Supply Chain Logistics and Applications

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Dedication

This book is dedicated to my family—Rani, Apsara, and Vidhya—
and to the memory of my parents.

—Ananth Iyer

Introduction

This volume, Supply Chain Logistics and Applications presents an overview of supply chain functions such as logistics, purchasing, and transportation and then a closer applied study of each of several of types of Supply chains such as spare parts, groceries, apparel. It also includes full chapters on reverse logistics and humanitarian needs chains. The Four Cs framework is applied in these chapters as well. This volume, like it's companion, Introduction to the Four Cs of Supply Chains, is a derivative of the complete course text, Managing Supply Chains, which also includes teaching and learning support by way of homework problems and case assignments.

Preface

Why are there pictures of coffee, chocolate, cake, and coupons on the cover of this book? They were gifts from German students who had just finished my class on supply chain management and were intended to represent the Four C framework that underlies this book's content. In this book, however, the Four Cs are *Chain structure and ownership, Capacity, Coordination,* and *Competitiveness.* If you visualize the set of ordinary items on the cover of this book, you can use them as a mnemonic to remember the Four Cs of supply chain management—and we have accomplished a key goal of this book in this very first paragraph.

This book has been several years in the making. My goal is to bridge the gap between applications, tools, and concepts, linking ideas generated by researchers, practices described in the press, and tools that can be used to generate insights. Connecting these worlds, each of which has been developed by people passionate about supply chain management, will make for a smoother transition between theory and practice. This textbook is a static object that can serve as the start of conversations between you, your professor, your fellow students, your current or future work colleagues, and me, albeit remotely, engaging your heart and mind in understanding, managing, and enabling supply chain systems—leading to growth and commerce, while promoting sustainability. In order to support those conversations, I write a daily blog (http://aviyer2010.wordpress.com/) to cover current ideas linked to global supply chain management.

Supply chain management is primarily about a collection or a chain of companies that coordinate their activities and choose the appropriate capacities and some metric of competition to deliver a valuable product or service to customers. This activity is inherently global in many industries and is thus subject to the vagaries of economic shocks, political upheavals, weather-related disruptions, and many other factors. Ensuring that the supply chain keeps its commitment to customers requires planning, contracting to share risk, and adapting to changes in all functions and transactions. Ensuring that transportation capacity is available and deliveries take place as scheduled, suppliers invest effort, people, and resources to keep component designs competitive, and warehouses and associated inventories are deployed to optimize performance. These are a few examples of topics we will discuss in detail.

Information systems now have a ubiquitous presence, enabling customers to access data regarding products and schedules from product genesis to final delivery, and judge whether they approve. Virtually, the supply chain sits in a glass box, with every decision or choice documented and rated, thus impacting customer purchase decisions, the top-line revenue of the firm, and, finally, the bottom-line profits. Customers care about sustainable choices, and firms who recycle and reuse both reduce costs and attract customers. Matching information and material flows is key to effective supply chain management and sustainability.

This book is written to make you aware of the choices made by existing supply chain managers and to provide you with suggestions for alternate solutions as well as the tools to analyze their impacts. Vigilance about the competitiveness of current choices ensures that managerial interventions can be made when necessary to make course corrections.

Circumstances may require a shift to outsourcing from local sourcing, which may involve higher costs but also higher profits, if the resulting decisions are made quickly and adapt to current trends. For example, moving from a promotion-intensive retail environment to an every-day-low-price format may improve or decrease profits, depending on the context. The models and tools we will discuss will enable these decisions.

The concepts in this book have been tested on over a thousand students, and the book includes new cases developed to illustrate contexts based on my consulting and research experience. Several of the chapters are motivated by the content of research papers, which I have adapted to be accessible to students in a business school or an industrial engineering course. The problem sets provide many contexts to test your ability to apply the tools we will learn. The applications are highlighted with specific case studies, references to websites that provide updated content, and trade and government publications to let you gauge the financial impact of choices. Through this work, I hope you will be convinced and understand that supply chains can and do have a significant impact.

This book is built on the shoulders of insight generated by practitioners in industry, as well as by researchers and students in universities. But it would not have been possible without the support of my family, to whom I am eternally grateful. I am also grateful for the environment in the operations management group, and all the faculty colleagues and graduate and doctoral students at the Krannert School of Management here at Purdue, where I have been fortunate to try out many of these concepts on students. I take responsibility for any errors and have endeavored to acknowledge all sources for their input.

I would like to acknowledge the many coauthors and students over the years who have made the journey to write this book memorable. My students and now faculty include professors Apurva Jain at the University of Washington at Seattle; Jinghua Wu at Renmin University; Zhengping Wu at Singapore Management University; Mohammad Saoud at Kuwait University; Hung Do Tuan at the University of Vermont; Asima Mishra at Intel Labs; and Kyoungsun Lee, now in South Korea. Other collaborating faculty whose insights and research influenced and are represented in this book include Professors Sridhar Seshadri at the University of Texas at Austin, Arnd Huchzermeier at WHU-Koblenz, Vinayak Deshpande at the University of Texas at Austin, Svenja Sommer at HEC Paris, and Lee Schwarz at Purdue University. I deeply appreciate the opportunity to work with each of them.

The following colleagues provided detailed reviews and hundreds of very thoughtful and valuable suggestions for improvement to this text. I am very grateful to each and hope each will be pleased with how it has turned out.

Sridhar Seshadri, University of Texas, Austin
Apurva Jain, University of Washington, Seattle
Mark Ferguson, Clemson University
Vijay Kannan, Utah State University
Corrington Hwong, Baruch College, The City University of New York
Adam Rapp, Kent State University
Howard Kreye, University of New Mexico
Paul Hong, University of Toledo

My publisher, Dick Hercher, has been a staunch advocate of this book through its many manifestations—I hope you enjoy his efforts and enable his fledgling company to soar. Jennifer Murtoff, the copyeditor, has been a diligent and effective advisor, turning notes into precise text and reminding me time and again of the reader's perspective. My daughters Apsara and Rani have suffered through many years of hearing about the Four Cs (which I tried out on them during their elementary school years), and my wife Vidhya has endured the long journey of this book from start to finish—I thank them for their patience and support on this journey.

So please enjoy this book, and, if you can, drop me an email so that I can learn of your experience with it. If you decide to make a career in managing supply chains, you will find a large global community ready to welcome your ideas. Enjoy the ride and remember the Four Cs described in this book.

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CHAPTER 1

Transportation

The role of transportation in a supply chain is to change the physical location of products and get supplies to the demand location. Transportation in the United States in 2012 was a $760 billion industry, with truck transportation accounting for 78% of domestic movement ([12]). A large portion of this market, around 70%–80%, is accounted for by contract trucking, where a trucking company operates as a dedicated carrier for the user during trips. The location of suppliers, intermediate processing plants, final assembly plants, finished-goods warehouses, customers, and so on, and their respective decision making regarding the transportation carriers used, determine the chain structure that has to be supported by transportation flows. The choice of transport mode (truck, rail, or air), and the associated capacity, e.g., container size, wagon load, or truckload, determine the size of shipments and thus the frequency of deliveries required to satisfy demand. The nature of the coordinating contract, e.g., spot capacity, core carrier programs, volume commitments, and so on, determine the impact of coordination agreements on transportation flows. Finally, the performance of a transport mode is determined by the metrics of its competitiveness, i.e., minimum cost, on-time delivery guarantees, dynamic routing, downstream services, as well as the availability of credible alternative carrier choices and their capacity.

Of the $1.2 trillion spent in 2010 in the United States on logistics costs, with $2.06 trillion of inventory, transport accounted for over

63% of the total expense ([12]). The industry is competitive, with over 10,000 trucking companies declaring bankruptcy over a two-year period. Indeed, it is probably appropriate to visualize a mode management terminal as similar to the National Aeronautics and Space Administration's (NASA's) flight control center, with streams of data flowing into a central hub, and dispatch decisions being fed back to truck drivers, with everything being monitored by a global positioning system (GPS) for location and speed.

A similar transport picture exists in Europe, where trucks account for about 75% of surface freight, while trains provide less than 20% of the capacity. The river primarily plays the role of feeder traffic for merchant shipping—but has the potential to play a much bigger role in the future. Auto companies such as Nissan and Honda use inland barges, an effective approach to transport about 30%–40% of their automobiles. Reports suggest that Nissan achieved this efficiency by using barges to transport vehicles from Amsterdam, the Netherlands, to Warth, Germany, and then delivering them by truck to their final destination ([94]).

Intuitively, it is clear that each mode choice has its unique cost structures, shipment volumes, and delivery lead times. Large-volume shipments at low transport costs per unit with long lead times favor rail. Smaller-volume shipments with higher costs per unit and faster delivery favor truck. An even more rapid delivery requirement with significantly higher costs per unit favors air. Barge shipments by river and shipments by sea further differentiate transportation cost choices. The appropriate question then is how to integrate transportation into a supply chain's architecture.

1.1 Transportation Transactions and Supply Chain Architecture Interactions

1.1.1 Chain Structure

Because the role of transportation is to move product between supply chain locations, the locations of entities in the supply chain and the magnitude and frequency of material flows have a significant impact on this function. The nature of material flows also impacts the choice of transportation mode and thus the shipment size that proves most economic. In addition, the location of suppliers and customers affects the feasibility of backhaul (or continuous) moves, that is, shipments on trucks during their return to the source, as a means to reduce overall costs. In a global supply chain, the wide dispersion of locations means that different transport modes and their associated lead times will impact overall supply chain cost. There may also be cost differentials in different directions. In 2006, the cost to move a 20-foot container from the United States to China was $200, while the cost to ship a container from China to the United States was $1400, about seven times higher [44]. Such distortions have significant impacts on optimal supply chain flows.

1.1.2 Capacity

Transport capacity varies by choice of transportation mode. Shipments by sea are measured by container size, shipments by rail use wagon capacity, shipments by truck involve full truckload, and shipments by air may vary depending on the trade-off between weight and volume. In addition, while air shipments may provide the lowest lead time for transit, costs are such that these shipments usually involve light, smaller-volume quantities. The truck capacity decisions associated with transportation may involve planning the number and location of trucks, location and capacity of crossdocks, and capacity of terminals, roads, and tracks. Finally, routing choices for transportation can impact the timing and capacity available in a supply chain.

1.1.3 Coordination

A shipper and a shipping company can coordinate based on advance information regarding planned shipments, the creation of preferred carriers who manage the bulk of the loads, delivery window guarantees, and so on. Crossdocking is a process that involves linking truckload arrivals from different suppliers to truckload deliveries to retailers in order to convert static inventory into rolling stock, thus decreasing overall inventory levels and delivery lead times. Implementing crossdocking requires coordination of deliveries within specified time windows, linking containers from truck to rail, and allowing volume and schedule commitments to enable continuous routes. For rail shipments, coordination issues include planning routes, tracking containers along routes, managing blocking and bracing, coordinating local pickup or delivery at both ends, and shipment preparation. Shipments by barge involve coordinating material handling at the barge terminal and managing hand-offs to trucks at terminals. Finally, many shipping companies guarantee delivery within specified time windows, which generates contractual or pricing agreements to guarantee their feasible execution.

1.1.4 Competitiveness Measures

For shippers and transportation providers, an important metric is the total supply chain cost of transportation transactions. This total supply chain cost includes the effect on both transport costs and associated inventory costs. In addition, measures of performance include delivery lead time, percent on-time delivery or delivery within time windows, and schedule flexibility to accommodate shipment reschedules. Given the large volume of shipments that occur on dedicated contract trucking, there is scope for use of information, coordination agreements, and associated capacity commitments to improve performance across a supply chain. Competing carriers sell bundled routes to minimize shipper costs.

1.2 A Shipping Company Context

ABC Rail faced the following problem: How should the company convince shippers of the benefit of its services relative to other modes of transport? How could the company adjust its schedules to be competitive in the marketplace? Reducing costs for rail shipments involves maximizing the number of wagons hitched to the engine, because once a trip is chosen and all labor, fuel, and track access charges are evaluated, the goal is to minimize costs. Each successive wagon thus increased the cost to ABC Rail by a small margin, hence the benefit of long trains.

While rail offered low transport costs, it also involved larger delivery sizes and longer transit times and thus higher inventories across the supply chain. In addition, waiting to ship loads meant that shippers faced a longer and potentially more variable lead time. This impact on lead times increased costs for the shipper. How should ABC Rail generate competitive schedules that could win business while still being profitable?

Perhaps it would help to view the decision from the perspective of the shipper. The shipper had to contend with the transport costs, inventory costs, other incidental costs as a total supply chain cost effect. Would it help if ABC enabled customers to evaluate the total supply chain cost of alternatives? If salespeople for ABC Rail could get an idea of competitive total supply chain cost by customer route, then ABC could identify how to adjust schedules and decide the number of wagons to wait for in order to beat the competition. Such an approach, repeated over and over across customers, would generate a customer-responsive train freight schedule. ABC had heard of an initiative by Burlington Northern called ShipSmart, which offered a similar service to shippers. Should ABC Rail use such an approach?

1.3 Total Supply Chain Costs and the Impact of Transportation Mode

Consider a retailer in location B who purchases product from a supplier in location A. Customer demand at location B is satisfied from stock at a warehouse at B. The retailer takes possession of goods at A and arranges transport, manages inventories and order placement, and so on. The retailer can choose any mode of transport to get product from A to B. How should the retailer take account of total supply chain costs in making this decision?

