3 THE ROLE OF INVENTORY IN SUPERIOR SUPPLY CHAIN PERFORMANCE

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1. Introduction

Over the past decade, there has been a growing awareness in industry of the importance of effective supply chain management. A recent study provides powerful support for this increased interest by linking supply chain management and shareholder value (Singhal and Hendricks 2002). The study found that when a company announces a supply chain malfunction, its stock price immediately tumbles 7.5%. Losses average 18.5% over a one-year period. While results like these have helped the term supply chain management become a standard part of the business vocabulary, one can find almost as many definitions for the term as articles or books on the topic. A central theme in all definitions, however, is integration. Superior performance can be achieved by taking an integrated view of all the activities required to turn elementary raw material into a completely finished product. A direct result of poor integration is inventory. Extra inventories are necessary to buffer the uncertainties and inefficiencies introduced when one link in the supply chain acts independently from another. Consequently, inventory has been a focal point of supply chain management from the beginning. In fact, the term supply chain first widely appeared in the logistics and inventory management literature.

Better management of inventories throughout the supply chain represents a huge opportunity for businesses. At the present time, the total value of inventories in the United States is close to $1.5 trillion (Economic Report of the President, January, 2001). This is despite the fact that aggregate inventory-to-sales ratios have fallen significantly since the early 1990s. Indeed, the President’s report credits an increased focus on supply chain management, supported by new information technologies, for the decline in relative inventory levels. Even with this decline, the opportunity remains huge. The success of companies like Dell and Wal-Mart that have been pioneers in the management of supply chain inventories is well documented. Perhaps even more publicized are the recent inventory blunders of companies like Nike and Cisco. Effective supply chain inventory management can be crucial for corporate success.

Inventory is critical to supply chain management because it directly impacts both cost and service. Since demand is almost always uncertain and it takes time to produce and transport product, some amount of inventory is inevitably required somewhere in the chain to provide adequate service to the end customer. However, each dollar invested in inventory typically generates an incremental cost of 20 to 40 cents per year for the company that owns it. Increasing supply chain inventories typically increases customer service and consequently revenue, but it comes at a higher cost. This relationship can be described by a graph often referred to as the “efficient frontier” (Figure 3.1). For each possible end customer service level, the efficient frontier plots the minimum amount of supply chain inventory required to achieve that level of service. The aim of supply chain inventory management is both to get a supply chain onto the efficient frontier by right-sizing inventories and to shift the efficient frontier outward through better inventory strategies and supply chain designs.

The goal of this chapter is to illustrate the opportunities and challenges of managing inventories in a supply chain. We begin by highlighting the importance of inventory in the next section and discuss the different types of inventories in section 3. We then present examples of current practice in supply chain inventory management.
The Role of Inventory in Superior Supply Chain Performance

Figure 3.1  The efficient frontier and inventory improvement goals.

We start with single-stage approaches since they are the most common and represent the building blocks for more sophisticated techniques. We proceed to collaborative approaches between adjacent echelons in a supply chain since they represent the first step beyond local decision-making. We then cover multi-echelon, end-to-end approaches, the ultimate objective of supply chain management. We conclude the chapter by highlighting some important issues that practitioners must keep in mind.

2. The Importance of Inventory

The efficient frontier demonstrates the tradeoff between inventory and service. In this section we highlight the importance of inventory by exploring its impact on cost and service in more detail. We also present recent examples of companies who have managed inventory in their supply chains well and examples of ones who have not. The repercussions of these inventory successes and failures speak for themselves.

2.1. Cost

In our experience working with a number of companies, we have found widely differing views about the costs of inventory. This is largely because inventory costs are hard to quantify. Unlike material or freight costs that are direct expenses with well-established locations on the income statement, inventory-driven costs are mostly indirect and appear in a variety of places on the income statement and balance sheet. Because they are hard to isolate and quantify, inventory-driven costs are often ignored or understated when making important supply chain decisions or measuring employee performance. This is a mistake that companies must avoid because the costs of inventory are very real and can be very significant.

Inventory driven costs in the supply chain include the following: traditional carrying costs, opportunity cost, devaluation, obsolescence, rework, price protection, and returns. Carrying costs include the cost of providing space to store the inventory, taxes, insurance, breakage, spoilage, and shrinkage (Nahmias 2001). These are the costs traditionally associated with inventory, however they often constitute a relatively small percentage of the total inventory driven costs. Opportunity cost captures the
return that could have been achieved if the money invested in inventory had been invested elsewhere. It is often a significant contributor to inventory driven costs.

The inventory costs resulting from devaluation, obsolescence, and rework have taken on greater significance in the last decade as the rate of technology change has increased and product lifecycles have shrunk. *Devaluation* occurs when product held in inventory loses value over time. For example, inventory in the personal computer (PC) industry loses 1% to as much as 4% of its value each week (Kuhel 2001; Park and Burrows 2001; Taylor 2001). *Obsolescence* costs are incurred when a part or product reaches the end of its life and all remaining inventory must be scrapped or sold at extreme discounts. In the programmable logic industry, for example, obsolescence costs are on the order of 5–10% of the gross inventory value (Brown et al. 2002). A company incurs *rework* costs when existing inventory must be reworked to meet engineering changes. A manufacturer of computer printer components found that obsolescence and rework combined to increase its inventory driven cost rate from 24% to 40% (Lee and Billington 1992).

As policies have evolved between supply chain partners, companies find themselves exposed to the costs of inventories not even in their possession. *Price protection* and *returns* are policies that suppliers may extend to their channel partners. Suppliers may offer price protection policies that grant retailers credits applied to the retailers' unsold inventories when prices drop during the product life cycle. Suppliers may also allow the retailer to return units from inventory at some rebate. These types of channel policies are employed in a number of industries, most notably computer products and peripherals, electronic components, and even books and recorded music (Taylor 2001). These policies expose the supplier to the costs of inventories held by their downstream partners. Companies also should not ignore *off-balance-sheet inventory liabilities* they might have with their suppliers. In 2001, after years of chasing surging demand and maneuvering to secure scarce supply, many manufacturers found themselves no longer needing the large outstanding orders that they had with their suppliers. As much as $24 billion in orders were canceled for semiconductors and electronic components alone from the second quarter of 2000 to the third quarter of 2001 (Nied et al. 2001). Even though these liabilities are not captured on the manufacturer's balance sheet, they are very real to cash-strapped suppliers and contract manufacturers. When these suppliers make a claim, a manufacturer's options are limited and the likelihood of a cash payout is high.

All of the different costs related to inventory can add up to a very big number. It is not uncommon to see total annual inventory driven cost rates as high as 40 or 50%. This means that on an annual basis, every dollar of inventory generates 40 or 50 cents of cost for the supply chain holding it. In some industries, inventory costs can account for more than 20% of a company's total supply chain cost (Shapiro 2001). In fact, at Hewlett-Packard, inventory often represents the most critical cost category in deciding on a particular supply chain structure (Cargille and Bliss 2001).

2.2. Service

Inventories throughout the supply chain directly impact the availability of products, how quickly they are supplied to market, and at what cost. These are all critical components of good customer service. Companies define and measure service in
many different ways, but service is almost always related to the ability to satisfy a customer demand within a certain time. The location and amount of inventories drives a supply chain’s ability to provide short customer response times and reliably meet a high percentage of what is often very uncertain demand. Even if customer expectations and competitive pressures do not necessitate the stocking of finished product, inventories of components or raw materials are necessary to provide high service through assemble-to-order business models.

