt{\frac{2.10.10}{15}} = 3.65 \sim 4$$

Find the smallest r such that

$$G(r) \geq 1 - \frac{hQ_0}{bD} = 1 - \frac{15.4}{40.10} = 0.85$$

Hence $r_0 = 13$

Step1
Compute Q_1

$$Q_1 = \sqrt{\frac{2D(A+br(r_0))}{h}} = \sqrt{\frac{2.10(10+40.0.32)}{15}} = 5.51 \sim 5$$

Recalculate r_1 as the smallest r such that

$$G(r) \geq 1 - \frac{hQ_1}{bD} = 1 - \frac{15.5}{40.10} = 0.81$$

From the table r_1=13

Again if we calculate Q_1 and r_1 we will find the same values.

Q1=5
R1=13

HENCE

(Q, r) model suggests Q=5 and r =13 at WAREHOUSE i.e. the engine should be replenished in a year with Q=5 and should be replaced when the inventory level is at 13.
Safety stock level = r-θ
= 13-10=3
Similarly we can find out r and Q at Primary Supplier and Secondary Supplier and also for Replenishment lead time of 8 months, 6 months, 4 months and 2 months. (Table 5a and 5b).

5. SUMMARY OF RESULTS FROM BASE STOCK MODEL

Table 2 summarizes all the results for base stock model and frequency of order. We are considering the order cost at $ 25 per order. Earlier we have made assumption that Base stock model assumes no setup cost. Since we want to compare both models (Base Stock and (Q, r)), we have assumed an order cost associated with Base Stock Model. The total cost is calculated by using

$$TC = c\left(\frac{Q}{2} + r - \theta\right) + \text{Order cost.}$$

5.1 Total cost VS. Replenishment Lead-time

Replenishment Lead Time (months)	Warehouse ($)	Primary Supplier ($)	Secondary Supplier ($)
12	925	1175	1450
8	741.25	925	1175
6	775	925	1225
4	725.5	975	1350
2	316.25	450	650

Table 4. Summary of results of costs (Base Stock Model)

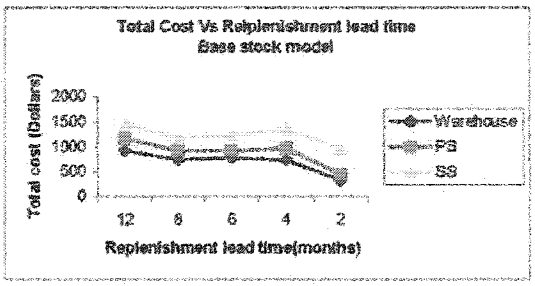


Figure 3. Total cost vs. replenishment lead- time (Base Stock Model)

The total inventory cost decreases with replenishment lead-time for Base Stock Model. We can conclude from Figure 3 that there is decreasing trend in costs of warehouse, primary supplier and secondary supplier for the same replenishment lead-time.

5.2 Reorder point vs. Replenishment Lead time

Replenishment lead time (months)	Reorder point at warehouse	Reorder point at primary supplier	Reorder point at secondary supplier
12	14	19	25
8	10	14	19
6	8	11	15
4	6	9	13
2	3	5	8

Table 5. Reorder point for Base Stock Model

The reorder point is decreasing with replenishment lead- time. The graph in Figure 4 shows decreasing trend in r from warehouse to secondary supplier for the same lead-time

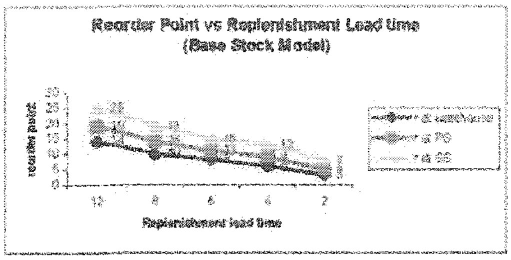


Figure 4. Reorder point vs. replenishment lead-time (Base Stock Model)

6. SUMMARY OF RESULTS FROM (Q, r) MODEL:

Table 6a and 6b summarizes all the results for (Q, r) model. We are calculating frequency of order, service level and total inventory holding cost. The steps in algorithm are summarized in the table.