There are three separate categories of costs that are considered:

1. **Transport Costs:** These costs are a function of transportation mode used. Assume that full truck- or full carload shipments are used and that transport capacity is not shared with any other products. This minimizes transport cost per unit on the route and therefore is the natural choice for transportation managers who seek to minimize transport costs alone.

   Given its larger capacity, rail transportation will be lower per unit shipped than truck, thus a goal to minimize transport costs will result in choice of large loads moved infrequently. If the transport capacity is C and the demand rate is D, the transport cost per unit for full load shipments is $\frac{KD}{C}$.

2. **Inventory Costs:** This cost category examines the effect of transit times (both mean, variance, and shipment size) on inventory. Under this category, we consider three sets of inventory levels.
   a. **In-transit Inventory:** This refers to goods that are on the trucks or railcars in the process of being moved from the source to destination. The average value of in-transit inventory is just the demand rate times the transit lead time: $D \times L$. This inventory level increases as the average transit time increases. Note that in-transit inventory is independent of the shipment size. This is because the inventory policy is assumed to follow a replenishment system whereby the order releases track demands. Thus doubling the shipment size merely halves the shipment frequency, leaving the in-transit inventory unchanged. The cost of this in-transit inventory is thus $h \times D \times L$ where h is the holding cost per unit of inventory.
   b. **Cycle Stock:** This refers to inventory levels required to satisfy expected demand. Thus, if we assume there is a constant and an average demand each period, the average inventory level is half the order size per cycle. If there are Q units in each delivery, the cycle stock will be $\frac{Q}{2}$ (see the section on economic order quantity [EOQ] in Chapter 15 for details). The cost associated with the cycle stock will be $h\frac{Q}{2}$.
   c. **Safety Stock:** This refers to inventory required to meet variable demand or effects of transit time variance. Typically the safety stock level is chosen to guarantee a certain probability of having no stockout. Assuming a normal distribution of demand over the delivery lead time, a standard deviation of demand over lead time of σ_{DL}, and an in-stock probability of *ser* (the service level), the safety stock is $Z_{ser}\,\sigma_{DL}$. The associated holding cost is $hZ_{ser}\sigma_{DL}$.
3. **Blocking and Bracing Costs:** These are costs applicable for rail car shipment where the product in the car must be "carefully packaged to prevent damage" for protection. This is usually a per-shipment charge.

1.4 An Example Problem

Fixit is a hardware chain focused on do-it-yourself customers. Fixit operates in the Pittsburgh area and has a distribution center that receives shipments from its supplier, Acme, located in Seattle, Washington. Demand at Fixit each month is 30,000 packs of bulky widgets. Currently shipments from Acme to Fixit are sent by truck. The capacity of a truck is 5,000 packs. Transit time for the truck from Seattle to Pittsburgh is 5 days. In addition, analysis of the data shows that the lead time has a standard deviation of 2 days.

Fixit's accounting group has estimated that the annual holding cost is 20% of the cost of the product. Acme supplies a case of widgets for a price of $15 per pack. Assume a desired service level of 95% and a current safety stock of 1 day of inventory at Pittsburgh to counter delivery lead time variation. The cost for a truckload shipment from Seattle to Pittsburgh, by third-party carrier, is $3,000.

1.4.1 Truck Shipments

1. **Transport Cost per Month:** Given Fixit's demand of 30,000 packs per month and the truck capacity of 5,000 packs, the system needs $\frac{30{,}000}{5{,}000} = 6$ shipments/month. The monthly cost of these truck shipments is $6 \times \$3{,}000$ per truckload $= \$18{,}000$ per month.

2. **Inventory Related Costs:**
   a. **Cost of In-Transit Stock:** The monthly demand of 30,000 packs, with each pack spending an average of 5 days in transit, implies that we have $\frac{30{,}000 \times 5}{30} = 5{,}000$ packs of in-transit inventory. Using a holding cost of $0.20 \times \$15$ per pack per year or $\frac{\$0.20 \times 15}{12}$ per pack per month $= \$0.25$ per pack per month, we get a holding cost of $1,250.

   b. **Cycle Stock Cost:** Since order size is one truckload, cycle stock is $\frac{5{,}000}{2}$ or 2,500 packs. Thus the monthly holding cost of cycle stock is $\$0.25 \times 2{,}500 = \$625$.

c. **Safety Stock Cost:** The safety stock covers the demand during the variability of lead time and is expressed as $Z_{services}D$, where σ is the standard deviation of lead time (in days) and D is the daily demand. Thus the safety stock carried at Pittsburgh to deal with transit time variability is $1.65 \times 2 \times 1{,}000 = 3{,}300$ packs. The holding cost of this safety stock is $0.25 \times 3{,}300 =$ \$825.

Thus total supply chain inventory cost is \$1,250 + \$625 + \$825 = \$2,700.

Thus total supply chain cost is \$18,000 + \$2,700 = \$20,700.

1.4.2 Total Supply Chain Costs Using the Existing Rail Option

Railcar, a rail brokerage that works closely with railroads to schedule shipments, has made Fixit an offer to move product. Railcar also coordinate schedules with the railroads to improve supply chain costs for shippers. The current offer by Railcar is a shipment price of \$6,000 for one wagonload of widgets from Seattle to Pittsburgh. The capacity of a wagon is 15,000 packs. Transit time is expected to be 15 days with a standard deviation, based on current performance, of 10 days.

If Fixit were to use rail to ship product from Seattle to Pittsburgh, what would be the impact on total supply chain costs?

1. **Transport Costs per Month:** As before, we take the average of the rail shipments 30, 000 each month and multiply it by the cost per rail shipment to get $\frac{30{,}000}{15{,}000} \times 6{,}000 = \$12{,}000$ per month.
2. **Inventory Costs:**

   a. **Holding Cost of In-transit Inventory:** The in-transit inventory is obtained as $\frac{30{,}000 \times 15}{30} = 15{,}000$ packs. The corresponding holding cost is $0.25 \times 15{,}000$, which is \$3,750.

   b. **Holding Cost of Cycle Stock:** The cycle stock level is $\frac{15{,}000}{2} = 7{,}500$ packs. Thus, the holding cost of this cycle stock is $0.25 \times 7{,}500 = \$1{,}875$.

c. **Safety Stock Holding Cost:** The safety stock held to compensate for transit time variability is $1.65 \times 10 \times 1{,}000 = 16{,}500$ packs. Thus the holding cost of this safety stock is $0.25 \times 16{,}500 =$ \$4,125.

The total of supply chain inventory costs is \$3,750 + \$1,875 + \$4,125 = \$9,750.

The total of supply chain costs for shipping by rail is \$12,000 + \$9,750 = \$21,750.

Notice that the total of supply chain costs for the the rail proposal is more than truck. However, the observed train average lead time and associated lead time variance is based on the current mode of minimizing costs to ship by rail. This suggests that using rail mode creates a lead time due to the need to maximize the number of wagons and to route the wagons to minimize costs. This is similar to trying to minimize costs for a set of trips made by airplane—often the cheapest route involves going through airline hubs. However, as in the airline case, it may be possible to reduce lead time, increasing the transportation cost, and yet make it profitable for the shipper. The shipper can choose alternate modes of transportation, resulting in market pressure, which requires the train schedules to be competitive and profit maximizing rather than cost minimizing and thus potentially not generating revenues. We explore such an adjustment in Section 1.4.3.

In particular, consider an alternate proposal for the rail option, whereby the trains travel at a lower average lead time that is less variable. Since transport cost per unit of train shipments is low, these lower average lead time and less variability could reduce both the in-transit inventory holding costs to ship by rail and the associated safety stock. We examine next the impact of these changes on the total supply chain cost experienced by the shipper.

1.4.3 A Revised Rail Option

Railcar has developed another shipping proposal by coordinating with the railroads so that the cost to ship remains the same but delivery performance is improved. Railcar's proposed schedule drops the transit time to 10 days and the variation in transit time to 3 days. This may increase actual rail operating costs but may also increase revenues if it generates supply chain costs that are more competitive than truck shipments. What is the impact of this schedule on total supply chain costs at Fixit?

1. **Transport Costs:** The transport costs per month remain the same as in the previous scenario: $\frac{30{,}000}{15{,}000} \times 6{,}000 = \$12{,}000$ per month.
2. **Inventory Costs:**
   a. **In-Transit Inventory Costs:** The in-transit stock is $\frac{30{,}000 \times 10}{30} = 1{,}000$ cases with a holding cost of $\$0.25 \times 1{,}000 = \$2{,}500$.

   b. **Cycle Stock Costs:** The level of cycle stock is determined by the shipment size and is $\frac{15{,}000}{2} = 7{,}500$ packs. The associated holding cost is $\$0.25 \times 7{,}500 = \$1{,}875$.

   c. **Safety Stock Costs:** The safety stock held to compensate for transit time variability is $1.65 \times 3 \times 1{,}000 = 4{,}950$ packs. Thus the holding cost of this safety stock is $0.25 \times 4{,}950 = \$1{,}237.50$.

   The total of supply chain inventory costs is $\$2{,}500 + \$1{,}875 + \$1{,}237.50 = \$5{,}612.50$.

The total supply chain cost is $\$12{,}000 + \$5{,}612.50 = \$17{,}612.50$.

1.4.4 Mode Choice and Its Impact on the Supply Chain

The example above shows the impact of competing modes of transport, creating schedule changes that increase the competitiveness of rail. In this case the chain structure involved four companies: Acme, the transport company (and possibly a transport broker like Railcar), Fixit, and Fixit's customers. Railcar had to identify its competitiveness by examining the impact on total supply chain costs. Railcar then had to coordinate with railroads to adjust their schedules so that transit times could be improved and variation decreased. The larger capacity for rail shipments provided a lower cost per unit but correspondingly increased Fixit's cycle stock inventory in Pittsburgh. Railcar was able to improve the supply chain architecture because it understood the impact of the current supply chain architecture on Fixit's mode choice decision and adjusted the architecture to become competitive relative to other mode choices.

1.5 Using Coordination Agreements to Improve Transportation Systems

Coordinating agreements can be implemented between a shipper and a transport provider to improve performance. Consider a supply chain consisting of suppliers, manufacturing plants, and customer locations. In the original system, suppose each plant runs as an independent profit center, choosing its own transportation. To create scale economies as well as increase the fraction of line and backhaul routes, an alternate system can be implemented to coordinate across locations and with a transport company. Consider the potential impact on the system as it transitions from independent transport choices to a corporate load control center that enables performance improvement.

There are several companies that face such a transition, especially during establishment of a core carrier program. There is an important difference between centralization of transportation and coordination of transportation. Under a centralized system, a central entity decides how to handle all loads. Under a coordinated system, the load control center offers possible delivery times and defines associated costs, but the individual locations make the final decision. Thus in a coordinated system, individual profit centers decide on the tradeoff between customer service and related costs and revenue benefits.

1.6 Reynolds Metals and Core Carrier Programs

This section summarizes the article in [88]. In 1988, Reynolds Metals Corporation was a $6.2 billion company that carried a variety of aluminum-intensive products—from aluminum foil to airplane parts. Reynolds had 120 shipping locations and 5,000 shipping destinations and used 200 van and flatbed carriers. Reynolds prided itself on being a decentralized corporation where the local plant manager chose the transport with an emphasis on quick delivery to meet customer schedules. Reynolds spent $80 million in transport costs. Transport was handled by over 200 trucking companies, each working with a particular location or shipping lane. The net results were low use of continuous loads, low volume discounts due to the small volume with each trucking company, and poor on-time delivery performance. Reynolds management wanted to realize the benefits of coordination between loads without eliminating the flexibility afforded to each location.

Reynolds needed to create a corporate logistics entity to provide reduced costs and improved service. The company created a load control center (LCC) to coordinate loads across locations and offer larger volumes to trucking companies without centralizing decision making. When a location was planning to ship a load, the LCC would choose a trucking company, quote a price, and provide an estimated delivery time to the shipping location. LCC would then select from a small subset of trucking companies that would get an annual volume commitment in return for lower prices and a higher service level. Next Reynolds needed to identify a way to share demand risk (for trucks) with the trucking company so as to improve performance for both shipper and shipping company.

The LCC needed to identify loads in opposite directions that could be combined to create continuous moves. This would enable reduction of deadhead moves (return trips without a load) by the trucking company and thus reduce costs for Reynolds and the trucker. Such moves require flexibility regarding ship times and delivery times, a decision that only the local manager can make. Suppose the LCC could offer the opportunity to reduce shipping costs by coordinating loads. Assuming local plants are profit centers, the choice for a location is based on the benefit of lower shipping costs vs. the flexibility to deliver the loads. In addition, if the LCC could guarantee delivery reliability and tracking of deliveries by pooling all transactions, that increases the benefits for individual locations.

Reynolds achieved a $7 million annual reduction in transport costs, which consisted of a 70% reduction due to volume buying, and a 30% due to a 600% increase in continuous moves while increasing on-time delivery from 80% to 95%. This was achieved along with reducing the number of transport companies from 200 to 5 van carriers and 8 flatbed carriers. How are such dramatic improvements achieved within a corporation?

1.7 Coordinating Freight Operations—Core Carriers and Pareto Improvement

To understand the benefit of a coordination approach to improve performance, consider a change from an arm's-length relationship to one that is based on a risk-sharing agreement in the transportation context. We show that risk-sharing coordinating agreements can improve the performance of both the shipper and the carrier, thus generating Pareto-improving performance. Pareto-improving performance requires that no participants to the agreement are worse off, and at least one of them is better off, than before.