A recent A.T. Kearney study found that leading companies were able to deliver product by the customer’s requested date 99% of the time (Lowe and Markham 2001). The average company performance in this study was 89%. In our experience, companies typically target a service level around 95%, but it is not uncommon to find their actual service levels below 80%. The higher service provided by the leading companies represents a significant competitive advantage.

The repercussions of poor service include lost sales and, in some cases, financial penalties imposed by supply chain partners. If product is not available when a customer wants it, the supply chain may lose that sale. Proctor & Gamble estimates that it loses the sale of its product 29% of the time when a retailer is out-of-stock. The particular retailer loses that sale 41% of time (Albright 2002). The cost of this lost sale is not limited to the single transaction and can be enormous. For example, a lost sale of a Hewlett-Packard inkjet printer results in lost profit margin on the printer, lost profit margin on future supplies for that printer (such as ink cartridges and paper), and a hit to HP’s efforts to build brand loyalty that could impact future product sales. For a typical inkjet printer (which costs HP about $150 to build), the lost margins on the supplies over the life of the printer (about $40) actually exceed the lost margin on the printer (about $35) (Johnson and Anderson 2000). Imation, a leading provider of removable storage products including diskettes and recordable CDs, found its retail partners such as Best Buy and Staples starting to charge penalties for late deliveries. In many cases these penalties far exceeded Imation’s margin on the entire delivery. By improving their inventory strategy across the supply chain, Imation was able to increase service by 25–30 points and eliminate millions of dollars in penalties (Optiant, Inc. 2002).

2.3. Examples

Dell and Wal-Mart are widely considered to be two of the great business success stories of the past decade. Their supply chain inventory practices have been largely credited for their success. Dell pioneered the direct model, a supply chain approach that is elegant in its simplicity. Dell takes orders directly from its customers and builds PCs to demand, bypassing the traditional dealer channel. As a result, Dell eliminates the costs and risks associated with carrying large inventories of finished goods. Dell has also used technology and information to blur the traditional boundaries between itself and its suppliers in an approach it calls virtual integration (Magretta 1998). Factory scheduling algorithms run every two hours, and Dell posts the results (as well as forecasts and inventory levels) on its supplier extranet, Valuechain.Dell.com (Kuhel 2001). Suppliers maintain a standard five days of inventory in multi-vendor hubs located within close proximity to Dell’s factories. This helps Dell carry just four days of total inventory in its facilities as compared to 30 days at some of its competitors.
With this lean supply chain model Dell has become the world’s number one PC maker and was able to chalk up $361 million in profits in 2001 while the rest of the industry logged $1.1 billion in losses (Park and Burrows 2001).

Wal-Mart was a pioneer of Collaborative Planning, Forecasting, and Replenishment (CPFR) and currently provides detailed information about sales and inventory in every one of its approximately 2700 stores to its 10,000 suppliers via a proprietary inventory management system known as SupplierLink (Heun 2001). Wal-Mart has been an active adopter of Vendor Managed Inventory (VMI) and no longer owns the stock for many of the items it carries. Wal-Mart has also helped to make cross-docking famous, using its own network of warehouses as inventory coordination points instead of inventory storage points. These supply chain innovations have combined to give Wal-Mart the highest inventory turnover ratio of any discount retailer and have helped make Wal-Mart the largest and highest-profit retailer in the world (Simchi-Levi et al. 2000). In contrast, Kmart, the number two discounter who is known more for its marketing than its supply chain innovations, recently declared bankruptcy.

While Dell and Wal-Mart exemplify the benefits of lean supply chain management, Nike and Cisco have recently committed major inventory blunders that have dramatically decreased their shareholder value. During its third fiscal quarter of 2001, Nike under-ordered on some footwear models and over-ordered on others. The result was unexpected sneaker shortages and surpluses. The shortages cost the company as much as $100 million in sales for the third quarter. Meanwhile, it took Nike six to nine months to reduce inventories to normal levels for the surplus models (Financial Times Ltd. 2001). As a result of this announcement, Nike’s shares fell nearly 20%. Nike’s CEO Phil Knight blamed the problems on Nike’s supply chain management system supplied by i2 Technologies causing i2’s share price to plummet almost 23% (Spain 2001).

In 2000, Cisco Systems had enjoyed 40 straight quarters of staggering growth and at one point briefly topped GE as the most highly valued company in the world (Berinato 2001). Because Cisco had the fortunate problem of being unable to keep up with demand, it built up its component inventories and entered into long-term commitments with its manufacturing partners and key component makers. However, partly due to communication gaps between the multiple tiers of Cisco suppliers, double and triple orders were placed in an attempt to lock in scarce components during the boom (Kathila 2002). Cisco got caught in a vicious cycle of artificially inflated sales forecasts and did not see the economic downturn coming until it was too late. As a result, in May 2001 Cisco was forced to take the largest inventory write-down in history: $2.2 billion erased from its balance sheet for components it ordered but could not use. Cisco’s stock sunk to less than $14 when just thirteen months earlier it had been $82.

As these examples demonstrate, effective inventory management is critical to corporate and supply chain success. The impact of inventory on supply chain cost and service should not be underestimated.

3. Inventory Classification

Inventory is often reported as one total number or at best divided into raw material, work in process, and finished goods subtotals. For accounting and benchmarking
purposes this level of aggregation can quickly summarize overall inventory performance. However, it does not provide the level of granularity required to satisfactorily address three key questions. Location—where should we hold inventory in the supply chain? Level—how much inventory should we hold? Timing—how should the location and level decisions vary over time?

Companies hold inventories to exploit economies of scale in procurement, to utilize capacity efficiently if demand is seasonal, to speculate on future price changes or to buffer against supply and demand uncertainties. Classifying inventories according to these motives provides a richer picture that better enables managers to address the inventory planning questions around location, level, and timing. Such a classification is well covered elsewhere (Nahmias 2001; Silver et al. 1998) and we only touch upon it here. However, we wish to emphasize that inventory classification traditionally takes a local perspective when identifying the motive. Because production and inventory decisions ripple across the supply chain, managers should take a global perspective in identifying the true underlying motives for holding inventory.

To see how the local and global perspective can differ consider Monsanto’s crop protection business in the mid-1990s. Monsanto worked with a number of channel partners (agents and distributors) and thousands of retailers. Monsanto offered generous payment terms well before the selling season. Speculating (correctly) that the in-season prices would be higher, the distribution channel placed orders early and built up inventories ahead of the season. From a local perspective price speculation appears to be the motive driving distribution channel inventory. But what was driving Monsanto to offer generous terms before the selling season? Capital-intensive production coupled with highly seasonal demand led Monsanto to pursue a production smoothing strategy that resulted in anticipatory (also called pre-build) inventory. However, Monsanto had insufficient finished goods storage capacity to hold this inventory. By offering attractive payment terms Monsanto was able to induce its downstream supply chain participants to hold the anticipatory stock for them. From the global supply chain perspective the channel partner speculation stock is actually driven by a combination of production smoothing and lack of storage at the manufacturer. For a detailed description of Monsanto’s production and inventory challenges and initiatives, see Graves et al. (1996).

We have focused here on classifying planned inventory. Of course inventory is not always a result of good planning. Large mismatches between supply and demand can and do occur due to either poor planning or poor execution.

4. Single Location Approaches

We begin our review of supply chain inventory management approaches by looking at single-location inventory models. While the whole idea of supply chain management is to take a global view of all locations that make up a chain, we start with single-location models since they are the most common in practice and can be linked together to form more complete supply chain inventory models. Further, single-location statistical methods represent an improvement over the current inventory practices at many companies. It is not at all uncommon even today for companies to use simplistic,
generic stocking policies such as holding three weeks of supply for all A items, four weeks of supply for all B items, and so on. Single-location approaches that capture the uncertainties in demand and supply by stock-keeping unit (SKU) can produce significant improvements in inventories and service levels.