6.1 Total cost vs. Replenishment Lead- time

Replenishment Lead Time (months)	Warehouse Storage Cost ($)	Primary Supplier Storage Cost ($)	Secondary Supplier Storage Cost ($)
12	875	1021.43	1182.14
8	774.5	956.25	1189.29
6	662.5	958.33	1196.43
4	675.5	900	1125
2	562	825	1143.75

Table 7. Cost table for various replenishment lead-time ((Q, r) Model)

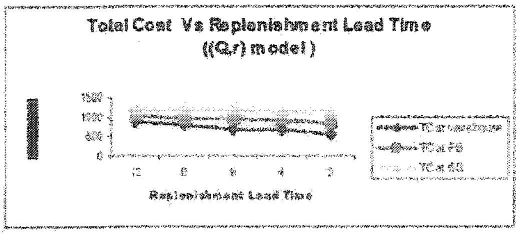


Figure 5. Total cost Vs replenishment lead -time ((Q, r) Model)

The total inventory cost decreases with replenishment lead-time. We can conclude from Figure 5 that there is decreasing trend in costs of warehouse, primary supplier and secondary supplier for the same replenishment lead-time.

6.2 Reorder Point vs. Replenishment Lead-time

Replenishment lead time (months)	Reorder point at warehouse	Reorder point at primary supplier	Reorder point at secondary supplier
12	13	16	20
8	9	12	16
6	7	10	14
4	5	8	11
2	3	5	8

Table 8. Reorder point for (Q, r) model

Reorder point is decreasing with replenishment lead-time. The inventory increases with increase in value of reorder point. Hence the lead-time having low reorder point is necessary to reduce inventory.

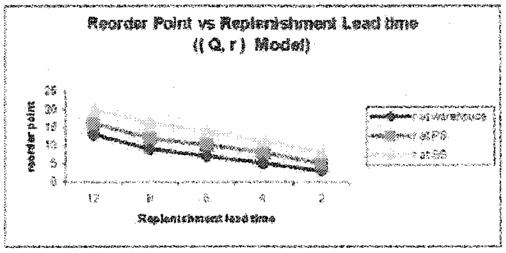


Figure 6. Reorder point vs. replenishment lead-time ((Q, r) Model)

If we compare figure 3 and figure 5, we observe that inventory-carrying cost is much lower for (Q, r) model as compared to base stock for the same replenishment time. Also we are observing that the reorder point is greater for Base stock model as compared to (Q, r) model. Thus Base Stock model results into more inventory as compared to (Q, r) model.

7. COMPARISON OF TOTAL COST

Comparison of total cost at (Q, r) model and Base Stock model for secondary supplier indicates that as the replenishment lead-time decreases, the total cost for base stock is less than (Q, r) model. (Q, r) model is better for large lead-time. But when lead- time is very small, base stock produces better results in terms of inventory holding cost.

The total cost at secondary supplier are plotted in figure 7 for various lead-time for both Base Stock and (Q, r) model.

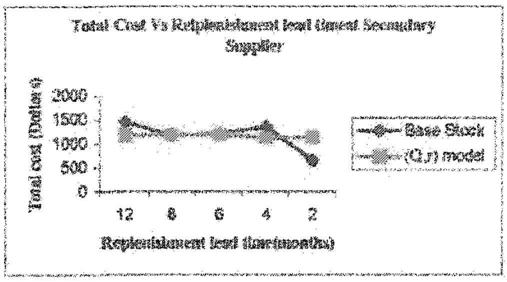


Figure 7. Comparison of total cost for Base Stock and (Q, r) Model.

8. Conclusion

Base Stock and (Q, r) inventory control models are compared for different replenishment lead -time. If we compare the results from table 2 (Base Stock Model), table 6a and table 6b ((Q, r) model), there is significant decrease in the frequency of order in (Q, r) model as compared to Base Stock model. The frequency of order plays an important role here, as there is cost associated with placing the order. Replenishment at higher frequency however, may be beneficial from the point of customer satisfaction and Lean implementation.

Base Stock model emphasizes on replenishment quantity of 1 and it increases the frequency of order. (Q, r) model provides lower total cost, since the frequency of order is less. The Service factor obtained for (Q, r) model is in the range of 0.94-0.98, which falls within an acceptable range for most organizations.