Recall the Reynolds Metals case discussed in Section 1.6. This example shows how a volume commitment can be used to get a cost reduction and improved service while generating Pareto-improving benefits for the carrier.

1.7.1 The Impact of Truck Volume Commitment—An Example

Consider a supply chain consisting of a manufacturer (Smart) who requires trucks to pick up material from one location every day to be delivered to a customer. The number of trucks required by Smart varies daily. A histogram of the history of daily truck usage indicates the following probability distribution (Table 1.1):

Table 1.1 Daily truck usage

Trucks Required	Probability
0	0.2
1	0.2
2	0.2
3	0.2
4	0.1
5	0.1

The data above suggest that a trucking company providing trucks faces demand risk because on 20% of the days Smart will require no trucks, while on 10% of the days Smart will require 5 trucks. The next step is to understand how a carrier has to plan capacity to make trucks available to Smart. Smart has contacted a trucking company (Quick) that will supply these trucks. Smart notifies Quick of the trucks it will need on a given day, and Quick sets them aside the day before they are needed. It costs Quick $100 to make a truck available. The current agreement between Smart and Quick is as follows: If Smart uses a truck on any day, Smart pays Quick $200 per truck. However, if a truck requested by Smart is not available at Quick, Quick pays Smart a penalty of $200 per truck. In that case, Smart has to pay a spot rate (market rate without a contract) for transportation of $900 per truck to have shipments handled by another trucking company.

1.7.2 Profits at Quick and Costs to Smart with No Coordination

Question 1: How many trucks will Quick commit to maximize its expected profit each day?

Note that Quick and Smart are separate companies, each seeking to optimize their performance. Thus, Quick will choose a planned capacity to maximize its profits. Suppose Quick commits T trucks. The corresponding expected profit for Quick is as follows:

$$-100T + \sum_{i=0}^{T} 200 \times i \times p_i + \sum_{i=T+1}^{5} 200 \times T \times p_i - \sum_{i=T+1}^{5} 200 \times (i - T) \times p_i$$

Suppose $T = 3$, the expected profit for Quick, is as follows:

$$-100 \times 3 + \{(200 \times 0 \times 0.2) + (200 \times 1 \times 0.2) + (200 \times 2 \times 0.2) + (200 \times 3 \times 0.2)\} + \{(200 \times 3 \times 0.1) + (200 \times 3 \times 0.1)\} - \{(200 \times 1 \times 0.1) + (200 \times 2 \times 0.1)\} = 0$$

A summary of Quick's expected profit under different numbers of committed trucks is as follows (Table 1.2):

Table 1.2 Expected profit with no coordination

Trucks Committed	Quick's Expected Profit
0	– 420
1	– 200
2	– 60
3	0
4	– 20
5	– 80

Thus committing 3 trucks maximizes Quick's expected profits.

Note, of course, that the problem faced by Quick is a classic newsvendor problem. The optimal solution to the newsvendor model is to first determine the cost per unit short, C_s, and the cost per unit of excess inventory, C_e. In this case, C_s is equal to the sum of lost profits plus the penalty $= (200 - 100) + 200 = 300$. Also, C_e is equal to the cost of the truck (assuming that it has to be held on standby the whole day and thus cannot be deployed for other purposes) $= 100$. Thus the optimal critical fractile $\dfrac{C_s}{C_s + C_e} = \dfrac{300}{300 + 100} = 0.75$. The lowest capacity that provides this desired service level is three trucks (observe that at three trucks, the cumulative probability is 0.8). The optimal capacity thus coincides with the results observed from Table 1.2.

Question 2: What is the impact of Quick's decisions on Smart's costs?

Given Quick's decision to reserve 3 trucks, Smart's expected cost is as follows:

$$(0.2 \times 1 \times 200) + (0.2 \times 2 \times 200) + (0.2 \times 3 \times 200) \\ + (0.1 \times \{(3 \times 200) + (1 \times 900) - (1 \times 200)\}) \\ + (0.1 \times \{(3 \times 200) + (2 \times 900) - (2 \times 200)\}) = \$570$$

Note that if demand by Smart is for three or fewer trucks, the entire demand is satisfied by Quick. If demand is for four or five trucks, then Quick satisfies the demand for three trucks, and the unfulfilled demand is satisfied by Smart from the spot market with associated penalty payments by Quick. While this maintains service level for Smart's customers, it does require Smart to scramble to satisfy demand.

1.7.3 Impact of a Volume Commitment by Smart

Can an agreement between Smart and Quick improve their respective performance measures, i.e., increase expected profits for Quick and decrease expected costs for Smart? In order to devise such an agreement, consider the fact that Quick has to balance the potential revenues from high truck demand with the potential costs associated with unused trucks if demand is low. One approach is for Smart to decrease demand risk for Quick by offering a take-or-pay contract in return for a higher service level commitment.

Consider the following contract: "Smart guarantees use of at least two trucks every day, i.e., Smart will pay Quick at least $400 every day, even if Smart does not need two trucks. In return, Smart demands a 100% service level from Quick."

How will this affect Quick's expected profits and Smart's costs? Note that under this scheme, Quick has to commit at least two trucks.

Quick's expected profit is as follows:

$$=(-100 \times T)+\sum_{i=0}^{2} 400 \times p_i+\sum_{i=3}^{T} 200 i p_i$$
$$+\sum_{i=T+1}^{5} 200 \times T \times p_i-\sum_{i=T+1}^{5} 200 \times (i-T) \times p_i$$

Table 1.3 Expected profit with volume commitment

Trucks Committed	Quick's expected profit
2	60
3	120
4	100
5	40

The table shows that to offer a 100% service level, Quick has to reserve five trucks and that Quick can commit up to five trucks and still improve its expected profit.

The impact of Quick's commitment of five trucks on Smart's expected costs is as follows:

$$(400 \times 0.2) + (400 \times 0.2) + (400 \times 0.2)$$
$$+ (0.2 \times 3 \times 200) + (0.1 \times 4 \times 200) + (0.1 \times 5 \times 200) = \$540$$

The results show that the agreement between Quick and Smart results in an increase in expected profit for Quick from $0 to $40 and a decrease in expected costs for Smart from $570 to $540. Thus, in this example, both Quick and Smart improve their performance and Smart's service level from Quick increases from 80% to 100%. Such an agreement can be considered to be Pareto improving.

Note that similar calculations show that if Quick commits three trucks, Smart's costs are $690; if Quick commits four trucks, Smart's costs are $590. Thus only a 100% service level commitment by Quick creates a Pareto-improving system.

The example discussed shows that take-or-pay commitments can potentially permit both cost reductions and service-level improvements. The Reynolds case suggests that the company saw significant performance improvement as a result of a combination of both volume commitments as well as coordinated volume buying due to the aggregation of moves throughout the system. The example suggests that adjusting the supply chain architecture (changing the coordination agreement and thus adjusting the capacity) can improve the competitiveness of the supply chain as a whole.

1.8 E-Commerce and Transportation

The transportation industry was impacted by the rise of the dot com companies and consequent use of competition across carriers as a mechanism to improve transport costs for a shipper. In these markets, transport services face an important spatial dimension that affects costs ([111]): (1) where a truck ends its journey affects how valuable it is to handle follow-on loads and (2) the ability to develop balanced networks allows carriers to maintain equipment regularly at fixed locations and get their drivers home frequently and predictably. Thus the bids offered by a carrier to a shipper depend on how the loads carried for one shipper will interact with loads carried for other shippers in order to permit effective utilization of the carrier's assets over time. E-commerce hubs for transportation use auctions as a mechanism to increase the range of participants, thus potentially lowering costs.

1.9 Transportation Auctions

Transport costs depend on the location of the pickup and delivery points and thus rely on the spatial link to other routes served by the trucks. In addition, the cost to a trucking company to service a shipping lane from Chicago to Los Angeles (LA) depends on what is committed in the Los Angeles-to-Chicago direction. Thus, if another lane, say St. Louis to Chicago, is part of the return trip, then the transport company may be able to offer a better deal for the combined Los Angeles-to-Chicago and St. Louis-to-Chicago routes than for the sum of the individual routes bid separately ([77]).

Ledyard et al. ([77]) provide the following example that clearly illustrates the impact of spatial demand on costs. A retail company requires five truckloads from Los Angeles to Chicago, seven truckloads from Chicago to New Orleans, and ten truckloads from New Orleans to Los Angeles. One solution is to lease ten trucks and use them to complete the moves. But what if there are three trucking firms with the same costs but different customer bases? Firm 1 has five loads from Chicago to Los Angeles and a current return trip that generates a revenue of X. Firm 2 has ten loads from New Orleans to Chicago and a current return trip that generates a revenue of Y. Firm 3 has ten loads from New Orleans to Los Angeles and a current return trip with a return revenue of Z. If the cost to ship from Los Angeles to Chicago is $> X$, then any price that is such that $X <$ *price* $<$ *cost* (*LA to Chicago*) generates benefits to both Firm 1 and the retail company. Similarly Firms 2 and 3 would be willing to carry the loads for prices that exceed Y and Z respectively. However, notice that Firm 3 would be willing to transport loads from LA to Chicago and from Chicago to New Orleans for any price greater than $Z +$ *cost* (*LA to Chicago to New Orleans*) $-$ *cost* (*LA to New Orleans*). Notice that the price for a lane is a function of the revenue currently generated for the return legs for travel by the three firms, which in turn is affected by the revenues generated in the outgoing legs of travel. This spatial link between loads shipped currently and the impact of the economics of return moves makes the transport industry pricing decisions complex.

In practice, the shipper would seldom know about the revenues earned during the return trips for transport firms. Auctions allow transport companies to reveal as much of this information as possible out of a desire to win the bid. The following examples provide such initiatives at two companies.

1.9.1 Sears Logistics Service

Sears Logistics Services (SLS) is a wholly owned subsidiary of Sears, Roebuck and Co., and is one of the world's largest procurers of trucking services.

SLS controls the movement of products from vendor to distribution center to stores. Ledyard et al. ([77]) describe an application of combined value auctions for transport services at SLS. This approach was used to purchase 1,390 lanes of transport services for $597 million. Over a three-year period, SLS saved more than $84.75 million by running six such auctions.

An outline of the approach used is as follows: A subset of fourteen national and regional carriers was identified and given exclusive rights to provide a sealed bid during the auction. At the end of the round, the auctioneer announced provisional winners and revealed all the winning bids. The next round was open only to the winning set of carriers, who would bid against the current provisional winners. If total acquisition cost did not decline by a fixed percent over the previous round, the just-completed round would be declared the final round.

The bids submitted by carriers were input into a computer simulation that modeled a shipping lane scenario. The winning bids adequately provide transportation while preventing the total number of trucks from exceeding carrier specified capacity. The goal was to maximize the surplus for the shipper, defined as the amount below the shipper's reservation price. The details of the model used to select the winning bids and allocation will be provided in section 1.9.3.

The key decisions that supported this transportation auction include the description of the ending round, the training of suppliers as they put together bids, and the process of selection of winning carriers between rounds.

1.9.2 The Home Depot

The Home Depot also uses transportation auctions ([34]). The Home Depot was founded in 1978 in Atlanta, GA. Home Depot is the world's largest home improvement retailer. The 1,000 stores are supplied by thirty-seven distribution centers in forty-five states. The supply chain includes over 7,000 suppliers who provide over 40,000 SKUs to stores and DCs across locations. Over 90% of the products move on trucks. In 1999, the company made 7.1 million less-than-truckload shipments and 219,000 full truckload shipments. These were expected to change to 4.7 million less-than-truckload and 877,000 full truckload shipments in 2003.

Until 1996, the Home Depot asked carriers to submit bids on a standard Excel spreadsheet. Procurement still continued by lane separately, and thus carriers were unable to make informed bidding decisions that reflected synergies across lanes. Carriers also did not have adequate visibility of demand across Home Depot's network.

A new bidding process was announced in January 2000. Before the bidding process started, carriers were provided data regarding origin and destination locations, lane details, and demand forecasts. Carriers were permitted to bid on individual lanes or on groups of lanes. Lane groups represented geographic areas or groups of facilities or were customized by the carrier to fit into an existing schedule. There were also no constraints on the number of bids for a lane and the combinations of bids that could be offered. Carriers were also allowed to specify constraints across bids so that the resources required were available. The penalty for not having the resources to service a winning bid was that the carrier lost all of the lanes that had been awarded.

The bids were accepted at sealed-bid, single-round auction. Once bids were submitted, Home Depot solved an integer program whose goal was to (1) provide service on all lanes; (2) allocate a lane to one single carrier; (3) select allocations that satisfied shipper and carrier constraints; and (4) meet nonprice goals such as carrier reliability, load balancing among carriers, preferences to incumbents, hub locations of carriers, safety ratings, and so on. In other contexts [111], the shipper may adjust shipper bids based on its on-time delivery performance and its importance to the recipient.

The model used by the Home Depot to choose successful carriers is described in Section 1.9.3. In October 2000, the bidding was carried out with 111 carriers. The bidding process was expected to involve one round only, but decisions were made for 80% of the lanes in round one. For the remaining 20% of the lanes, Home Depot held a second round of bidding and invited sixty-two bidders, of which thirty-six submitted bids. Even after this round, some lanes were not covered because Home Depot felt that carriers available for some lanes were not acceptable. The average number of carriers bidding on each lane was 14, with a minimum of two and a maximum of 33 across lanes. Home Depot claimed that it received lower rates, while carriers expressed satisfaction from the part of the business they were awarded.