In our experience, the most common inventory model in practice is the Base Stock (or Periodic Review, Order-Up-To-Level) model. In this model, each planning period an order is placed or production is begun to bring the inventory position to a predetermined level known as the base stock or order-up-to level. The base stock level is set so as to provide a desired level of service in each period. This means the base stock level must be large enough to cover both the expected demand until the next replenishment and the possible upside in demand that is implied by the service level. The portion of the base stock that protects against uncertainties in demand and supply is referred to as safety stock. The relative size of the safety stock increases as the uncertainties in demand or supply increase, the expected lead time or review period increases, or the desired service level increases. The mathematics of this model are summarized in the appendix to this chapter.

The base stock model is widely applied because it is a good mix of realistic business assumptions and mathematical tractability. It captures the key drivers of inventory in a relatively simple equation. Its regular ordering intervals fit well with typical business planning cycles and allow a business to coordinate transportation across many SKUs. The calculation of inventory requirements in response to a target service level is also consistent with management thinking and data availability.

The base stock model can be extended to capture additional business complexities. When the expected level and uncertainty of demand change frequently over time, a different base stock level reflecting these changes can be calculated for each time period (Kimball 1988). More commonly in these situations, the stationary model described above is used to determine the safety stock requirements expressed in terms of weeks of supply (WOS). The number of safety stock units required for each time period is then calculated by multiplying the WOS target by the weekly forecast for that planning horizon. Additional extensions to model limited capacity (Glasserman and Tayur 1996), non-zero customer delivery times (Graves and Willems 2000), and other complexities are also possible.

Hewlett-Packard's Strategic Planning and Modeling (SPaM) team has had remarkable success implementing a customized version of the base stock model across HP (Cargille et al. 1999). SPaM was formed by HP almost 15 years ago with the goal of developing practical supply chain solutions and disseminating them broadly across HP's many business units. While working with a number of HP divisions on supply chain strategy projects, SPaM realized that most organizations lacked the knowledge and tools to set inventory levels appropriately. The businesses often used simple approaches without regard to demand or supply uncertainties, desired part availabilities, or costs. As a result their inventories were typically 25 to 50% higher than necessary. SPaM's solution was to build a simple and inexpensive inventory tool in Microsoft Excel based on the base stock model. This tool, known as the Part Inventory Tool (PIT), can be quickly customized for each division through a software wizard created by the group.

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1 This approach assumes the relative uncertainty of demand (i.e., coefficient of variation) stays roughly constant over time.
Customized versions of PIT are now in place across a wide variety of HP product lines and geographies. The results have been impressive. HP's Integrated Circuit Manufacturing Division was able to cut finished goods inventory by $1.6 million while simultaneously improving on-time delivery performance from 93% to 97%. These circuits are now available more often for assembly into many different HP and partner products, enabling these partners to reduce their downstream inventories. The Microwave Instruments Division (MID) used multiple PITs to determine appropriate stocking levels at points throughout its vertically integrated supply chain. Within three weeks of implementing the new approach MID experienced remarkable availability improvements with no increase in inventory investment. Perhaps most importantly, the inventory tool diffusion process has helped to transfer capabilities to the HP divisions. The tool helps users perform what-if analyses and make more data-driven supply chain decisions.

While the base stock model does a good job of capturing the most common drivers of inventory, there are environments that call for a different approach. We have encountered the following single-location approaches in our work with different practitioners and software vendors. The Economic Order Quantity (EOQ) model is the granddaddy of all inventory models. It makes a number of fairly restrictive assumptions, the most glaring of which is that demand is known and constant. However, when the fixed costs of each replenishment are significant, the EOQ model is useful for capturing the tradeoff between fixed costs and inventory.\footnote{The most common fixed costs include order processing and handling costs, manufacturing set-up costs, and/or fixed transportation costs.} If demand is known but variable and fixed costs are still a key driver of inventory, then Lot Sizing algorithms (such as the Wagner-Whitin method and Silver-Meal heuristic) are helpful tools. These techniques are widely used as part of Materials Requirements Planning (MRP) systems. If demand is uncertain and the product is perishable or near its end-of-life, the Newsvendor model can be used to guide a last-time-buy. The Newsvendor approach is also appropriate when the product's lifecycle is shorter than the supply chain's replenishment lead time, an increasingly common phenomenon. If demand is uncertain and the fixed costs of replenishment are significant, the Min Max or Order-Point, Order-Up-To-Level model is most appropriate. Whenever inventory falls below the minimum level, this policy places an order to bring the inventory up to the maximum level. It is beyond the scope of this chapter to go into more detail about each of these models. We refer the interested reader to books on the subject by Nahmias (2001) and Silver et al. (1998). Figure 3.2 can be used as a guide to select the appropriate approach depending on the most significant drivers of inventory for the business.\footnote{Since the newsvendor model contains a single order opportunity, fixed costs are not relevant. For this reason it appears in the bottom right quadrant of Figure 3.2. The base stock model also does not explicitly consider fixed costs. However, fixed costs can be considered when setting the review period for the base stock model through an EOQ-type analysis. The fixed timing of reviews and the insensitivity of the optimal EOQ make the base stock policy attractive when fixed costs can be shared across multiple SKUs. For example, a common review period may allow different SKUs to be shipped on the same truck. For this reason the base stock model appears in the middle of the fixed cost axis of Figure 3.2. Note that additional drivers of inventory not depicted in Figure 3.2 include supply uncertainty and constrained capacity. As discussed previously, the base stock model can be extended to address these complexities.}
Together, these single-site approaches form a powerful toolkit from which the supply chain inventory practitioner can build.

5. Collaboration Between Adjacent Echelons

Single-location inventory models can be a big improvement over the simple rules-of-thumb still used by many companies. However, these models require the user to provide the demand and supply linkages between different locations in a supply chain in order to understand the impact of one site's inventory decisions on another. If each location makes decisions independently from all others, inefficiencies may be introduced. One well-documented result of independent decision-making in a supply chain is the bullwhip effect (Lee et al. 1997). The bullwhip effect refers to the systematic amplification of demand variability as orders are passed along the supply chain from customer to supplier. This increase in variability typically requires upstream locations to carry additional inventory. In an effort to eliminate or at least reduce inefficiencies like the bullwhip effect, many supply chains have turned to collaboration between supply chain partners. While the ultimate goal of such efforts is usually end-to-end supply chain coordination, these efforts typically start between adjacent echelons or partners in a supply chain.

Collaboration between supply chain partners can take many forms and include many functional areas including production, distribution, procurement, marketing, and product development. It is beyond the scope of this chapter to cover the many different forms of supply chain coordination. We refer the reader to the chapter by Kulp, Ofek, and Whitaker in this text for a more complete review of this topic. In this section we focus on the different ways that adjacent supply chain partners collaborate to manage inventories.