Though we have relaxed assumption of no order cost for Base Stock model, we are creating common platform for comparison of both models. The total cost for each case is calculated. The total cost includes the inventory holding cost and order cost. Thus, (Q, r) model is superior than Base Stock Model in the two- tier supply chain discussed in this paper.

Base stock model proves to be better for small lead-time. For long lead-time (Q, r) model produces low inventory holding cost as compared to Base Stock model.

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Replenishment Lead Time	Demand	Reorder Point(r)	Q		Frequency of order (F)	Average demand	Order Cost	Total Cost
12	10	14.00	1.00	Warehouse	10.00	10	250	925
12	14	19.00	1.00	PS	14.00	14	350	1175
12	19	25.00	1.00	SS	19.00	19	475	1450
8	6.67	10.00	1.00	Warehouse	6.67	6.67	166.75	741.25
8	10	14.00	1.00	PS	10.00	10	250	925
8	14	19.00	1.00	SS	14.00	14	350	1175
6	10	8.00	1.00	Warehouse	10.00	5	250	775
6	16	11.00	1.00	PS	16.00	8	400	925
6	22	15.00	1.00	SS	22.00	11	550	1225
4	10	6.00	1.00	Warehouse	10.00	3.33	250	725.5
4	18	9.00	1.00	PS	18.00	6	450	975
4	27	13.00	1.00	SS	27.00	9	675	1350
2	1.67	3.00	1.00	Warehouse	1.67	1.67	41.75	316.25
2	3	5.00	1.00	PS	3.00	3	75	450
2	5	8.00	1.00	SS	5.00	3	125	650

Table 2. Summary of results application runs of Base Stock model

	D(Deamnd)	Q_0	Q integer	1-(hQ/bD)	n(r)	Q_1	Q integer	1-(hQ/bD)
RLD=12	10	3.65	4.00	0.85	0.32	5.51	5.00	0.81
	13	4.16	4.00	0.88	0.28	6.06	6.00	0.83
	16	4.62	5.00	0.88	0.24	6.47	6.00	0.86
RLD=8	10	3.65	4.00	0.85	0.29	5.37	5.00	0.81
	13.5	4.24	4.00	0.89	0.16	5.43	5.00	0.86
	18	4.90	5.00	0.90	0.25	6.93	7.00	0.85
RLD=6	10	3.65	4.00	0.85	0.26	5.22	5.00	0.81
	14	4.32	4.00	0.89	0.20	5.80	6.00	0.84
	20	5.16	5.00	0.91	0.19	6.85	7.00	0.87
RLD=4	10	3.65	4.00	0.85	0.21	4.95	5.00	0.81
	15	4.47	4.00	0.90	0.12	5.44	5.00	0.88
	24	5.66	6.00	0.91	0.13	6.97	7.00	0.89
RLD=2	10	3.65	4.00	0.85	0.13	4.50	4.00	0.85
	18	4.90	5.00	0.90	0.15	6.06	6.00	0.88
	30	6.32	6.00	0.93	0.12	7.69	8.00	0.90

Table 6(a). Summary of application runs of (Q, r) Model

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ASSESSMENT TOOLS FOR LEAN ENTERPRISE IMPLEMENTATION

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1. INTRODUCTION

Lean enterprise focuses on the efficient operation of the entire value chain, from supplier to internal processes to customers. It is therefore very important to assess the progress made during Lean implementation by periodic assessment of this effort using these tools.

An ideal assessment tool must capture performance within various facets of Lean implementation. It should include assessment of Value Stream Mapping, Supplier management, Takt time, flow, TPM, set-up, Poka-yoke, Kaizen, production planning, pull, inventory, uptime measurement, equipment flexibility, employee training, quality awareness, standard work, etc.

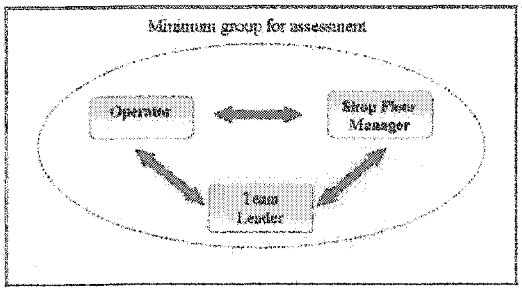

Figure 1. A generalized team used for assessment

Lean assessment should utilize a team. Figure 1 shows the key personnel that should be involved during the assessment efforts. During assessment, it is very important to include people who are immediately affected by the implementation of effort like workers. The supervisors/Team leaders who overlook the process should also be included along with management. Different assessment questioners should be made for each group.