1.9.3 Selecting Carriers

Given bids from many independent carriers that specify the rate by lane or by groups of lanes, the minimum expected number of trucks by lane segment, the demands for trucks by lane, as well as the maximum rate the shipper would be willing to pay per lane, the goal of the model is to help the shipper select a prescribed number of different carriers that will satisfy carrier demand at minimum cost.

Suppose R_l refers to the reservation rate for lane l (the reservation rate for a package k, R_k would be the sum of the reservation rates for the lanes in the package); b_{jk} refers to the minimum dollar amount needed by firm j to supply package k; u_{jk} refers to the capacity estimated by firm j for package k; $U(j)$ is firm j's total capacity; x_{jkl} is 1 if firm j's package k contains lane l as part of the package and 0 otherwise; $d(j,k)$ is 1 if firm j's package k is selected, 0 otherwise.

The model will seek to maximize $\Sigma_{j,k}(R_k - b_{jk})d(j,k)$

subject to

$\Sigma_{j,k}x_{jkl}d(j,k) \leq 1$ for all lanes l

$\Sigma_k u_{jk}d(j,k) \leq U(j)$

$d(j,k) = 0$ or 1

The model described above permits the shipper to incorporate carrier cost structure into the choice of carriers that will minimize costs. There have been several experimental investigations of such bidding schemes that will provide outcomes that maximize carrier surplus. The approaches used by Sears and the Home Depot represent two such schemes.

1.10 Chapter Summary

For supply chains, transportation flows enable products or components to change location, thus enabling them to be used at their demand points. The timing of these transportation flows in turn interacts with transport capacity and chain structure to impact supply chain performance. Given this interaction, the total supply chain impact of a choice of transportation flows has to include transport costs, cycle stock costs, safety-stock costs, and in-transit inventory costs. For each possible transport mode, there are different impacts on associated capacity and transit time. Thus, optimal transport mode requires consideration of the impact of different components of the supply chain costs and thus may impact associated capacity. The core carrier program discussion shows how a coordination of transportation using a Pareto-improving contract with carriers can decrease supply chain costs and increase on-time delivery. Given that the carrier industry is competitive, a company can use auctions as a mechanism to permit transport bundles to be bid on by carriers, thus decreasing overall costs. This chapter focuses on transportation decision impact of capacity, coordination with carriers, chain structure, and competitive benefits—all the four Cs associated with effective supply chain management.

CHAPTER 2

Warehousing

The use of just-in-time inventory at manufacturing plants and dispersed production of components have increased the need for inventory management and therefore warehousing operations in the supply chain. The *competitiveness* metrics of performance for a warehousing function include inventory turns, productivity (lines per hour), inventory availability, or cost performance. The location of warehouses within the *chain* structure assigns its role as a buffer against supply disruptions if it is located upstream or as a catalyst for efficient plant production scheduling while providing promised delivery performance if it located downstream. The *capacity* of the warehouse is determined both by its physical size and flow management capability, as well as the nature of the resources used for warehouse management: automatic, manual, or hybrid material handling systems. In addition, the number and locations of the warehouse doors determine the feasibility of handling crossdocking operations. Finally, *coordination* agreements (such as vendor-managed inventory) developed with suppliers impact the performance of the warehouse.

2.1 Delco Electronics Case

A study ([9]) described General Motors (GM) as carrying over $7.4 billion in inventory and incurring $4.1 billion in freight costs in 1984. The questions the study explores are the following: How could this total supply chain cost be decreased? Could the approach be used by decision makers throughout the GM system to impact supply chain costs and thus improve performance?

In 1984, Delco Electronics, which was a division of GM, faced a problem. Three component plants, in Matamoros, Mexico, Milwaukee, WI, and Kokomo, IN, supplied radios, heater controls, electronic modules respectively to thirty GM assembly plants located throughout the country. Figure 2.1 shows the location of the supplier component and assembly plants. The original supply chain configuration used full truckload shipments from component plants to a consolidation warehouse in Kokomo. From this consolidation warehouse, full truckload shipments containing a mix of radios, heater controls, and electronic controls were shipped to each assembly plant. Delco wanted to identify alternate ways that product could be moved from component plants to assembly plants to decrease the $11.2 million in inventory costs.

Figure 2.2 shows seven possible solutions for the problem. The routes examined included direct shipments from component plants to assembly plants, shipments through the warehouse, peddling (whereby trucks, originating from component plants, would make deliveries across various assembly plants), and combinations of such strategies. For each route, the shipment size could be full truckloads or the optimal shipment size. Figure 2.2 also shows the composition of transport and inventory costs in each of the seven possible logistics systems.

The alternatives described in Figure 2.2 indicate the many different ways to manage the network of warehouses and associated transportation.

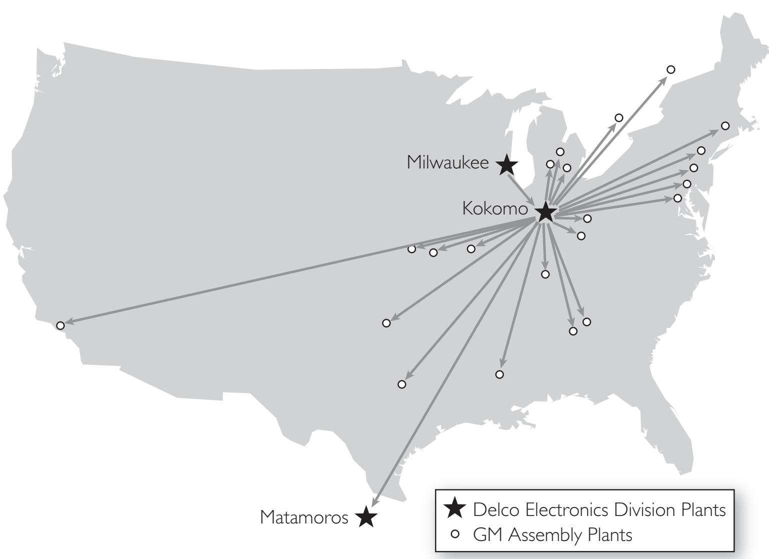

Figure 2.1 The Delco Electronics supply chain subset

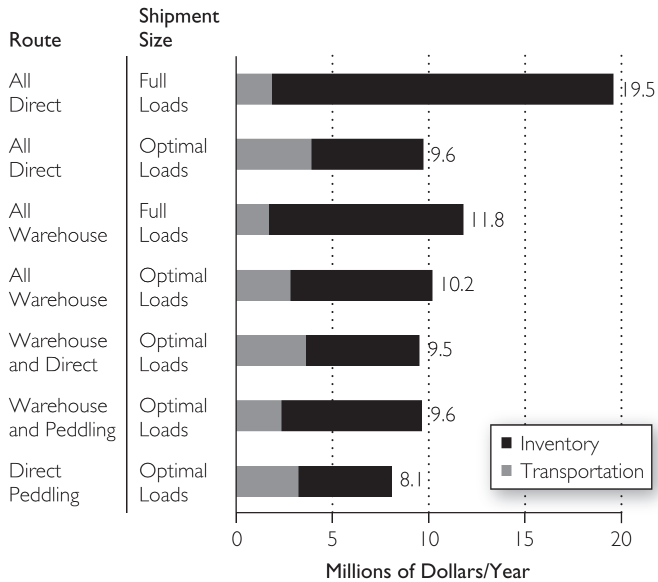

Figure 2.2 Seven possible solutions for the Delco Electronics supply chain

Each of these flows is impacted differently by business conditions, thus changing the ideal choice over time. The role of the analysis was to both identify and quantify the impact of each of these choices.

GM devised an easy to use software to calculate the costs for each of these alternatives. The resulting approach, Transpart II, has been used at over forty locations producing annual savings ranging from $35,000 to $500,000. When used at Delco, Transpart II saved over 26% of logistics costs for an annual savings of over $2.6 million. The implemented solution at Delco involved speeding up the material handling at the Kokomo warehouse from two days down to half a day and peddling out of the Milwaukee warehouse. Projected savings were expected to increase as holding costs increased.

2.2 Merloni Elettrodomesticii Case

Merloni Elettrodomesticii is an Italian appliance manufacturer that sells white goods: washers, dryers, dishwashers, refrigerators, and so on ([56]). Merloni had promised all retailers delivery of orders within twenty-four hours. This arrangement was part of the guaranteed service that enabled Merloni to have a dedicated set of retailers who sold its product to the Italian consumer.

Merloni had five plants spread throughout Italy. Each plant had a focused product line with focused plants enabled substantial scale economics as well as a consistent approach to choice of technologies and equipment. The products from each plant were shipped to a central warehouse in Fabriano. From Fabriano, products were shipped to a network of seventeen regional warehouses, using long-haul trucks. Each regional warehouse then shipped orders to retailers within twenty-four hours of receipt of the order. Merloni carried a total of 14,330 units in finished goods inventory at the warehouses.

A bold experiment, the Transit point experiment, focused on the Milan warehouse, which was cleared of all inventory. Orders would be placed every day by the manager at Milan and transmitted to Fabriano. Trucks would be loaded and arrive in the morning at the Milan warehouse. Goods would be crossdocked into smaller trucks and delivered to retailers. With this new system, retailers continued to receive orders within twenty-four hours and were unaware of the change in regional warehouse inventory. This approach, if expanded through the Merloni network, had the potential to reduce operating costs by up to 80%. The new network required close coordination between regional warehouse, central warehouse, and plants to ensure product availability, minimal disruptions, and reduced costs.

2.3 Letin Electronics Case

Bill Rogers faced a problem. As warehouse manager for Letin Electronics, he knew that his presence in the logistics network facilitated system-wide cost reductions. Letin's five focused plants shipped to Bill's consolidation warehouse. Bill then shipped to twenty-five distribution centers that supplied large distributors of Letin's products. But the current corporate staff at Letin was hard pressed to generate a return on investment (ROI) for Bill's operation. Costs incurred by the warehouse and his component of costs as a percentage of sales were easy to calculate. But the system-wide return that he generated was more complicated. How could Bill justify that his costs actually saved money overall for Letin Electronics?

Bill suggested the following thought experiment: Suppose Bill's warehouse were shut down. How would Letin operate and supply its distribution centers? A quick calculation provided the total supply chain costs that would be incurred under this alternate system. Inventories would increase at distributors as Letin would try to manage transport costs by shipping full truckloads. Distribution centers would have to expand and carry more inventory of full truckload shipments from plants. Could the difference between the costs in that configuration and the current costs provide an estimate of the benefits of Bill's warehouse? If that difference were significant compared to Bill's costs of operation, would that generate an ROI that corporate could use to decide the fate of the warehouse? How robust would that decision be to changes in transport costs and holding costs?

2.4 Problem Abstraction and Analysis

Each of the three problem contexts described earlier has the following basic structure: A set of sources of supply has to be linked by a supply system to a set of demand locations. Figure 2.3 shows the supply and demand nodes for Delco (three supply nodes and thirty demand nodes). Merloni had five supply nodes and seventeen demand nodes. Letin had five supply nodes and twenty-five demand nodes. Notice that in the Delco case, the flows from supply to demand nodes consist of components used to assemble cars. In the Merloni and Letin cases, the flows consist of finished goods from assembly plants to locations closer to customers. But the abstraction of these problems has the same structure. What are possible ways to create a supply chain from these supply locations to the demand locations?

One approach is to focus on minimizing the transport cost per unit. Under such an objective, it is best to ship directly from supply to demand points. Figure 2.3 shows the direct shipping for the Delco supply chain, which would result in ninety shipping lanes. Figure 2.4 shows a direct shipping approach for the Merloni case that would result in 105 shipping lanes. Finally, Figure 2.5 shows the direct shipping lanes for Letin, which would result in 100 shipping lanes.

A second approach is to ship from all supply points to a single consolidation warehouse. Then mixed shipments would go from this warehouse to the demand locations. Figures 2.6 through 2.8 show the supply chain flows through a consolidation warehouse. Under such a supply chain, Delco would have thirty-three shipping lanes. The Merloni system would have twenty-two shipping lanes, and Letin would have twenty-nine shipping lanes.