Many names and acronyms have been applied to recent supply chain coordination programs that, among other goals, have attempted to reduce inventories by creating strategic partnerships and sharing demand and inventory data. An industry-wide effort by U.S. apparel firms that began in the late 1980s was called Quick Response (QR),
while a similar but broader effort by the grocery industry in the mid-1990s was labeled Efficient Consumer Response (ECR) (Buzzell and Ortmeyer 1995; Food Marketing Institute 2002). A key practice within the ECR movement is known as Continuous Replenishment (CR). In a CR program, the downstream supply chain partner (we'll call them the distributor, although this could occur at any point in the supply chain) sends daily sales and inventory data to its upstream partner (we'll call them the supplier). The supplier is then responsible for replenishing the distributor's inventory in order to maintain mutually agreed upon inventory levels. A very similar system, popularized by Wal-Mart and Proctor & Gamble beginning in the mid-1980s, is known as Vendor Managed Inventory (VMI) or Supplier Managed Inventory (SMI) (Taras 2002). VMI appears to be almost identical to CR, except perhaps in a VMI program the supplier has more complete control over the determination of the distributor's inventory levels and replenishment frequencies. Two classic Harvard Business School case studies on Campbell Soup (McKenney and Clark 1994) and Barilla SpA (Hammond 1994) describe early implementations of VMI. Collaborative Planning, Forecasting, and Replenishment (CPFR) builds upon ideas from CR and VMI but is broader in scope. CPFR includes a set of business processes in which suppliers and distributors jointly develop sales forecasts and replenishment plans. CPFR is designed in a set of guidelines supported by the Voluntary Interindustry Commerce Standards (VICS) Association and initially published in 1998 (VICS Association 2002).

These supply chain coordination programs differ somewhat in scope and definition. Further, implementations of the same program often differ from one company to the next as different elements are emphasized or interpreted differently. However, from an inventory standpoint, the programs share a common, fundamental idea. All describe a process in which: (1) the supplier and distributor share inventory and sales data, and (2) the supplier participates in and perhaps even controls the management of inventory at the distributor.

5.1. Benefits

The benefits of VMI and related programs can be significant. Many benefits stem from the fact that the supplier receives a timely and undistorted demand signal. Without these programs, the supplier merely receives replenishment orders from the distributor. These orders are often quite different than the distributor's actual demand. In addition to actual demand, a distributor's order may include adjustments to inventory as the distributor's forecasts for future demand changes. The order may also be artificially inflated if the distributor suspects that the supplier has limited capacity and will be unable to meet its full order. Finally, a distributor might batch a number of periods of demand into a single order, creating a lumpy demand stream for the supplier. Under VMI and related programs, the supplier typically gets a daily feed of actual distributor demand and inventory levels through electronic data interchange (EDI) or over the Internet. In addition, the distributor may share information about upcoming promotions or big customer deals as part of a formal collaboration process. All of this combines to reduce the supplier's demand uncertainty. With more predictable demand, the supplier is able to simultaneously reduce its inventory levels and improve its service to the distributor. As a result of the improved service, the distributor
is able to reduce its inventories and increase its service, resulting in increased sales for the entire supply chain.

The potential benefits do not end there. Because it controls the replenishment process, the supplier is often able to achieve additional economies of scale. For example, if the supplier has multiple distributors in a similar geographic area, the supplier can coordinate transportation of replenishments and receive full-truck-load discounts. The supplier may even choose to establish a warehouse or hub in close proximity to the distributors. This allows the supplier to pool the inventories for many distributors. A supplier may also be able to better coordinate production across customers when it controls the timing of replenishments. Clariant, Inc. entered a VMI arrangement with Unilever in 2000 to supply sodium isothionate, a key ingredient in Unilever’s soap products (Hicks 2002). Through better planning with a Web-based tool provided by Unilever, Clariant has been able to improve utilization of manufacturing equipment. Equipment that was once dedicated to Unilever is now used to produce products for other customers, increasing the effective capacity of that equipment by 40%.

VMI processes are often automated, which may enable a reduction in planning cycles (and consequently inventories) and free procurement and distribution personnel to focus on other tasks. Processing speeds are improved and order preparation tasks and data entry errors are eliminated. Finally, collaboration programs provide the motivation for supply chain partners to take a close look at their processes. Redundancies can be eliminated and best practices can be shared. For example, the supplier may possess more sophisticated techniques or systems for setting inventory levels, and now both partners can benefit from this expertise.

5.2. Risks

While very few people will argue against the theory of VMI and related programs, successfully implementing these programs is easier said than done. The costs to set up a VMI program are nontrivial. They include investments in information systems and frequently external resources such as consultants or system integrators. They may also require internal expertise to manage the systems. Additionally, the supplier may take a one-time hit in sales revenue as excess stock is withdrawn from the supply chain.

More daunting than the costs, however, are the organizational challenges. Job functions, processes, and performance measurements all need to change. Concerns about the roles of buyers and sales people in the new environment need to be addressed. Compensation systems that reward employees, at least in part, on the basis of common performance measures must be developed. Trust must be established in what once may have been an adversarial relationship. The distributor must feel comfortable sharing proprietary data with the supplier. The distributor must also trust that the supplier will manage inventories in both parties’ best interests. The rules of the relationship must be worked out, including inventory ownership, financial terms, inventory and service goals, and the division of the costs and benefits of the program. More operationally the supplier must possess and demonstrate the expertise to manage inventories well. The distributor must communicate to the supplier any promotions, events, or large changes in the customer base. Otherwise, valuable information will be lost as responsibility for inventory management is moved up the supply chain. Extensive testing
should be done to validate the EDI or Internet data exchange. Both parties must understand that these programs take time. Committed senior management and strong program management are a necessity. The Barilla SpA case study contains a number of examples of the challenges faced when setting up a VMI program (Hammond 1994).

5.3. Examples

Despite the challenges highlighted above, a number of companies have successfully utilized VMI and related programs. From November 1999 to February 2000, Hewlett-Packard rolled out a VMI-type program with its commercial distributors known as Automated Inventory Replenishment (AIR) (Daggett 2000). HP sold the great majority of its commercial PC and printer products through distributors such as Ingram Micro, Tech Data, Pinacor, and Synexx. A number of issues between HP and its distribution channel motivated the implementation of AIR. HP was experiencing high order variability from its distributors. Promotions and shortage gaming made it difficult for HP to decipher true demand. Partly as a result, HP found it challenging to reliably deliver product to its distributors. In periods of adequate supply, distributors might get product in a couple of days. When supply was constrained, it could take weeks. This all led to high channel inventories that were expensive for the distributors to maintain and came back to bite HP in the form of price protection and returns.

The solution was to use information to streamline the supply chain between HP and its distributors. Through AIR, HP took responsibility for recommending replenishment quantities and inventory levels for each of its distributors. Distributors were already providing HP with daily EDI feeds of sales and inventory data. Historically, however, these had only been used to calculate sales commissions. The goal of AIR was to use this information to more efficiently manage the supply chain. AIR consisted of five components. First, HP created a weekly allocation system to ensure that each distributor received its fair share of available supply in order to maximize overall product availability to end-users. This system utilized an accurate and timely picture of both total supply (including inventory already in the distributors' warehouses) and total demand (using actual sell-thru as opposed to artificially inflated orders). The second component was a statistical forecasting engine. This engine utilized historical sell-thru data and a number of different forecasting algorithms, from which the best performing forecast was selected. The third component was a weekly collaboration process between an HP AIR specialist and a buyer at the distributor. Each week they reviewed all data and replenishment plans, managed promotional exceptions, and executed new orders in a secure Internet location known as an E-room. The fourth component was an inventory calculation engine supplied by HP's SPaM team. A customized base stock model was used to calculate inventory targets by SKU at each distributor location. Lastly, HP used a supply chain planning application from i2 Technologies to manage the actual replenishments to the distributors.