The fundamental goal of the assessment effort is to add value for the corporation, and to establish better communication with the workforce and members of other organizations.

2. LEAN ASSESSMENT TOOLS – WHY?

Lean assessment enables a company to establish their progress on the "Lean" implementation journey. The Lean enterprise assessment has a set of questions that explore progress in key areas. There are couple of questions for each area with multiple-choice answers. Many of the questions will require some research. The user is required to evaluate the relative strategic impact of each area. Implementing Lean practices involve changing a work area or a business process to maximize efficiency, improve quality and safety, eliminate unnecessary motion and inventory, and save time. Although a company implements "Lean" principles, it is of no use if it is not implemented completely. Here assessment tool helps in identifying the areas where more efforts are needed.

The basic requirements for any assessment tool is as follows:

1. It should be simple, easy to use and require minimal time to create instructions and mechanism for use.
2. It should focus on Lean attributes.
3. Should be able to accommodate all levels and functions of an organization.
4. It should provide guidance regards future course of action.
5. It should go hand in hand with company's goals.
6. It should not give ambiguous results.
7. It should have repeatability.

3. CURRENT LEAN ASSESSMENT TOOLS

3.1 LEAN MANUFACTURING SCREENING ASSESSMENT TOOL

This tool [1] was developed at university of Toledo
This lean tool is intended to be a screening tool for establishments that want to assess the level of lean practices being implemented in their facilities.

The software is designed in Visual Basic. It assesses the implementation of lean practices. The entire assessment has been divided into 4 sections, namely, materials and inventory, training, preventive maintenance and quality, to enable greater understanding of the various facets of lean industrial practices. The output is in the form of a excel sheet or a .txt file, giving the percentage of Lean implementation.

Green practices have also been included in the assessment to showcase how environment friendly measures will help not just the organization save money but will also contribute to pollution prevention.

3.2 VIRGINIA'S PHILPOTT MANUFACTURING EXTENSION PARTNERSHIP (VPMEP) LEAN ASSESSMENT TOOL

VPMEP [2] has developed a Lean assessment tool, which can be used to compare business enterprise against world-class metrics. This lean assessment tool has two purposes. First is to enable the user to take inventory of those Lean best practices that are deployed in the enterprise and how prevalent those practices are found throughout the business. Second is to provide the user with an awareness of those Lean best practices that are in place or are not currently applied and hence, should be considered for implementation.

The Lean assessment tool contains ten category worksheets describing the Lean best practices that constitute the following attributes of Lean manufacturing.

1. Communication & Cultural awareness
2. Visual Systems (5S) & workplace organization
3. Standard Work
4. Continuous Improvement
5. Operational Flexibility
6. Mistake proofing/Poka-Yoke
7. SMED/Quick Changeover
8. TPM Total Productive Maintenance
9. Pull Systems
10. Balanced Flow

Each category worksheet needs to be completed as part of a review of the actual situation in the enterprise to ensure the accuracy and applicability of the results. Final results obtained are shown in table 1 and are plotted as graph in figure 2.

3.3 A MODEL FOR EVALUATING THE DEGREE OF LEANNESS OF MANUFACTURING FIRMS

A research instrument for measuring the degree of leanness possessed by manufacturing firms is made [3]. Research questions were developed and incorporated into structured survey questionnaires for both manufacturing directors and managing directors that enabled a quantitative assessment to be made for the various components of leanness. The survey was completed by over 30 firms in the UK ceramics tableware industry and so represents a comprehensive overview of the state of play in that sector. The figures derived allowed for hypotheses testing and a quantitative analysis. Nine variables of leanness were identified, namely: the elimination of waste (EW), continuous improvement (CI), zero defects (ZD), JIT deliveries (JIT), pull of materials (PULL), multifunctional teams (MFT), decentralization (DEC), integration of functions (IF), and vertical information systems (VIS). It also incorporates the measurement of managerial commitment to lean production. Questionnaires were designed to measure variables related to assessment of adoption of lean production principles. The questionnaire measure two dependent and nine independent variables, as follows. The first dependent variable, "degree of adoption of lean production principles" (DOA), was rated on a seven-point scale. The second dependent variable was "degree of leanness" (DOL), was measure as a mean of nine independent variables defined earlier. This paper argues that, though developed specifically for the tableware industry, the research instrument can be adapted for use in other industries.