A third approach would be to create routes that start from each supply location and visit a set of demand locations that would share the truck capacity (i.e., peddling routes). Figure 2.9 shows such a system for

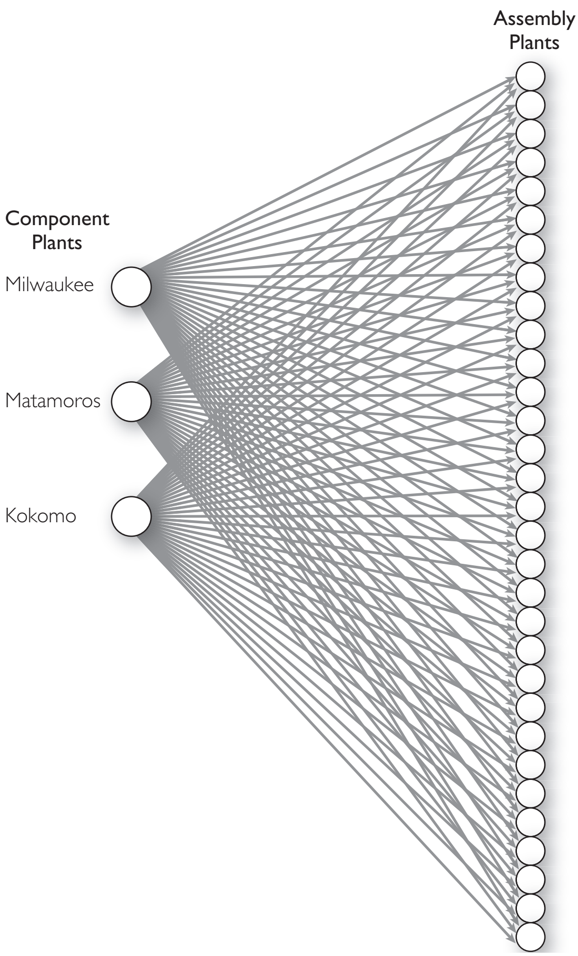

Figure 2.3 Direct shipping for the Delco supply chain

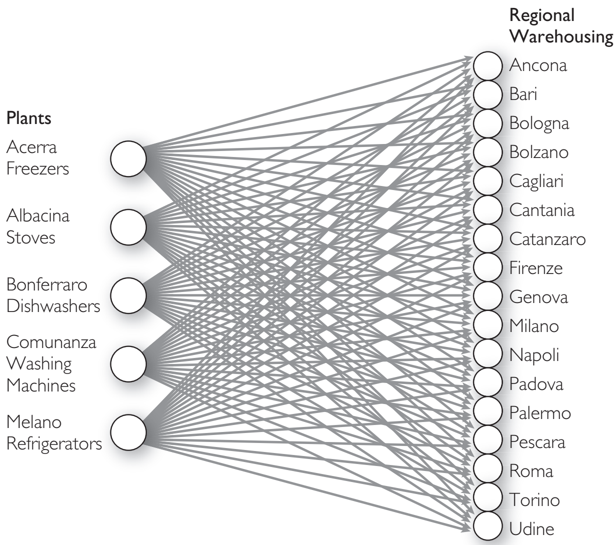

Figure 2.4 Direct shipping for the Merloni case

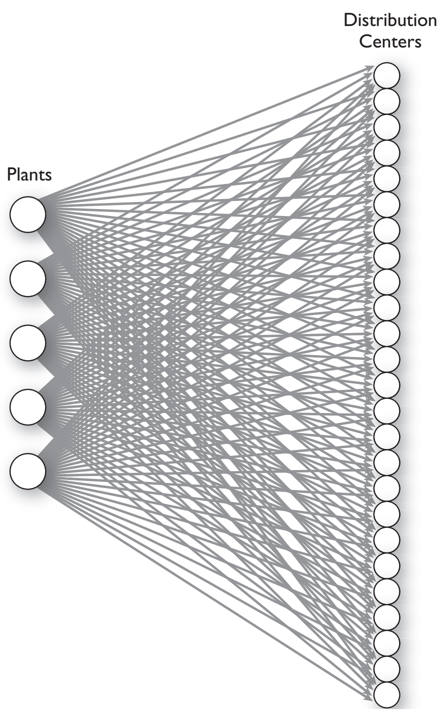

Figure 2.5 Direct shipping for the Letin case

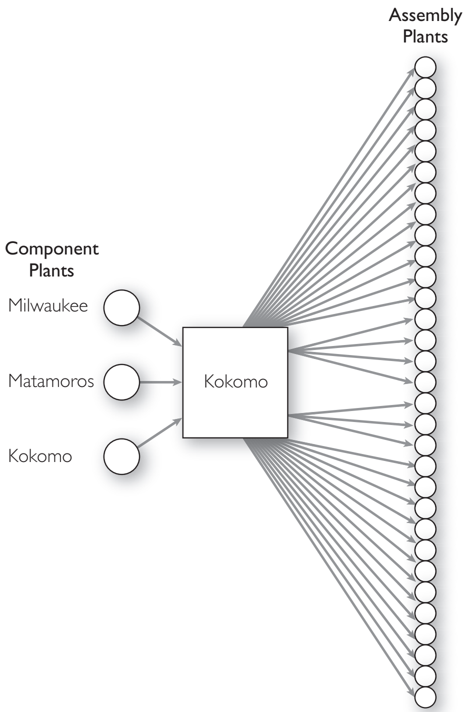

Figure 2.6 Consolidation warehouse for the Delco supply chain case

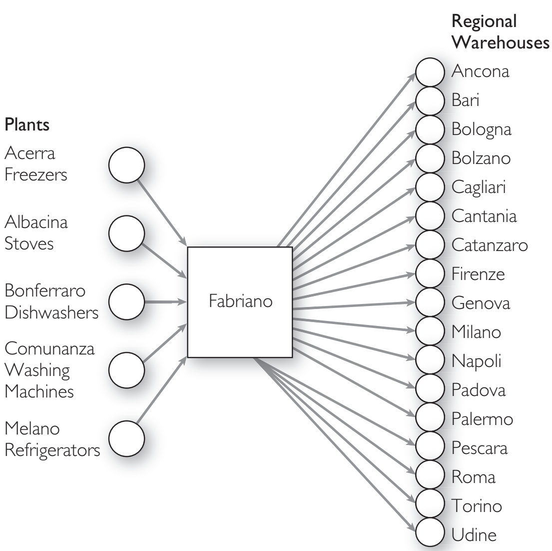

Figure 2.7 Consolidation warehouse for the Merloni case

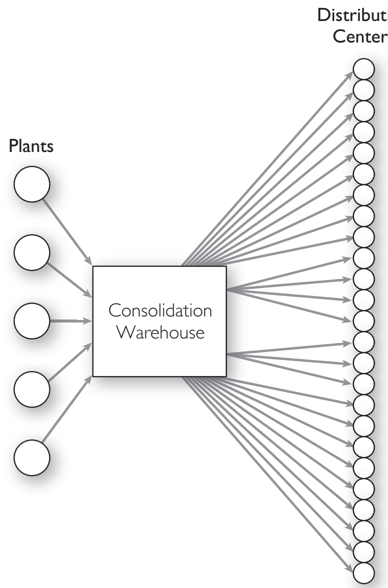

Figure 2.8 Consolidation warehouse for the Letin case

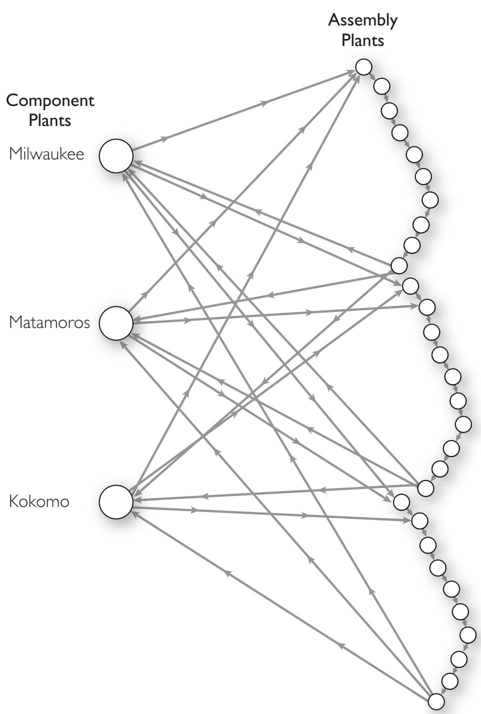

Figure 2.9 Delco supply chain with direct peddling routes

the Delco Electronic case. Under such a supply chain, the number of shipping routes would depend on the number of demand points sharing trucks from a common supply point.

In addition to the choices above, there can be a number of hybrid versions of the supply chain architecture. The appropriate choice clearly affects the performance of the supply chain architecture.

2.5 Total Supply Chain Costs

Total supply chain cost is the sum of inventory, transport, warehousing, and routing costs. This cost is affected by the structure of the chain, capacity of transportation, required coordination between locations for managing consistent operation, and competitiveness of the mode used, which will affect costs and the competitiveness of the business environment, thereby affecting the desired service required.

The components of the total supply chain cost are

1. **Transport cost per unit time:** Across each shipping lane, suppose the capacity of transport is C. Let the amount shipped during each delivery be Q. To be feasible, we need to ensure that $Q \leq C$. Assume the demand that generates flows on this lane is D per unit time.

   Then to satisfy the demand rate, deliveries must be received every $\frac{Q}{D}$ periods. If the transport cost per delivery on this lane is K, then the transport cost per unit time is $K\frac{D}{Q}$.

   Notice that in the absence of any other costs, it is optimal to ship at full mode capacity.
2. **Cycle stock at demand points:** When demand points receive delivery, the quantity delivered is Q, described earlier. This delivered quantity may be greater than the demand each period. If so, the demand location carries cycle stock, which is the average inventory across successive deliveries.

   If profile of inventory is observed between successive deliveries, then note that the inventory starts at a level of Q and drops to zero just before the next delivery is received. (Note that in the presence of any uncertainty, safety stock would have to be carried over and above the cycle stock.) Given a demand rate of D, the time for the delivery to run out would be $\frac{Q}{D}$ periods. The average inventory level is thus the ratio of the area implied by the inventory, which is $\frac{Q^2}{2D}$ divided by the length of the cycle, which is $\frac{Q}{D}$ periods. This ratio is thus equal to $\frac{Q}{2}$. The holding cost per unit of product per unit time reflects the costs associated with carrying inventory. This marginal cost can include (1) the cost to finance this inventory or the opportunity cost associated with it, (2) the insurance costs against shrinkage or damage, (3) the obsolescence-related costs if the inventory has to be salvaged, (4) storage costs. These costs reflect the system-wide impact if inventory is carried in a supply chain.

3. **Intransit inventory costs:** When inventory is shipped from the supply point, we assume that title for the goods passes to the buyer, who then arranges all transport. Thus the buyer is responsible for the inventory of goods in transit between supply and demand points. What is the level of inventory in transit from the supply to demand points?

   Note that supply chains are replenishment systems, thus the average amount shipped should match the average demand. If the transport lead time were L, the average in transit inventory is LD. Notice that this is just Little's law from queueing theory, which says that the average work in process inventory is equal to the demand rate times the average lead time through the system.

   Given a holding cost per unit per unit time, the associated in transit inventory cost is hLD. Note that the average in transit inventory is independent of the shipment size Q but only depends on the transport lead time and the demand rate.

4. **Safety stock costs:** If the demand time, the transit time, or both are uncertain, it may be necessary to carry inventory as a buffer against demand uncertainty. As discussed earlier, the extent of this inventory buffer depends on the magnitude of the demand uncertainty during the supply lead time and the planned in-stock service level. If the planned in-stock probability is expressed as *service* and the demand over lead time has a standard deviation of σ_{DL}, then the safety stock level is expressed as $Z_{service} \times \sigma_{DL}$. (Note that we assume that

demand follows a normal distribution as an approximation: there are more detailed models available.) The associated holding cost is $hZ_{service}\sigma_{DL}$.[1]

2.6 Computing Total Supply Chain Costs—An Example

The Optima Corporation produces two different types of widgets, A and B. Each widget type uses two components, 1 and 2. Widget A requires two units of component 1 and one unit of component 2 per unit of widget A. Widget B requires two units of component 2 and one unit of component 1 per unit of widget B.

Widget A is manufactured at a plant in Boston, MA. The plant produces 100 units of widget A each day. Widget B is manufactured at a plant in Jersey City, NJ. The plant produces 100 units of widget B each day.

Component 1 is manufactured at a plant in Santa Fe, NM, and component 2 is manufactured at a plant in Portland, OR.

Products are shipped in full truckloads directly between plants: Full truckloads of component 1 are shipped from Santa Fe to the Boston plant and from Portland to the Jersey City plant. Similarly, full truckloads are shipped from the Portland plant to the Boston plant and from the Portland plant to the Jersey City plant (Figure 2.10).

Holding cost is estimated to be \$0.40 per component per day for both components. Both components have similar physical volume. Each truck can hold 3,000 components (of either component 1 or 2). Each truckload shipment costs \$4,000 between either pair of locations, i.e., Portland to Boston, Portland to Jersey City, Santa Fe to Boston, or Santa Fe to Jersey City. Travel time between any of the location pairs is estimated to be six days.

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[1] If demand is normally distributed with mean μ_D and standard deviation σ_D and the lead time is normally distributed with mean μ_L and standard deviation σ_L, then the demand during the supply lead time is distributed with a mean $\mu_{DL} = \mu_D \times \mu_L$ and the standard deviation of demand during lead time is $\sqrt{\mu_L \sigma_D^2 + \mu_D^2 \sigma_L^2}$

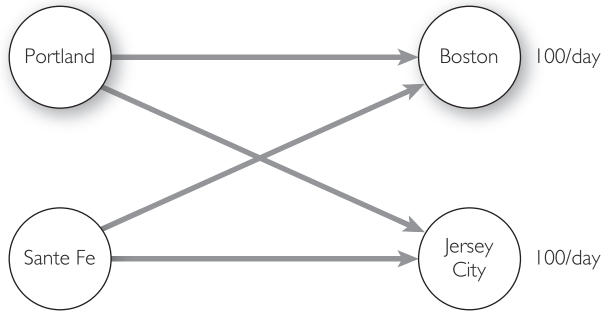

Figure 2.10 The Optima direct shipping supply chain

2.6.1 A Minimum Transport Cost Supply Chain

Notice that minimizing transport costs is equivalent to using a full truckload direct shipment system. The next steps will provide details of the total supply chain costs for this mode of operation.

Cycle Stock Costs: Given the full truckload shipments, the size of the deliveries of each component received by each assembly plant is 3,000 units. In the absence of demand uncertainty at each plant, the next truck delivery would be scheduled when the components in this delivery are consumed. This means that the inventory level cycles between 3,000 and 0 units. The average inventory is thus the average height of a right triangle whose height is 3,000 units and whose base is $\frac{3{,}000}{D}$ where D is the demand rate. Thus the average height of this triangle is $\frac{3{,}000}{2}$. This average inventory multiplied by a holding cost per unit per unit time provides the cost associated with cycle stock carried at the assembly plants.