AIR was implemented by an HP printer division in two phases. The allocation engine was developed over the course of three months, while the replenishment process took nine months to develop but less than three months to roll out. The development process included very detailed pilots with two distributors and only a few products. These pilots were critical in order to refine the process and build trust and
mutual confidence with the distributors. Since inventory management had historically been a core competency of the distributors, a certain amount of push-back had to be overcome. After implementation of the AIR program, distributors' service levels were raised to 95% and their inventories were reduced by 40%. Additionally, HP's roll-over costs (when discontinuing one product and introducing the next) were reduced by millions of dollars. HP is now expanding the AIR program to include additional product lines.

Ace Hardware presents another example of successful supply chain collaboration. In 1999, Ace initiated a CPFR relationship with Manco, a company that supplies Ace with products like tape, glues, and adhesives (Cooke 2002). The two companies had been somewhat successful with a VMI program and saw CPFR as the logical next step. In particular, Ace hoped that CPFR would correct faulty promotional forecasting and provide visibility into manufacturers' inventory that was lacking in its VMI programs. The companies used a software application from E3 Corporation to exchange information and determine appropriate replenishment quantities. The results were impressive. Typical forecast percentage errors were reduced from 20% to 10%, freight expenses as a percent of product costs were reduced from 7.0% to 2.5% due to consolidated orders, and service levels were increased to 99%, all while increasing inventory turns. As of 2002, Ace makes $200 million worth of purchases through CPFR with 15 of its suppliers. Ace reports that in 2001 its CPFR suppliers as a group enjoyed a 10% year-over-year sales increase while other suppliers' sales remained flat in the soft economy.

VMI and related programs are not for everyone, however, as evidenced by Spartan Stores (Mathews 1995). In 1995, the grocery retailer and distributor shut down its VMI program a year after it began. Spartan found that inventory levels did not go down as a result of VMI beyond what Spartan could have accomplished by simply eliminating forward buys. Further, Spartan buyers were spending more time and effort on the ordering process than they did before VMI. Due to lack of confidence in supplier capabilities, the buyers felt the need to monitor the process very closely. The biggest problem, however, was promotions. The VMI process did not take promotions into account. Consequently, forecasts were off and availability was poor. It should be noted that Spartan continues to provide information to its suppliers via the electronic links established for VMI. However, in their case Spartan felt it was the right decision to maintain inventory responsibility at the store level.

When considering VMI or a related program, supply chain partners should carefully evaluate the costs and benefits for their particular chain. The base stock model described in the previous section can be used to quantify the inventory benefits of lower demand uncertainties and shorter review periods. As noted earlier in this section, another benefit of VMI is that it may allow a supplier to pool inventory across a number of different customers. Pooling inventories in this way enables a decrease in the total inventory required to provide the same level of service. The intuition behind this result is that when one location's demand is higher than expected, another location's demand may be lower than expected. The variabilities partially offset in this manner and the overall uncertainty is lower. Hewlett-Packard's SPaM team has created an effective, rough-cut approach for quickly quantifying the potential of this type of risk-pooling opportunity (Cargille and Bliss 2001). If the safety stock for
$n$ locations is pooled at a single location, the required safety stock is approximately reduced by a factor of $\sqrt{n}$. This rough-cut method is not as accurate as a more complete, detailed analysis but the estimates are directionally correct and save significant time in analysis. We note that this approach can also be applied to quickly evaluate the inventory benefits of other activities that produce risk pooling such as modular product design or SKU rationalization.

6. End-to-End Approaches

While programs like VMI can improve the inventory performance between adjacent echelons in a supply chain, the ultimate goal of supply chain thinking is to take a global view of inventory decisions. When multiple echelons in the supply chain are considered at the same time, the analysis needs to take into account the interactions between all of the stages. For example, consider a stylized supply chain consisting of five potential inventory locations in series. This could represent a supplier, semi-finished and finished inventory at a manufacturer, a distribution center, and a retailer. Suppose each location or "stage" has a lead time of 20 days. If we further assume that the final customer requires immediate delivery of the product, then the stage satisfying customer demand must hold inventory and there is a total of 100 days of time in the supply chain that has to be buffered with inventory. Even if we restrict our attention to "all-or-nothing" policies in which a stage either holds no inventory or holds enough inventory to provide off-the-shelf service, 32 policies are feasible. If we enumerate all of the base-stock policies that can allocate the 100 days of time across the five stages, the number rises to the millions.

Figure 3.3 graphically illustrates three feasible policies for this example, with safety stocks represented by triangles. The first policy holds inventory at every stage in the supply chain. Informally, this is a "sprinkle-it-everywhere" policy that is often

\[\text{Figure 3.3} \quad \text{Three feasible inventory policies for the serial supply chain example.}\]

\[\text{4 The model being informally presented in this paragraph is described more rigorously in Graves and Willems (2000).}\]
seen in practice. By holding inventory at every stage in the chain, each stage is buffered from the actions of adjacent upstream and downstream stages. There can be two significant problems with this approach. First, there is a tendency for stages to deviate from target inventory levels since there are more inventory locations to manage and deviations can be absorbed by adjacent buffers. Second, in percentage terms demand variability is greatest over a short interval of time. Therefore, if each stage is covering its own lead time then there is no opportunity to take advantage of pooling lead times across stages.

The second policy holds a decoupling inventory at the end of the process and no other safety stock in the chain. The downside of this system is that inventory is held at its most expensive point in its most differentiated form. Practically speaking, this type of configuration is precisely what multi-echelon approaches are attempting to avoid.

The third policy holds an inventory at the second stage to buffer the first two stages and an inventory at the final stage. If stage 3 has an extremely high cost added, it is quite possible that this is the optimal configuration that supplies immediate service to the final customer at the lowest possible safety stock cost.

6.1. Multi-Echelon Challenges

Optimizing multi-echelon systems poses multiple problems. In particular, the major issues include problem scope, granularity, data definition, objective function determination, and centralized versus decentralized control.

The first question is how much of the supply chain to model. Where does it begin and where does it end? If you trace any supply chain from its most basic raw materials through to its final point of consumption, the supply chain’s length will stretch to hundreds of days and tens of echelons. This scope is almost surely too large for an initial analysis.

Scope has to be defined in terms of the decision maker that is driving the project. She has to look at the area that is within her control, and scope the project appropriately. In many companies, inventory responsibilities are still split into two areas: manufacturing and distribution. Consider the stylized supply chain in Figure 3.4. The person in charge of distribution controls the management of finished goods. In the most expansive situation, this begins with the company’s distribution center and ends with the point of consumption. Manufacturing controls the procurement of materials and the manufacturing of product.

![Figure 3.4](image-url) Multi-company supply chain example.
When scoping a project, the challenge is to define a problem large enough to create significant opportunity while making it tractable enough to make the analysis and subsequent implementation feasible. For a VP of Manufacturing, her scope could include her own in-house final assembly and test plus the contract manufacturer (CM) plus the parts vendors that supply the CM. This scope is feasible because the manufacturer still contracts with the raw materials suppliers directly. Therefore, all of the members in the analysis have an incentive to work with the manufacturer.

The next issue is granularity. Once the scope has been defined, there is the issue of how much detail to go into. How many items on the bill of materials should be represented? What level of process representation is appropriate? For the manufacturing side, a good rule of thumb is to ask the person with profit and loss responsibility what the key finished goods are. Next go to commodity management and ask what key raw materials go into these products. Then ask the respective departments to build the connections between the raw materials and the finished products. For a typical product line, it is not uncommon to have 50–200 stages (SKU-location combinations) in an initial supply chain map, with many of the stages representing the key finished goods and raw materials.