3.4 ASSESSMENT TOOL BY SATURN ELECTRONICS & ENGINEERING INC.

This assessment tool [4] was developed for suppliers to evaluate their progress toward implementing a lean business system. The four categories (Organizational environment, Systems, Tools and Techniques, and Metrics) form the foundation for a holistic approach to a lean business system - an approach that engages the entire organization in the drive to eliminate waste. The primary use for this assessment is for the organization to assess their progress toward implementing a lean business system and to uncover areas where focused activities need to occur to spur improvement.

Following are the steps taken during assessment.

1. Select a representative sample of the organization (comprising all levels and all functions) to fill out the Assessment. A sample size of 2% to 10% based on organization size would be appropriate.
2. Gather the completed Assessments and compile the results.

3. Results can then be analyzed and reported to be used as a part of the management review, strategic planning, and goal setting activity, or shared with the organization at large.

Once the completed assessments have been collected, results are tabulated. The average score, the mean, and the number of respondents should be calculated for each question, and an average for each of the four categories should be calculated as well.

3.5 WEST OF ENGLAND AEROSPACE FORUM (WEAF)

WEAF [5 developed this tool to enable Small and Medium-size Enterprises (SME) to establish their progress during "Lean" implementation.

The following criteria where established in developing the tool:

- Involvement in assessing and scoring from the SME's own people.
- Simple to use Radar Scoring (explained below)
- Agreed target scoring
- Opportunity for SME to use as self-assessment tool (dependent on Lean knowledge)

The assessment tool consists of simple Excel file. The assessment is done in JIT, Autonomation, and FMS. By selecting appropriate boxes corresponding to the questions, a radar chart is generated as shown in figure 3. From the Radar chart a clear view can be seen of the maturity of deployment of Lean in that company.

The center of the Radar chart is zero, or worst score. The outer most area of the radar is 4, or as close as possible to the goal you have set for yourself. One might even use percentages to determine where each indicator is within a company.

For example, if visual management program is only 50% implemented, you might score this indicator 2 out of 4. Scale can be increased to depict results that are more accurate.

This methodology can be used to define the specific areas that will impact the business most. A profile can be constructed that shows the gap analysis of where the company needs to go. A program can then be devised that addresses, in a structured manner, the work required to redress this gap that will give sustainable improvement in Lean.

3.6 LEAN AEROSPACE INITIATIVE - LEAN ENTERPRISE SELF ASSESSMENT TOOL (LAI-LESAT)

This is a tool [6] for self-assessing the present state of leanness of an enterprise and its readiness to change. It comprises of capability maturity model for enterprise leadership, life cycle, and enabling processes.

LESAT took into consideration the entire enterprise, which the previous assessment tools failed to take into account. It also provided both a measure of Lean and Gap analysis. It also clearly identifies the "next" steps to be taken.

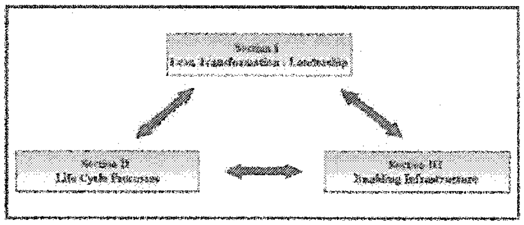

Figure 4. LESAT Architecture

The LESAT architecture consisted of three main sections namely

1. **Lean transformation/Leadership:** the process and leadership attributes nurturing the transformation to lean principles and practices.
2. **Life cycle processes:** the processes responsible for the product from conception through post-delivery support.
3. **Enabling infrastructure processes:** the processes that provide and manage the resources enabling enterprise operation.