Thus, the holding cost of the cycle stock of component 1 at Boston is

$$0.4 \times 3{,}000/2 = \$600/\text{day}$$

(In the above calculation, 3,000 is the truck capacity, 3,000/2 is the average inventory level at Boston and 0.4 is the holding cost per day provided in the problem.)

Similarly, the holding cost of the cycle stock of component 2 at Boston is:

$$0.4 \times 3{,}000/2 = \$600/\text{day}$$

The holding cost of the cycle stock of component 1 at Jersey City is:

$$0.4 \times 3{,}000/2 = \$600/\text{day}$$

The holding cost of the cycle stock of component 2 at Jersey City is:

$$0.4 \times 3{,}000/2 = \$600/\text{day}$$

Thus total cycle stock holding cost across the two components and at the two assembly plants is $2,400/day.

In-Transit Inventory Costs

The average in-transit inventory between any two locations is equal to

$$\text{Transit time} \times \text{Demand rate}$$

Notice that the equation above is Little's law, which states that the average number of units in a queue is the demand rate times the average lead time. Little's law links lead time to work in process inventory. In our case, the inventory in transit is work-in-process inventory between the component plant and the assembly plant where it is required. Once we get the average in-transit inventory, we merely have to multiply it with the holding cost per unit per unit time to get the holding cost associated with the in-transit inventory.

Using this relation, we get

In-transit inventory holding cost between Santa Fe and Boston (component 1):

$$0.4 \times 6 \times 200 = \$480/\text{day}$$

In-transit inventory holding cost between Portland and Boston (component 2):

$$0.4 \times 6 \times 100 = \$240/\text{day}$$

In-transit inventory holding cost between Santa Fe and Jersey City (component 1):

$$0.4 \times 6 \times 100 = \$240/\text{day}$$

In-transit inventory holding cost between Portland and Jersey City (component 2):

$$0.4 \times 6 \times 200 = \$480/\text{day}$$

Thus, total in-transit inventory holding cost between all component plants and assembly plants = \$1,440/day.

Transport Cost

We now focus on the average transport cost between every pair of locations in the supply chain. Shipment sizes refer to full truckloads and routes are direct from component plant to assembly plant. Thus the corresponding transport cost obtained is the minimum possible value.

Average transport cost per day from Santa Fe to Boston:

$$\$4{,}000 \times 200/3{,}000 = \$266.67/\text{day}$$

(In this calculation, \$4,000 refers to the cost for one truckload, 3,000 is the truck capacity, and 200 is the demand rate for component 1 at Boston.)

Average transport cost per day from Santa Fe to Jersey City:

$$\$4{,}000 \times 100/3{,}000 = \$133.33/\text{day}$$

Average transport cost per day from Portland to Boston:

$$\$4{,}000 \times 100/3{,}000 = \$133.33/\text{day}$$

Average transport cost per day from Portland to Jersey City:

$$\$4{,}000 \times 200/3{,}000 = \$266.67/\text{day}$$

Total transport costs = $800.00/day

Thus the total supply chain cost across all locations = $2,400 + 1,440 + 800 = $4,640/day.

2.6.2 *Optimal Shipment Sizes and Their Impact on Supply Chain Cost*

Suppose Optima were to replace full truckloads by optimal shipment sizes. How would the optimal shipment sizes be determined? Given the symbolic description earlier, consider the expression for the total logistics cost for a component from its component plant to the assembly plant. This total logistics cost is expressed as

$$\frac{KD}{Q} + \frac{hQ}{2} + (hDL)$$

Figure 2.11 shows the three components of the total logistics cost. Given the shape of these costs, the optimal shipment size calculated above, if feasible, is the one at which the average transport cost equals the average holding cost. The corresponding shipment quantity is obtained as

$$Q^* = \sqrt{\frac{2KD}{h}}$$

Note, however, that once this quantity is obtained, feasibility of implementation requires that this quantity not exceed truck capacity. If it does exceed capacity, then it is optimal to ship at full capacity. Thus the optimal shipment quantity would be set as minimum $\{Q^*, C\}$ where C refers to the truck capacity.

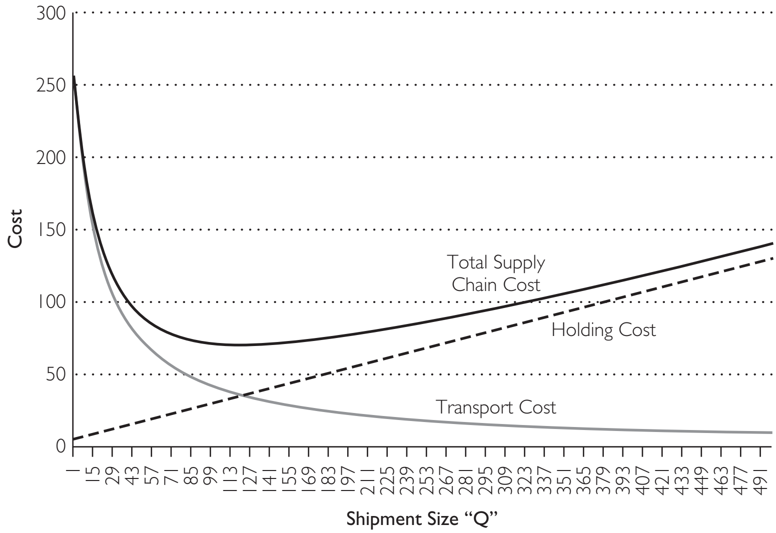

Figure 2.11 Cost components and optimal shipping quantity

Thus the shipment sizes and the associated total supply chain costs for Optima can be computed as follows:

Optimal shipment size from Santa Fe to Boston (EOQ):

$$\sqrt{\frac{2 \times 4{,}000 \times 200}{0.4}} = 2{,}000$$

(In the above expression, \$4,000 is the fixed ordering cost for one truckload, 200 is the demand for component 1 at Boston each day, and 0.4 is the holding cost per unit per day.)

Note that the above computation suggests that it is optimal to ship at less-than-full truckload, thereby reducing truck capacity utilization.

Similarly, the optimal shipment size from Santa Fe to Jersey City (EOQ):

$$\sqrt{\frac{2 \times 4{,}000 \times 100}{0.4}} = 1{,}414$$

The optimal shipment size from Portland to Boston (EOQ):

$$\sqrt{\frac{2 \times 4{,}000 \times 100}{0.4}} = 1{,}414$$

The optimal shipment size from Portland to Jersey City (EOQ):

$$\sqrt{\frac{2 \times 4{,}000 \times 200}{0.4}} = 2{,}000$$

Note that since all of the optimal shipment sizes are below the truck capacity, it is optimal to ship these quantities. Recall, however, that trucking costs will still be assessed at full truckload levels.

Given these optimal shipment sizes, the associated costs are calculated as follows:

Cycle stock costs:

Boston (component 1) holding cost:

$$0.4 \times 2{,}000/2 = \$400.00/\text{day}$$

Boston (component 2) holding cost:

$$0.4 \times 1{,}414/2 = \$282.80/\text{day}$$

Jersey City (component 1) holding cost:

$$0.4 \times 1{,}414/2 = \$282.80/\text{day}$$

Jersey City (component 2) holding cost:

$$0.4 \times 2{,}000/2 = \$400.00/\text{day}$$

Total cycle stock holding cost = $1,365.60/day

In-transit costs:

Verify that these costs remain the same, and the total in-transit cost = $1,440.00/day

Transport costs:

Santa Fe to Boston (component 1):

$$\$4{,}000 \times 200/2{,}000 = \$400.00/\text{day}$$

Santa Fe to Jersey City (component 1):

$$\$4{,}000 \times 100/1{,}414 = \$282.80/\text{day}$$

Portland to Boston (component 2):

$$\$4{,}000 \times 100/1{,}414 = \$282.80/\text{day}$$

Portland to Jersey City (component 2):

$$\$4{,}000 \times 200/2{,}000 = \$400.00/\text{day}$$

Total transport cost = \$1,365.60/day
Total supply chain cost = \$1,365.60 + 1,440 + 1,365.60 = \$4,171.20/day

How did the total supply chain cost decrease even though the transport cost increased from the earlier value of \$800 to the new value of \$1,365.60? Notice that given the holding cost, optimizing the transport cost forced high levels of inventories at the assembly plants. Shipping less-than-truckloads increases the transport costs but decreases the corresponding inventory costs. The net result is that the total supply chain cost is decreased by changing the composition of the total cost. This trading off of local costs to decrease global costs is a basic idea in many supply chain management contexts.

The managerial implication is that to realize these savings, it is important to create accountability for these total supply chain costs whereby the supply chain manager has responsibility for the total cost. In the absence of such managerial responsibility, it is difficult to realize such adjustments and thus such savings. This is one of the reasons why supply chain management requires a senior management position that can affect such changes and thus realize supply chain savings.

2.6.3 *Impact of Adding a Warehouse*

Optima is considering the option of establishing a consolidation warehouse at Chicago. In the new system, full truckloads of components 1 and 2 would be shipped to Chicago from Portland and Santa Fe. These trucks would have a capacity of 3,000 units and would deliver to Chicago once every ten days.

The transport cost of a truckload is \$2,500. Travel time between locations is estimated to be three days.

Once every five days, a truck would leave Chicago with 1,500 units of component 1 and 1,500 units of component 2. This truck would travel three days. The Boston plant would receive 1,000 units of component 1 and 500 units of component 2, and the Jersey City plant would receive 1,000 units of component 2 and 500 units of component 1.

Holding cost at Chicago is also \$0.40 per component per day.

Provide the total logistics costs for this logistics system.

Figure 2.12 provides a map of the corresponding supply chain.

Given the role of the warehouse in Chicago and the shipment schedule, here are the calculations:

Cycle stock costs:

Boston (component 1):

$$0.4 \times 1{,}000/2 = \$200/\text{day}$$

Boston (component 2):

$$0.4 \times 500/2 = \$100/\text{day}$$

Jersey City (component 1):

$$0.4 \times 500/2 = \$100/\text{day}$$

Jersey City (component 2):

$$0.4 \times 1{,}000/2 = \$200/\text{day}$$

Chicago (component 1):

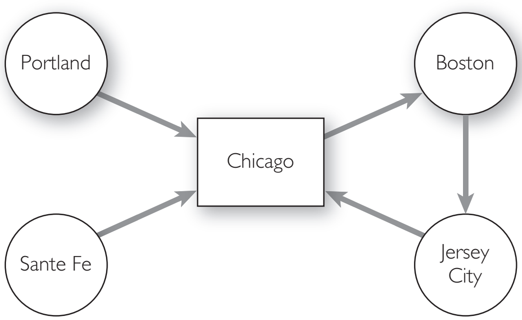

Figure 2.12 The Optima supply chain with the Chicago warehouse

Note that Chicago receives a shipment of 3,000 units from Santa Fe every ten days and ships out 1,500 units every five days to the east coast. Thus the cycle stock at Chicago during every ten-day cycle is 1,500 units for the first five days of the cycle and zero units for the remaining five days. Thus the average cycle stock of component 1 at Boston is

$$((5 \times 1{,}500) + (5 \times 0))/10 = 750$$

The associated cycle stock cost = 750 × 0.4 = \$300/day

Chicago (component 2):

$$0.4 \times ((5 \times 1{,}500) + (5 \times 0))/10 = \$300/\text{day}$$

Thus, total cycle stock cost = \$1,200/day

Transport cost:

Santa Fe to Chicago:

$$\$2{,}500 \times 300/3{,}000 = \$250/\text{day}$$

Portland to Chicago:

$$\$2{,}500 \times 300/3{,}000 = \$250/\text{day}$$

Chicago to Boston and Jersey City:

$$\$2{,}500/5 = \$500/\text{day}$$

Thus, total transport cost = \$1,000/day

In-transit inventory costs:

Santa Fe to Chicago:

$$0.4 \times 3 \times 300 = \$360/\text{day}$$

Portland to Chicago:

$$0.4 \times 3 \times 300 = \$360/\text{day}$$

Chicago to Boston and Jersey City:

$$0.4 \times 3 \times 600 = \$720/\text{day}$$

Total in-transit inventory costs = \$1,440/day

Thus total logistics costs = \$1,200 + 1,000 + 1,440 = \$3,640/day

Note that this results in a \$1,000/day savings over the scenario in Section 2.6.1. These savings can be used to pay for the managerial expertise required to manage the warehouse and schedule routes at Chicago as well as to pay for any fixed costs to acquire the warehouse at Chicago.

How were these savings realized? They required sharing of the outbound trucks across components and across the assembly plants, using the consolidation warehouse to continue to have full truckload shipments, managing the warehouse to realize crossdocking savings, and so on. In short, the reduction in costs per day is the direct result of supply chain management actions in the modified system. Note that this estimate of savings per day can be treated as the return on investment in the costs related to supply chain management.

2.7 Supply Chain Issues to Consider in Europe

Europe is densely populated, with over 85% of the population of 335 million living within a 500-mile radius. But the presence of many independent countries in Europe and the consequent regulation and political boundaries create unique supply chain challenges. Reference [94] provides a summary of many issues that have to be considered in managing supply chains in Europe. Some of the major characteristics of European logistics are

- Many companies make extensive use of local warehouses, often with one warehouse in each country of operation.
- The supply chain keeps small amounts of widely dispersed inventory, which prevents pooling benefits.
- At the start of European integration, in 2002, a large fraction of the shipping (around 60% of trucking) was by private fleets, but third-party logistics (3PL) options were emerging.