For the distribution side, a good rule of thumb is to again ask what the key finished goods are; in this setting, key finished goods could be defined in terms of configurations (i.e., combinations of finished goods) or particular variants of products at particular locations (i.e., SKU information by location). These key end items are then traced through the distribution network to the central distribution center (CDC). Initial projects focused on distribution can range from 50 to 1000 stages due to proliferation caused by the number and diversity of channels.

Once scope and granularity have been agreed upon, necessary inputs like demand, production times, and costs need to be gathered. Even if the data is readily available, this data can be very hard to assemble if more than one company is involved. In particular, does cost data include the true activity based costs across the chain or does it also include each company’s transfer price? In the chain depicted in Figure 3.4, for example, is the CM’s profit margin included in its cost? Since the part prices are known, if the CM shares the CM’s true cost data then the original equipment manufacturer (OEM) can infer the CM’s profit margin. In practice, a common way for the OEM to address this issue is to use the raw material vendors’ part costs and estimate the CM’s manufacturing cost.

For the OEM, there are multiple possible objective functions. The “noble” objective would be to minimize total supply chain cost subject to delivery time and service level constraints at the customer stages. In effect, this objective acts to create the leanest possible end-to-end supply chain. While intellectually appealing, this objective is likely not the one chosen because it does not guarantee to maximize the OEM’s profits. Instead, if the OEM is just trying to maximize her profits, the objective could be to minimize the OEM’s portion of the supply chain cost given all of the constraints at the customer stage. By optimizing only a subset of the chain, the solution to this modified formulation will push inventory to locations outside the subset. For example, if distributors are modeled in the channel, inventory will be pushed to their locations. The end-to-end pooling and cost advantages of holding at the OEM will be negated by the fact that there is no cost for the OEM when inventory is held at the distributor.
Control refers to the mechanisms that determine operating doctrines and information sharing across the supply chain. Under centralized control, there is one decision maker operating the supply chain. When making decisions, the decision maker has perfect knowledge of the state of information at each stage in the supply chain. Under decentralized control, independent agents at different stages make decisions that reflect their local information and objectives. While a centralized system is virtually impossible to create in reality, it does serve as a useful benchmark for what could be achieved if the various supply-chain participants work together. Therefore, significant effort focuses on how to make the decentralized system perform like a centralized system. One area that is commonly focused on is the communication of end-item demand information across the chain. As discussed earlier, efforts like CPFR have shown the inventory reductions that are possible through increased supply chain visibility.

6.2. Examples

This section summarizes a multi-echelon inventory optimization project at the Eastman Kodak Company. A more complete description is included in Graves and Willems (2000). Figure 3.5 depicts the original supply chain map that was created for Kodak's high-end digital camera group. The initial scope of the project encompassed only the parts of the process that were directly under the control of the final assembly group. From the perspective of final assembly, the digital camera was comprised of three major subassemblies: the camera body, the imager, and the circuit board. Raw materials that were considered "C" items in an ABC classification were split into two groups according to their lead times. While C items have a low dollar value in comparison to other

![Supply Chain Diagram]

Figure 3.5  Phase one supply chain map for high-end digital cameras.
The Role of Inventory in Superior Supply Chain Performance

parts, it was necessary to develop the appropriate stocking policy for these items so that adequate materials were available to produce the finished product. Stages were defined as locations that could hold safety stock. In reality, the build/test/pack operations were a sequence of ten steps that moved through six different work centers. However, given the limitations of space, it was only possible to hold inventory before the process (in the form of raw materials) or after all the steps had occurred. By choosing a level of granularity that only depicted locations that could hold safety stock, the supply chain map became a visual document that focused everyone on the multi-echelon nature of the problem.

The objective function was to determine the optimal safety stock plan from final assembly through distribution. Distribution posed an additional constraint that distribution must hold safety stock. After discussions with sales and marketing, the system was configured to provide a 95% service level within the five-day window the customer was willing to wait for the product. While the product passed through several departments at Kodak, all of the stages were owned by Kodak. As such, a project manager in final assembly was able to act as a central decision maker for the project.

The Strategic Inventory Placement model described in Graves and Willems (2000) was used to optimize Kodak’s supply chain inventory. The initial phase of the project reduced inventory levels by more than 20%. This was accomplished by: (1) removing finished goods inventory from the assembly site since customer demand was already buffered by distribution, and (2) right-sizing the inventory targets at all other locations. Given the initial success of the project, the scope was increased to include the imager production process since this subassembly was the highest-cost component. As a result of the imager modeling effort, the team decided to remove safety stocks from the end of two high-cost imager process steps. This required some increase in the downstream safety stocks of finished imagers, but the overall supply chain safety stock for imagers was more than halved. While these first two phases of the project focused on improving the operation of the existing supply chain, later work examined changing the structure of the supply chain. In particular, Wala (1999) describes the evaluation of different distribution methods for digital cameras.

Table 3.1 contains the financial summary for two Kodak assembly sites that use the model. Site A has applied the model to each of its eight products and Site B has

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applied the model to each of its three product families. The sales volume increased slightly over the three years. At the start of 1996, the sites moved from a make-to-schedule (MTS) to a replenish-to-order (RTO) system. The modeling effort began at the end of 1995 and was used to help guide the transition to replenish-to-order. The total value of the inventory for these products has been reduced by over one-third over the two years.

The model applied in the Kodak example is one of many multi-echelon inventory models that have been applied in practice. Lee and Billington (1993) and Ettil et al. (2000) both developed performance evaluation models of a multi-stage inventory system and applied them at HP and IBM, respectively. These models focus on properly characterizing the replenishment lead-time faced by each stage in the chain. They then formulate and solve a nonlinear optimization problem that minimizes the supply chain’s inventory costs subject to end-item service level targets. In contrast, Graves and Willems (2000) assume each stage will quote a guaranteed replenishment time to its customers. They then present an optimization model to determine these replenishment times.

The models described in the previous paragraph focus on optimizing safety stock levels in an existing supply chain subject to variability. However, better inventory performance can also be achieved by redesigning a product or its supply chain. A concept known as postponement has been applied with great success at companies like Hewlett-Packard and Imation. The basic idea of postponement is to delay the differentiation of a product into its final form until as close to the customer as possible. This can be done by redesigning the product to use common parts or redesigning the supply chain so that differentiating processes are performed at locations closer to the final customer. This allows a supply chain to keep more inventory in its undifferentiated form and take advantage of risk-pooling. See the chapter by Venkatesh and Swaminathan in this text for much more detail on the concept of postponement.

There are also separate but complementary streams of work in network design and production and distribution planning that address multi-echelon inventories in a deterministic setting. The chapter by Harrison in this text contains a description of network design approaches. The Kellogg Planning System described by Brown et al. (2001) is an example of a production and distribution planning system. In general, these models determine the minimum cost production and distribution networks and/or plans given the capacities, costs, and requirements across the network. Unlike safety stock models, they do not specifically consider uncertainties in demand or supply. Instead, inventory results when some of a stage’s demand is produced in an earlier period due to capacity constraints, fixed costs, or forced bounds on ending inventory. These approaches can be used in concert with safety stock models. For example, a company may use a network design tool to determine overall supply chain structure and a safety stock model to optimize inventories within that structure. Similarly, safety stock models can provide inventory targets to feed into a production and distribution planning system.

7. Practical Issues

In this final section, we briefly discuss a number of additional inventory topics that supply chain practitioners should keep in mind.
7.1. Setting Supply Chain Service Targets

Customer service is a critical dimension of supply chain competition and a key driver of inventory levels. Therefore, setting the correct service target is an important strategic decision for managers. While we do not attempt to provide an in-depth treatment of service-target setting, we wish to emphasize the following three points as being especially relevant to supply chain practice.