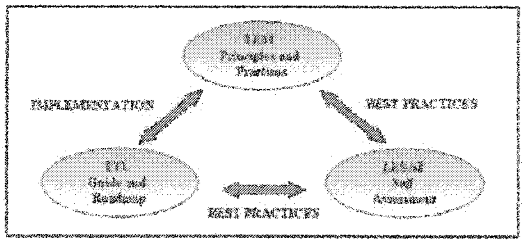

Figure 5. Lean Enterprise tool triad

Steps taken while deploying LESAT as a tool for measuring organizational leanness:

Step 1: Facilitate meeting to introduce tool.
Step 2: Enterprise leaders and staff conduct LESAT assessment.
Step 3: Leadership reconvenes to jointly determine present maturity level.
Step 4: Leadership determines desired level and measures gap.
Step 5: Develop action plan and prioritize resources.

3.7 THE LEAN EXTENDED ENTERPRISE ASSESSMENT PROCESS (LEEAP)

The Lean extended enterprise assessment process (LEEAP) [11] is the framework for measuring the Lean Extended Enterprise Reference Model (LEERM) as shown in figure 6. LEEAP includes detailed assessment and scoring process for the Lean extended enterprise across 7 best practice categories and 42 best practice criteria.

LEEAP provides a quantitative assessment of the organization's ability to execute, sustain, and realign itself for strategic improvement. It covers the extended enterprise, the enterprise, core business processes, and daily operations performance.

4. LEAN ASSESSMENT ANALYSIS AND IMPLEMENTATION

After doing the Lean assessment survey, it is very important to interpret the results correctly and to implement the necessary improvements or changes in the enterprise. However it should also be kept in mind that the purpose of assessment is to provide feedback to management team on how well the implementation of lean is going and highlight areas of concern or lack of progress.

Process and system GAPs are identifiable impediments to better process performance. A process Gap is difference between what the process provides and the process customer's minimum acceptable standard. A system GAP is the difference between what the enabling information technology system provides and process owner's minimum acceptable standards.

Once the assessment is complete, an implementation plan must be established to schedule detailed actions [1]. The plan should state activities, the status of each activity, the start date, and expected completion date.

5. A NEW ASSESSMENT TOOL

This new assessment tool aims at addressing the shortcomings in the existing assessment tools. After performing a detailed study of the existing assessment tools, it was found that except for LESAT, rest of the assessment tools did not consider the Lean Enterprise as a whole. Even did not consider all the issues concerned with the enterprise assessment like production level assessment namely implementation of TPM, pull, etc, are not covered.

Table 2. shows the current distribution of the factors addressed by nine existing assessment tools. This chart pinpoints the missing factors from the existing tools. LEEAP covers the largest number of factors among the nine tools. However it fails to address the issues related to shop floor like TPM, quality, SMED, etc which are important assessment factors.

While conducting an assessment on a Lean enterprise, it should be broadly divided into three sections, customer assessment, supply chain assessment, and organization assessment, as shown in figure 7.

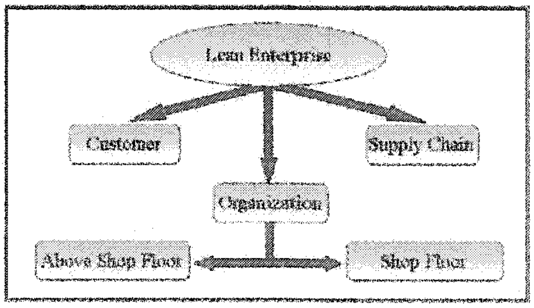

Figure 7. Lean Enterprise assessment structure

Organization assessment can further be divided into above shop floor assessment and shop floor assessment. This gives a comprehensive assessment of the whole enterprise. Each of these sections can be further subdivided into factors on which assessment should be done; this is shown in the figure 8.

Each of these topics will have set of questions that will help in capturing the actual Lean implementation. The scores of each of the individual topics should then be analyzed to give an idea about enterprise wide implementation of Lean. It is very important to realize that progress made by the enterprise as a whole is more important than progress in individual areas for maximum benefit.