Pan-European carriers were also emerging as possible solutions.

- Most movement of product involves circuitous routing, with associated unreliable service, resulting in very expensive transportation. One estimate suggests that over 40% of the ton miles are driven empty. Before European integration efforts, about 35%–45% of the time was spent waiting at borders.
- When the European common market was initiated, the projected European Union single-market benefits were that rationalization of production and distribution would potentially generate around 45% of the supply chain efficiencies. These efficiencies would occur through improved utilization of resources and higher reliability levels.

What does all this mean for a supply chain manager in Europe? It means that spatial distance may not be an appropriate way to look at the supply chain because country boundaries may have an impact. It means that individual country specific rules regarding truck sizes and movement would need to be considered while planning the supply chain network. Coordination agreements to decide how orders are initiated and delivered could have a significant impact on costs. In short, the supply chain architecture in Europe would have to respond to the specific European logistics context.

2.8 Managing Warehouse Operations

The next few sections focus on warehouse management examples and their impacts, including layout choices and their effects on crossdocking. Recall that crossdocking refers to using a warehouse (or transit location) as a coordination point to accept inbound shipments from suppliers and create outbound shipments to customers or stores or assembly plants with a mix of components. Successful crossdocking in a supply chain permits inventory to be converted to rolling stock, thus decreasing static inventories and permitting the inventory in transit to be used as de facto inventory with guaranteed availability at a specific location and point in time. Then the focus shifts to coordination of task allocation between workers in a warehouse. Section 2.12 examines a novel scheme in the literature called "bucket brigades" and its application to several applied contexts.

2.9 Description of the Sears Shoe Distribution Center

As described in [83], the Sears Shoe Distribution Center in Edison, NJ, a 408,000 square foot central distribution facility for footwear, opened in March 1996. The warehouse was planned to support 750 Sears stores nationwide. The warehouse received inbound shipments from over 100 suppliers. The estimated monthly shipment volume was 2.5 million pairs of shoes a month to seven regional DCs. Stores were permitted the flexibility to order inventory one pair at a time. Taking into account seasonal variations, the facility was planned to carry an inventory level of 9,000 active SKUs, but it was flexible enough to accommodate an additional 7,000 SKUs.

Orders from stores were sent electronically to the distribution center. A majority of the orders were from stores; however, the central buyers for Sears retailers also placed orders for shipments to stores, and there were orders for promotion items. Orders that were received were processed based on footwear type, given their different characteristics. The pick system had 14 pods with four carousels each and 180 locations in each carousel, thus generating a total of 10,800 locations that could handle the active SKUs in the system at any given time. The warehouse used a pick-to-light system, in which the next item to be selected is indicated by a spotlight as soon as the previous item in the list is picked. The warehouse order picker thus followed the lights to identify items in an order. As soon as workers filled a carton, it traveled to a conveyor for final sorting, was weighed as a final item verification check, and sealed, and a shipping label was attached. When the cartons were shipped, advanced shipping notices were sent to stores to provide notice regarding impending deliveries. There are several examples of such warehouse operational details in the articles provided in *Manufacturing and Material Handling* magazine.

2.10 The Walmart Distribution Center

In the United States, Walmart distributes products to its 3,000 stores from 158 distribution centers (DCs) ([129]). Individual DC locations may have over 12 miles of conveyor belts that facilitate the movement of goods: Inbound shipments from suppliers become outbound shipments to stores. Each DC supports around 100 stores within a 200-mile radius. A private fleet of trucks and 7,000 drivers convey goods from suppliers to stores, logging more than 700 million miles each year. Trucks using auxiliary power units enable savings in emissions and costs. This reduces the environmental footprint and lowers costs.

Walmart also focuses on reducing its environmental footprint within the warehouse. Changes to packaging, such as placing milk in caseless plastic containers ([130]) have eliminated crates or racks, resulting in a savings of $0.20 per gallon. Use of light-emitting diodes (LEDs) in refrigerated crates instead of fluorescent lights results in more efficient energy use. Products delivered to the stores are either in boxes or shrinkwrapped with recycled content, which is transported back to the DC by trucks.

In the DC, product is managed differently depending on whether it is a staple or a seasonal item. Staple items, such as toilet paper and toothpaste, are managed by supplier-provided managers who ensure that stores maintain high in-stock levels. Category managers look across products offered in a category to ensure effective forecasts and orders. Seasonal items are managed centrally by the buyer, who ships products to stores to balance observed demand and purchase efficiencies. Disaster response warehouses are maintained fully stocked to reduce response time for disasters. For detailed descriptions of both Walmart and several other warehouses, see [53].

The ideal location for product within the Walmart supply chain is the store, where goods can be purchased by customers, rather than in a warehouse. Over 100,000 suppliers, many of whom deliver daily, coordinate with DCs to keep product moving all the way to the store. Product brought into the Walmart DC is usually crossdocked and shipped out within 48 hours. Therefore the supply chain facilities are viewed as conduits for product flow rather than as storage units. By providing central buyers with the flexibility to adjust orders, crossdocking at Walmart can operate efficiently. Loads to stores can be optimized and balanced with store inventories. Goods arrive at store delivery docks during preplanned nighttime periods.

Walmart's next supply chain goal is to integrate e-commerce and store inventory. Customers can place orders on the company website and pick items up at stores. However, in some areas, they can also order at the store and get same-day delivery for a fixed delivery charge. All of these alternate flows of product make the DC and store inventory a seamless supply chain for the customer.

2.11 Crossdocking Layouts

Crossdocking is an approach that seeks to consolidate inbound shipments from many sources to generate outbound transportation while eliminating the consolidation warehouse inventory. The goal of crossdocking is to have rolling stock that is transferred from incoming shipments directly to outgoing trailers without storing them in between. Shipments typically spend less than twenty-four hours waiting at intermediate facilities.

In a traditional consolidation warehouse, goods are received from vendors and stored. Some time later, when orders are received, goods are picked from inventory and sent to the destination. In a crossdock, goods arriving from the vendor have a customer assigned so that workers need only move the shipment from the inbound trailer to an outbound trailer bound for the appropriate destination.

One way to classify crossdocking operations is according to when the customer is assigned to an individual pallet or product ([51]).

> "In pre-distribution crossdocking, the customer is assigned before the shipment leaves the vendor, so it arrives to the crossdock bagged and tagged for transfer. In post-distribution crossdocking, the crossdock itself allocates material to its stores. For example, a crossdock at a Walmart might receive 20 pallets of Tide detergent without labels for individual stores. Workers at the crossdock allocate 3 pallets to Store 23, 5 pallets to Store 14, and so on." ([51], p. 1)

Crossdocks come in different shapes, with associated implications for performance. The Gue article provides a summary of crossdocking types and examples of successful crossdock facilities. Further research by Gue

([52]) suggests that aisle shapes can affect picking efficiency significantly by changing travel time to pick orders. They recommend consideration of V-, fishbone-, and chevron-shaped aisle configurations, which have the potential to reduce travel time by up to 20%. Clearly reduced pick travel times imply faster order turnaround and thus higher productivity of the warehouse.

2.12 Allocating Tasks Between Workers in a Warehouse

Once a warehouse is configured and the crossdocking decisions made, productivity can be increased by changing how tasks are allocated to workers in the system. Bucket brigades are defined as "a way to organize workers on a flow line so that the line balances itself" ([6], p. 1). The order picking operation in a warehouse is a flow line. Items in the order are collected in a tote until the order is complete. The finished order is then packaged, labeled, and shipped, using the appropriate shipment mode.

Maximizing warehouse productivity requires balancing task allocation across workers. In many contexts, warehouse management systems are used to identify task content across orders and thus manage the system. Assembly lines are balanced using detailed algorithms. However, the bucket brigades proposed in [6] are self-organizing and thus have little need for centralized planning. The operational role of the supervisor is thus significantly reduced.

In a bucket brigade, the product is moved forward from start to finish by a collection of workers working in sequence. As the last worker finishes a product, he walks back and takes over the partially finished product from his predecessor, who walks back and takes over from his predecessor, and so on. The workers continue to move product forward.

If, in addition, workers are sequenced from slowest to fastest, they will probably gravitate to the optimal division of work so that throughput is maximized [6].

Some of the benefits to a bucket brigade system are the following:

1. The role of the supervisor is decreased substantially because bucket brigades make the line self-balancing.

2. The ability of bucket brigades to adjust themselves, without the need for supervisory or software intervention and associated delays, enables the lines to become agile and flexible.
3. Because the lines run optimally, throughput is increased with minimal work-inprocess inventory.

Details of a game to illustrate the impact of bucket brigades are provided in [6].

2.13 Bucket Brigades at Revco Drug Stores, Inc. (Now CVS)

One implementation of bucket brigades reported in [6] was at the national distribution center of Revco in Knoxville, TN. Prior to bucket brigades, Revco faced productivity issues because of its reliance on temporary labor and on overtime during peak periods. Revco used a zone-picking system in which the pick line was partitioned into areas based on the assumption of identical workers; but, given their employee experience mix, the actual pick rates of its workers could vary by a factor of three. The result was that the allocations of work were always unequal and the pick lanes were imbalanced: the slowest pickers were frustrated at falling behind and the fastest pickers were underutilized.

The report described in [6] claims that the idea of bucket brigades was explained to the workers in about fifteen minutes one morning. When implemented at Revco's warehouse, bucket brigades reduced work-in-process inventory, which relieved congestion on the conveyor. The reduced congestion and more effective task allocation increased pick rates and accuracy.

Under the new system, supervisors could monitor the relative progress of different lanes and adjust allocation of workers to keep the lanes coordinated (to reduce sorting downstream). Bucket brigades simplified the shifting of workers from a fast lane to a slow one because there is no need to redefine zones. The research measured a 34% increase in pick rates at Revco when they shifted to a bucket-brigade-based task allocation.

The report in [6] states that

> "Weekly average pick rates were measured by Revco over most of a year (normalized to Revco's work standard 1.0). Prior to the introduction of bucket brigades, Revco was picking at about 95% of their own work standard. After bucket brigades, this rose to 134% of their work standard." (p. 3)

The application of bucket brigades at Revco suggests that even after the warehouse location and layout are defined, there continue to be opportunities to improve performance by adjusting task allocation across workers to become more flexible and demand driven.

2.14 Chapter Summary

This chapter focused on managing the warehouse and associated flows in a supply chain as well as on the number of different ways flows from suppliers to users can be organized. It established that effective use of the warehouse to decrease supply chain costs often requires careful design and use of crossdocking as an operational tool. Finally, managing order picking can have a big impact on warehouse turn-around time. This chapter thus discussed how the chain structure, the capacity of transportation, and the coordination of material movement and inventory as well as workers in a warehouse improve the competitiveness of the supply chain.

CHAPTER 3

Purchasing

The purchasing function in supply chains focuses on the selection, contracting, design, and delivery of products from suppliers. Coordination with suppliers can generate significant benefits by leveraging supplier capability to adjust product specifications and required service. Purchasing managers can also leverage competition across suppliers to extract favorable contracts. If supplier capacity has to be reserved to guarantee supply, then competition across supplier types can be leveraged to optimize supply chain performance. This chapter will focus on coordination, competition, and capacity decisions within the purchasing function. The examples will illustrate the link between chain structure and the ability to effectively leverage the purchasing function.

The specific purchasing decisions include the make–buy decision for components and products, global location of sources for manufacturing and distribution facilities, and coordination with suppliers to maximize mutual benefit.

3.1 The Impact of Supplier Coordination

As companies rely more on their suppliers to decrease overhead and asset levels, managing suppliers is now an important capability. To get a sense of the magnitude of the supplier's role, consider that, in the automobile industry, estimates suggest that Chrysler outsources over 80% of the parts it assembles into cars; Ford, over 65%, and GM, over 55%. In the electronics industry, Cisco System partners provide final assembly for almost half of its switches and routers ([51]). Table 3.1 (from [51]) shows that suppliers and buyers have closely intertwined relationships with one another across a range of industries, from automobiles to banking and electronics to pharmaceuticals.

It is clear that supplier networks can have a significant impact, particularly when the suppliers are the ones investing in technology and who have the design and testing capability required for the development of innovative products. A study by John Henke [41, page 3] from Planning Perspectives calculates a Working Relations Index (WRI) that examines seventeen criteria under five broad categories related to the buyer–supplier relationship, OEM communication, OEM help, OEM hindrance, and supplier profit opportunity. The 2011 WRI considered 1,984 data points, and automakers could be awarded a total of 500 points. The WRI was 327 for Toyota, 309 for Honda, 271 for Ford, 247 for Nissan, 236 for General Motors, and 221 for Chrysler.

In a related context, an Original Equipment Suppliers Association (OESA)/McKinsey study suggested that interface costs between a supplier and OEM can be estimated to be 5.2% of total cost. The study also estimated that 80% of the waste in the auto industry was due to poor supplier management and was linked to product specifications, part complexity, and ineffective coordination of capacity and demand. The supply

Table 3.1 Possible applications of our model

Industry/Activity	Buyer Resource Commitment	Supplier Resource Allocation
Auto Parts	Concept (Ford)	Design, manufacture (Johnson Controls)
Pharmaceuticals Manufacturing	Drug development (Merck, Pfizer)	Scale up and manufacturing (Catalytica)
Pharmaceuticals Contract Research	Basic research (Merck, Pfizer)	Research, testing (Covance, Quintiles)
IT Hardware	Concept (Cisco)	Subassembly, final assembly (Solectron)
Food and Beverage	Brand management (Coca-Cola, Redox)	Bottling, distribution (Bottlers, Korex)
Financial Services	Product, service design (PNC, First Union)	Transactions (MBNA)
dot. com Business	Business plan	Transactions processing and Customer Relationship Management (CRM)

chain cost due to this waste was estimated to be $10 billion. Given these estimates, it is clear then that supplier management represents an important supply chain capability. The next few sections will focus on specific example to manage these costs.