First, service to the end customer is key. Customers care about the service they receive, not about the service provided by internal stages in the supply chain. Supply chains can achieve the same final customer service target with different designs. The lowest cost design may not have high service levels at all internal supply chain stages. Sometimes it can make sense to have lower service levels internally and to buffer these with high finished good inventory. Other times it does not. Either way, managers need to remember that service level to the end customer is key.

Second, service targets need not be the same for all products in the supply chain. For instance high margin products may benefit from higher service levels. Just as service targets may differ from one product to another, targets might vary from one customer to another. Key customers may receive better service than small volume customers.

Third, know how your customer measures service. Large retailers such as Wal-Mart, Office Depot, and Best Buy are demanding better service and are implementing late delivery/service penalties that can far exceed order margins. Critically, penalties are imposed if the order is not received on time and in full. As orders can comprise multiple line items, the order fill rate will be lower than the line item fill rate. Therefore, high order fill rate requirements have a serious impact on the line-item service levels managers should target.

7.2. Inventory Levels Across the Product Lifecycle

Traditional inventory models assume that demand inputs are stationary over time. That is, the demand distribution in the current period is identical to the demand distribution in previous and future periods. In reality, demand is rarely stationary. For most products there is a life cycle where demand builds steadily from nothing (i.e., growth phase), then levels off (i.e., mature phase) and gradually declines (i.e., end-of-life phase). Forecast uncertainty is usually very high in the growth phase, decreases during the mature phase, and often increases again at the end-of-life. When planning inventory levels, it is critical to know what phase the product is in.

If the product life cycle has three stages, one rule of thumb is to maintain service levels of 99%, 95%, and 60% over the respective phases. These service levels reflect the fact that holding costs typically increase over the product lifecycle while the costs of a lost sale typically decrease. The net effect of these parameters creates higher inventories at the beginning of the product life cycle and lower inventories as time moves forward. The intuition for this behavior is that growth in future periods is contingent on the product’s initial adoption. The inventory in early periods is also less risky because there is significant time left to sell off slow-moving items. Near the end of the life, demand is dropping significantly and there comes a time, particularly as new product gets introduced, that the product cannot be given away. Hewlett-Packard has used the approach of holding 6 weeks of inventory in the first third of the product
life, 4 weeks during the middle third, and 2 weeks for the last third (Johnson and Anderson 2000). The HP Network Printer Case presents an example of dynamic inventory levels over the product lifecycle (Lee 1999).

7.3. Local versus End-to-End Supply-Chain Metrics

"You get what you measure" is a well-known management axiom. Understanding and aligning metrics is a critical success factor in any improvement initiative. In the context of multi-echelon supply chains, developing metrics that can be applied across the supply chain is a major challenge.

As an example, let us first restrict our attention to determining the appropriate service levels across the supply chain. If a distribution center targets a 95% service level, what is the appropriate service level for a raw material that is used across several products? In general, this is a very hard question to answer. Should every stage adopt a high service level? In some cases, it may be optimal to have a stage maintain a lower service level, particularly if the item is expensive and the stage has sufficient capacity to react quickly to change requests. But while it is optimal, it presents a problem because the stage with the lower service level will look bad on a relative basis when compared to the other stages in the supply chain.

In the multi-echelon setting, it is also common for metrics to conflict with one another. For example, a factory might have a goal of 95% capacity utilization while the distribution center has a goal of eight inventory turns and 99% delivery performance. To maintain the high capacity utilization the factory may want to manufacture in large batches but this will act to create too much of some items and not enough of other items. Therefore, by maintaining 95% capacity utilization at the manufacturer, the distribution center will be unable to meet either of its objectives.

It is important that supply chain inventory metrics be multi-dimensional and global. If a stage is measured only on inventory level and not on service level, that stage is more likely to provide poor service. If a stage is measured only on its own performance and not on supply chain performance, that stage is less likely to care about its impact on other stages. We refer the reader to the chapter by Hausman in this text for a more complete discussion of inventory metrics in the supply chain.

7.4. Impact of Decentralized Inventory Ownership in the Supply Chain

Inventories reside throughout the supply chain and often no single company has financial ownership or control of all the inventories. In many supply-chain inventory initiatives companies must recognize the inter-organizational challenges that arise from decentralized inventory ownership. A power imbalance may reside in certain supply chains such that strategies to the benefit of a dominant party, but to the detriment of others, can be imposed. More typically change might only occur if it is to the benefit of many. In such instances supply chain parties must identify how to share the benefits of improvement initiatives.

CPFR, for example, holds the promise of reduced inventories through improved forecast accuracies. The word collaboration implies two distinct parties working together for their mutual benefit. Mutual benefit is often imperative if the promise of collaboration is to be realized. For example, a supplier wishing to convince a customer
to share its replenishment forecasts might offer to own and manage the inventory of its parts at the customer site. This reduces costs for the customer and therefore provides it with an incentive to share information. While the supplier now owns and manages inventory at an additional site it may be worth doing so if the increased forecast accuracy allows it to reduce its overall inventory costs. Of course managing customer inventory is not the only avenue available to a supplier to induce customers to share forecasts. The key point to remember is that companies often need to identify means of sharing the benefits with other parties in order to successfully implement inventory initiatives.

7.5. Data Availability and Quality

Data management is critical for best-in-class inventory control and planning. Data availability and accuracy are two key dimensions of effective data management.

Inventory control refers to the transactional-level decisions regarding replenishments and order fulfillment. For such decisions accurate data reflecting current demand, current resource capacities, and current on-hand, in-process, and on-order inventories are critical. According to a PricewaterhouseCoopers (PWC) 2001 survey (PricewaterhouseCoopers 2001), 24% of businesses have experienced either an “inability to deliver orders or lost sales because of incorrect stock records.” While ERP systems have helped companies improve the availability and quality of transactional-level data, there is still room for improvement. In supply chains it is often not enough that accurate inventory data be available to one stage in the chain, rather data needs to be available across the chain. According to the PWC survey, “almost a third [of companies] lacked even the most basic requirement of having information systems shared across departments.” With supply chains cutting across companies, this suggests that data availability may continue to be a challenge in supply chain inventory control. Supply chain visibility software aims to take advantage of the Internet to improve data availability and is discussed in the next section.

Inventory planning refers to tactical and strategic decisions such as inventory level and location decisions. For these planning decisions data regarding longer term demand and supply characteristics (forecast accuracy, replenishment lead times and reliability, and processing costs among others) are often required. Motorola has reported that they “have had major [supply chain] software projects fail for lack of good data” (Betts 2001). In our experience data gathering is a critical and often time consuming step in any successful inventory initiative. Therefore, it is imperative to define early on the key parameters affecting the planning decisions being made. Often an initial rough-cut analysis can identify what parameters have the most impact on the decisions and then effort can be focused on obtaining accurate data for these sensitive parameters.

7.6. Impact of the Internet on Supply Chain Inventory

The Internet enables the cost effective transmission and sharing of information. By improving information availability the Internet can help reduce the safety stock required to support a given service level. Collaboration and visibility are two emerging Internet supply chain applications aimed at improving information availability.
**Collaboration:** Supply chain participants typically forecast customers’ future orders. Presumably customers have a better forecast of their own replenishments than their suppliers have. If suppliers have access to their customers’ replenishment forecasts, they should be able to reduce their safety stocks as forecast accuracy improves. Collaborative planning software tries to leverage the Internet to help companies share demand and replenishment forecasts. This software is still relatively new and has yet to become pervasive. While it offers the potential to improve supply chain performance, there are obstacles to successful adoption. The Internet has reduced one key obstacle; data exchange infrastructure costs are no longer as prohibitive as in the day of electronic data interchange (EDI) systems. The real barrier may now lie in business process design. The premise of collaborative forecasting is that companies cooperate. Close cooperation requires agreed business rules. Designing and agreeing on such rules can be difficult.