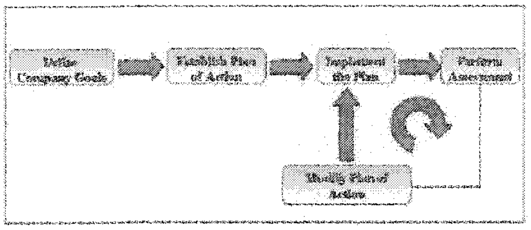

Figure 9. Steps for applying lean and sustaining it.

6. LEAN ENTERPRISE ASSESSMENT IMPLEMENTATION

The most important thing in any lean assessment tools is that it should have repeatability along with accuracy. The tool should be used to measure the progress of the enterprise towards Lean rather than just Lean implementation in individual value streams or functional areas. Even though a company may use the best Lean assessment tool, finally it falls upon the management to take necessary actions. For this reason, the management's involvement in Lean implementation is critical.

Figure 9 shows the steps to be taken while implementing Lean. First, the company should clearly define its goals. An assessment of the current state of the enterprise is generally the first step. This will help in chalking out an effective Lean strategy/plan, without which the company won't achieve the true benefits of Lean implementation. While deciding on the strategy, it is very important to get appropriate people involved. This will help in deciding the future performance targets. After a predefined time, assessment should be done again and the data collected should be analyzed. The data collected gives an idea whether the enterprise is moving in the desired direction with regards to Lean implementation. Lean implementation is a continuous improvement process, and therefore the assessment should be repeated periodically.

6.1 IMPLEMENTATION OF ASSESSMENT RESULTS

The final step in Lean assessment consists of wrap-up with the company's senior management to present observations, findings, and recommendations. The output of the Lean enterprise assessment provides:

- Detailed action items for best practice/business process improvement.
- Defined Lean Manufacturing pilot initiatives.
- Defined process improvement task teams.
- Detailed education plans to ensure employee involvement and continuous improvement in business operations.
- Implementation of key operating performance measurements to establish a habit of ongoing improvement.

7. CONCLUSION

The paper proposes a new assessment tool taking into account the drawbacks of the existing assessment tools. It considers all segments of an enterprise for assessment and addresses a broad range of factors to assess the current state of the enterprise. The assessment tool divides the enterprise broadly into three sections, namely customer, supply chain, and the organization itself, each further being divided into sub-sections. The paper also comments on the steps to be taken while implementing lean and sustaining it.

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#	Scores from assessment worksheets	Abv.	Score from sheet	X10	Score to plot	Target Score
1	Communication & Cultural Awareness	CCA	0.66	10	6.6	10
2	Visual Systems & Workplace Organization	VS&WO	0.42	10	4.2	10
3	Standard Work	SW	0.45	10	4.5	10
4	Continuous Improvement	CI	0.46	10	4.6	10
5	Mistake proofing/Poka Yoke	MP	0.39	10	3.9	10
6	Pull Systems	PS	0.25	10	2.5	10
	Total score				26.3	60

Table 1. VPMEP Assessment Score Sheet [2]

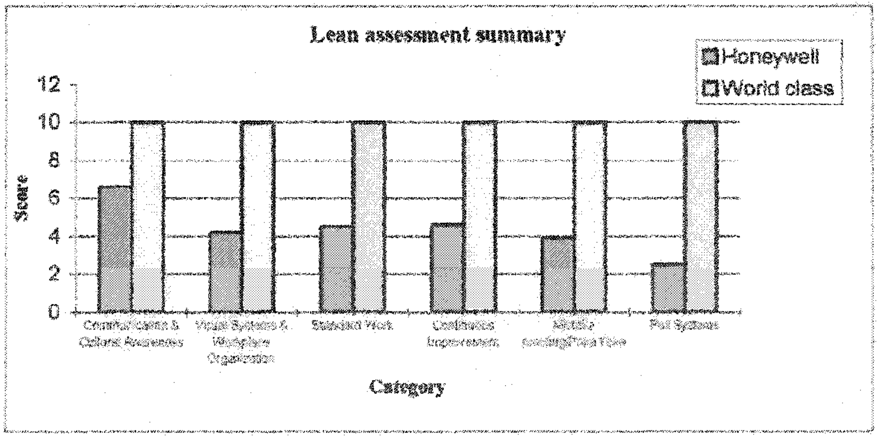

Figure 2. Lean assessment summary [2]

VITA

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