**Visibility:** Different parties in the supply chain often lack continuous information on the status of inventory levels, order progress, and shipments throughout the supply chain. Instead, they rely on periodic status reviews. This lack of continuous information drives up safety stocks because safety stock must cover the uncertainties during review intervals. Supply chain visibility software aims to reduce this supply chain uncertainty by continuously monitoring and sharing the supply chain status. Safety stock can be reduced because of this improved information.

The Internet brings with it exciting opportunities to improve supply chain inventory performance. Unfortunately, there is much hype surrounding the revolutionary impact of the Internet. In reality, the Internet’s impact is not revolutionary. It does not blow up the fundamental inventory tradeoffs; it does not alter the tradeoffs by reducing the costs of information transmission. Successful managers will recognize that they can use the Internet to improve their inventory performance by exploiting improved information. The chapter by Lee and Whang in this text provides much more detail about the impact of the Internet on supply chain integration.

### 7.7. Inventory for Service Parts and Reverse Logistics

The supply chain inventory story does not always end with the completion and sale of a final product. Sometimes the final product is an important piece of manufacturing service equipment and as such, the customer will want fast resolution of any product failures. Other times, the product is returned by the customer to the manufacturer for repair.

Timely product repair typically requires the availability of replacement parts. On-site repair will require service engineers to have access to a range of service parts. Choosing what service parts to carry and how much to carry are important inventory planning decisions for many companies. A key challenge in such systems is the selection of stocking locations—each field-based service distribution center and each service engineer’s vehicle might represent a potential stocking location. While spare parts inventory planning has been a focus of the military for decades, increased importance is being placed on this field in commercial enterprises. The emergence over the past decade of supply chain software companies focused on service logistics underscores this point. See Shapiro (2001) for a summary of the work...
carried out by Cohen et al. (1990) on a service parts inventory system, Optimizer, implemented at IBM.

Sometimes equipment is returned to the manufacturer for repair—for example aircraft engines. As inventory is flowing back in the supply chain, the term reverse logistics is often used. Spare parts inventory planning in this case is somewhat different from the field based inventory systems as the number of stocking locations can be orders of magnitudes lower. However, the logistics aspect can be more challenging; for example, there are cases where customers must receive the exact product they returned and not simply an identical product. Reverse logistics is not exclusively the domain of product repair supply chains. Some products are recycled for remanufacturing or reusability purposes. One-time-use cameras are a good example of a product with a supply chain in which key components such as the flash unit are recycled back into the production supply chain. Inventory planning in such cases needs to account for the opportunity to tap into this stream of components reentering the supply chain.

8. Conclusion

In this chapter we have identified the opportunities and challenges of managing inventories in a supply chain. We discussed the importance of inventory as well as the reasons it exists. We also reviewed increasingly sophisticated approaches for managing inventory that are being used by leading companies today.

Having worked with a number of companies across a wide range of industries, we offer the following inventory advice for supply chain practitioners. First, do not treat inventory costs as the poor stepsister to other Costs of Goods Sold (COGS) when making supply chain decisions. While each dollar of inventory may not translate into a full dollar of cost, the costs of inventory are significant and should not be underestimated or ignored. Second, do not use a one-size-fits-all inventory strategy. The technology (both math models and information technology) exists today to manage inventory in a smarter way. Take advantage of this technology to make sure you have the right amount of each SKU in the right place at the right time. Finally, use inventory as a strategic weapon to create competitive advantage through lower costs and/or better service. Look for opportunities to take advantage of risk-pooling or eliminate stocking locations, design products and supply chains to enable postponement, and collaborate with upstream and downstream supply chain partners. Companies like Dell and Wal-Mart have shown the gains that are possible through superior supply chain inventory management. It's not too late; there's still competitive advantage to be gained. However, as these approaches become more widespread, lean supply chains will be less of a differentiator and will instead become a competitive necessity.

9. Appendix: Base-Stock Inventory Model

This appendix presents an intuitive derivation of the key base stock equations. These equations have been applied with great success by a number of companies.
Recall that under a base stock policy, each planning period an order is placed to bring the inventory position up to the base stock level. Suppose the current planning period is at time \( t \). We will place an order to bring the sum of our inventory currently on-hand plus on-order to the base stock level \( B \). If \( R \) represents the time between successive planning periods (also known as the review period), the next opportunity to order will not occur until time \( t + R \). This next order will not arrive until \( L \) periods later, where \( L \) represents the replenishment lead time. Consequently, the inventory on-hand plus on-order at time \( t \) represents the total supply that we will have available to meet demand from time \( t \) until time \( t + R + L \). As a result, the base stock level \( B \) must be large enough to cover demand over the next \( R + L \) periods with the desired level of confidence (the service level). The sum of the review period and the lead time is often referred to as the exposure period since we cannot impact available supply within this window of time and are thus exposed to demand uncertainty over this period.

Expressing this in equations, we want to set the base stock level so that

\[
\text{probability}[\text{demand over exposure period} \leq \text{base stock}] = \text{service level}
\]

If we assume that demand over the exposure period is Normally distributed, this can be accomplished by setting

\[
\text{base stock} = \text{mean demand over exposure period} + (\text{safety factor} \times \text{standard deviation of demand over exposure period})
\]

where the safety factor is equal to the number of standard deviations of protection implied by the service level. The second term in the summation above represents the safety stock required to buffer against the uncertainty of demand over the exposure period. Sometimes demand will exceed its mean; other times it will be smaller than expected. On average, the inventory on-hand at the end of each review period will be the safety stock.

Note that each review period we place an order to replenish the demand that has occurred since the last review period. This order arrives \( L \) periods later and we gradually deplete it until the next order arrives \( R \) periods after that. This cycle of inventory build-up and drain-down is repeated over time. Since the average order is equal to the mean demand over the review period, the average amount of this cycle stock over time is equal to half the demand in a review period.

If we now consider the more general case where both demand and lead time are uncertain, the mean and standard deviation of demand over the exposure period can be derived under reasonable assumptions. Combining these well-established statistical results with the equations and observations above, we get the following results:

\[
\text{base stock} = \mu_D(R + \mu_L) + \text{safety stock}
\]

\[
\text{safety stock} = z \sqrt{\sigma_D^2(R + \mu_L) + \mu_D^2\sigma_L^2}
\]

\[
\text{cycle stock} = (R\mu_D)/2
\]

\[
\text{average on-hand inventory} = \text{safety stock} + \text{cycle stock}
\]
where
\[ \mu_D = \text{the expected (mean) demand per time period} \]
\[ \sigma_D = \text{the uncertainty (standard deviation) of demand per time period} \]
\[ \mu_{LT} = \text{the expected (mean) replenishment lead time} \]
\[ \sigma_{LT} = \text{the uncertainty (standard deviation) of the replenishment lead time} \]
\[ R = \text{the review or planning period (i.e., time between successive orders)} \]
\[ z = \text{the safety factor (a function of the desired service level)} \]

6 To accurately capture the uncertainty of demand, one needs to compare the forecast at lead time to the actual demand. While demand itself may be highly variable, if we can accurately forecast these changes in demand we do not need to hold as much inventory. Whenever possible the standard deviation of forecast error should be used to represent demand uncertainty in inventory models.

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