3.2 Supplier Management at Toyota

The book *Toyota Supply Chain Management* ([47]) describes the auto manufacturer's supplier management practices. One important practice is to spend sufficient time during supplier selection to ensure that the vendor will mesh with Toyota's network. Suppliers join a *keiretsu,* a connected network, and can expect to work with other members to ensure competitiveness of the supply base. One such role is membership in a *jushuken* of suppliers, a gathering of executives who, through mutual criticism and applications, leverage the Toyota production system across their companies. But Toyota, in turn, provides a combination of group and individual assistance to the *jishuken* members, thus enabling them to have a higher output, lower inventory, and better quality than other suppliers in the automobile industry. An example cited in [47] is Toyota's CCC21 program that managed to cut costs by 30% and $10 billion over a five-year period.

One key component of Toyota's supplier selection is frequent interaction with suppliers. Over 85% of the suppliers in Japan are located within fifty miles of the assembly plant. In the United States, over 80% of the suppliers are within a three- to five-day lead time, with sequence suppliers (those that adjust their components to match specific requirements in a car such as seats, dashboards, etc.) located close to the assembly plant. This frequent interaction not only coordinates supplier production with Toyota's requirement, but also permits visibility and quality control.

Toyota both hosts supplier managers at their facility and sends their own managers to supplier facilities to iron out potential issues. Thus, [47] claims that the company manages the downstream supply chain to stabilize order volumes and thus decreases variability faced by its suppliers through careful choice of variety offered, visibility of its data across the supply chain, a velocity that matches supply rate to demand rate.

3.3 Coordinating Buyer–Supplier Contracts

Core buyers and their management of the buyer–supplier relationships for product specification and production at Ford Motor Company are described in [51]. Ford has over 350 core buyers responsible for overseeing the relationship with approximately 1,150 suppliers. These suppliers provide component parts or systems (e.g., brake pedals, seats, car audio systems), which are, in turn, assembled into Ford's cars. The core buyers evaluate supplier capability; negotiate component specifications, prices, and quantities; and decide if suppliers should be offered engineering assistance. While no costs are charged to suppliers, the procurement manager chooses how to deploy these scarce resources to deliver benefits to Ford.

An example in [51] describes the possible coordination between the OEM and supplier to reduce costs for a radio. As a starting point, product designers at Ford provide initial specifications regarding the radio; an estimate of variables such as the heat generated around it, the expected vibration, and so on; and details regarding the audio specifications. But these specifications are then translated into final specifications and manufacturing capability through interactions between Ford's engineers and the supplier's personnel, with the joint goal of producing a competitive radio.

Consider a single resource termed *engineering-hours.* These engineering-hours could be deployed in different ways. A quote from [51] summarizes these choices:

> "Ford's engineering-hours might be employed to improve the initial design by using existing standards (e.g., the GAP standard dashboard cutout for head units), by eliminating/minimizing conflicts in the initial specifications (e.g., size and features), by applying design-for-manufacturing techniques, or by improving the communication of a given initial design (e.g., oral description versus written description versus digital files). Or, Ford's engineering-hours might be employed to cooperate with the supplier by testing prototypes in increasingly-sophisticated ways (e.g., CAD simulation) and providing the corresponding results to the buyer. Finally, Ford might employ its engineering hours independently, in parallel with the supplier's engineering-hours, on one or more of the steps in the transformation process."

The optimal level of supplier assistance will be described later in this chapter.

3.4 Coordinating with Suppliers at Bose Corporation: The JIT II System

The JIT II System ([21]) at Bose Corporation was championed by Lance Dixon while he was vice president of purchasing at the company. The Bose JIT II approach was different from the normal just-in-time approach (JIT) because it went further than a focus on inventory levels. Bose invited a supplier's employee to work as an in-plant representative, thus eliminating the need for a supplier to forecast buyer demands. The supplier was offered an "evergreen" contract that lasted over several years, an opportunity to access all of Bose's personnel and meetings and to influence designs during inception and an ability to do concurrent planning and concurrent design. In return, the supplier was expected to commit to price reductions and service improvements over the life of the contract.

Thus, under JIT II, Bose got a supplier employee, a reduction in purchasing overhead, a commitment to decreased prices, ideas focused on decreasing total costs rather than just component costs, better service and quality than market offerings, lower prices, and so on. As an example, a transport in-plant provided Bose an on-time delivery of 98%–99%, higher than the industry standard of 95%. Since over 60% of Bose's output was exported, an export–import in-plant specialist provided Bose with the ability to adjust shipments to meet shipping schedule changes and transit delays by identifying these changes early in the day and reacting appropriately. A metal-parts supplier who started direct meetings with Bose engineers provided suggestions for component redesigns and thus saved money for the supplier by using his existing tooling and decreased assembly costs to Bose. In effect, JIT II provided Bose virtual control over the supply chain without significant investments in assets. However, Bose only offers such an opportunity to suppliers who are already very competent and have delivered at a high level of reliability over time. No such agreements are made for acoustics and electronics, which remain in house.

Since supplier employees play a coordinating role, the corresponding buyer purchasing agent can be eliminated. Thus, Bose replaced a "market" read of supplier performance, through repeated supplier competition, with a nonmarket longer-term relationship. Consequently, it is important to project the potential cost reduction and service improvement over the life of the agreement and expect that in the contract. Choice of this commitment enables sharing of the cost reductions that are possible at the supplier end and sets expectations regarding how the supplier should leverage the increased access to the buyer realtime environment to reduce costs for the supply chain.

3.5 Japanese OEM Supplier Management

Empirical studies suggest that Japanese OEMs differ from US OEMs in their suppliermanagement practices. Japanese OEMs, in many instances, offer more flexibility to the supplier for part designs, but closely monitor manufacturing. The reverse seems to be true for US OEMs. Clark [13] states that "black-box" parts, "those parts whose functional specification is done by the assemblers (buyers), while detailed engineering is done by parts suppliers," account for 62% of Japanese automakers' total procurement costs, but only 16% and 32% for US and European automakers, respectively. However, detail-controlled parts, "those parts that are developed entirely by the assemblers (buyers), from functional specifications to detailed engineering drawings," account for only 30% of Japanese purchases, compared to 81% and 54% for US and European automakers.

Empirical studies (see [51] for citations) describe three levels of involvement between the buyer and supplier. These are described as the drawing-supplied system (DS), the drawing-entrusted system (DE), and the drawing-approved system (DA). Under the DS system, the OEM provides detailed drawings and supplier manufactures to those specifications. Under the DE system, the supplier creates the drawings, but the OEM claims property rights to those drawings. Under DA, the supplier creates and owns the drawings and supplies the part to the OEM.

At Toyota, between 1970 and 1990, the steering wheel remained a DA part, while interior parts were contracted as DS parts. For other components the level of supplier involvement changed, with weather strips evolving from being a DS part to becoming a DE part, while vibration proof rubber evolved from being a DS part to a DA part. It is thus clear that the level of supplier involvement evolves to adjust to the impact of the component's cost and quality on the final OEM product.

3.6 The Alps Structure for Procurement

Nishiguchi [70] describes the structure of purchasing used by Japanese OEMs as an Alps structure (that looks like the Swiss Alps). The auto assemblers are the peaks of the Alps structure. The first-tier suppliers, who have expertise in specific areas of component manufacture and systems development, form the first layer. Products they may handle include wire harnesses, instrument clusters, transmissions, radiators, and brakes. The second-tier subcontractors are smaller, with a lower systems capability level. They specialize in a smaller range of subassemblies: metal body parts, electrical relays, and seat frames. The third-tier subcontractors specialize in simpler parts such as small stampings for cores of motors and small plastic parts. The fourth-tier suppliers do simpler tasks such as preforming and sorting. The base of the Alps thus contains 30,000 to 50,000 small firms.

As described earlier, there is extensive delegation between the OEMs and the first-tier supply base for product designs. In addition, the same supplier may occupy different positions across tiers: for example a first-tier subcontractor to Honda may be a second-tier subcontractor for Nissan. Similarly a second-tier subcontractor to Nissan may be a first-tier supplier to Hitachi for computer components. This suggests that the tiered supply base is linked across many OEMs and products, thus generating an Alps structure.

The ability of suppliers to have a portfolio of customers enables flexibility of the supply base to absorb downturns in individual OEM volumes, thus providing the capacity adjustment flexibility for the OEMs. In addition, the ability for the base of smaller companies to easily adjust their production capacity by working longer hours and so on provides the ability to rapidly adjust upwards to demand increases.

3.7 Early Supplier Involvement (ESI)

Proactive purchasing groups typically consider the role of early supplier involvement (ESI) as a tool to improve the cost and quality performance of products. A paper by Zsidisin and Smith [92] summarizes the literature and a case study involving Rolls Royce (RR), which produces critical components for civilian and military aircraft. RR data suggests that 80% of product costs is locked during the design phase, thus demanding the need for suppliers to be involved during the design phase, given that the new-product development process lasts 10 to 20 years in this industry.

The key reason for RR to use ESI was the need to produce products at competitive prices, which required suppliers to use target costing approaches to produce competitive designs. The result was a set of suppliers and a collaborative approach to provide continued cost reductions during design and redesign. Legal liability and associated risks required sharing of expertise to reduce the risk of product failure and development of agreements to share gains, thus decreasing the risk of intellectual property rights concerns. Detailed tracking of supply base execution by tracking current suppliers enables choice of appropriate suppliers to be involved in ESI.

An important consideration is the supplier capacity availability to support production needs. Discussions with suppliers about their planning process, planned investments, and so on enables RR to be comfortable about supplier capacity availability. A key consideration for RR was whether the culture and philosophy of the supplier organization matched RR's culture and philosophy. A better match between RR and its suppliers' philosophy reduces the risk in new product development. Studies suggest that outcome-based management works best when risk is minimal for the product. However, behavior-based management focuses on approaches to decrease risk that then minimize the probability of problems arising. ESI plays the role of enabling the latter approach to managing suppliers.

3.8 Customer and Supplier Coordination at Rane Brake Linings

This section describes processes for customer and supplier coordination at Rane Brake Linings (RBL), Deming Award–winning brake lining supplier in India ([44]). One of RBL's customers introduced a new two-wheeler disc pad in the Indian market. While RBL produced the product to specifications, the pads were found to stick during use by the end customer. The customer reported the problem to RBL on 14 April, 2004. The two-wheeler manufacturer claimed that the parallelism of the installed pads was not up to standard and that the flatness and surface finish were not acceptable. The possible causes could be attributed to (1) the supplier of some components of the disc brakes to RBL, (2) RBLs manufacturing of the brake linings, (3) the customer (two-wheeler manufacturer) installation of the disc brakes in the two wheeler, or (4) its use by the end customer. However, given RBLs stated goal to maximize customer satisfaction, they decided to solve the problem for the two-wheeler manufacturer.

Historically, employees in the company would have focused on who would require the service, who would pay the costs, what the impact of a failure to solve the problem would be, if the customer would appreciate the effort, and so on—all risks associated with taking this action. But RBL was implementing total quality management (TQM). Within this context, the decision to lead development of a solution was easy. Since customer satisfaction was important, RBL offered to solve the problem and believed that its superior processes were capable of managing the execution.

The first step was to devise a measurement gauge that would be used by all three companies: the supplier to RBL, RBLs manufacturing personnel, and the OEM. The gauge measured thickness all around the pads. RBL stationed its engineers at the supplier and the two-wheeler manufacturing sites and proceeded to use the gauges to measure the pads. This step alone decreased error rate from 25% to 3%. The next step was to work on correcting the plate manufacturing process at the supplier's end. The original process at the supplier had a 0.2 mm gap between the rollers, the direction of pass of the roller (the side that faced the roller) was not specified, and the number of pieces per pass was not specified. In the modified process, developed jointly by RBL and the supplier, the machine was set to have a 0.1 mm gap between the rollers, the direction of pass was specified clearly, and the number of pieces per pass was set to one. These changes increased the acceptance rate from 75% to 98%.

At RBLs manufacturing, the grinding wheel was changed from a diamond wheel to aluminum oxide (60 grit). In addition, buffing was done to remove dust. This decreased productivity at RBL but increased the roughness necessary to deliver the required performance. To improve productivity, RBL changed to a 120-grit, three-step diamond wheel. The result was an improved disc pad in which the sticking problem was completely eliminated. The completion date of this project was May 10, 2004.

This example shows that RBL was capable of not only understanding how the company fit into the supply chain but also how the product was used by the customer. Management is interested and capable of both managing process improvement across the supply chain and completing the process in a short time frame. The top management goal of maximizing customer satisfaction meant that employees and managers at RBL do not need to spend time authorizing engineers and other personnel to tackle such problems. Suppliers and customers do not have to worry about paying for such service. This provides RBL with an edge over companies without such top management commitment.

How does this help a potential buyer of RBL's products? The buyer can now potentially decrease the overhead (engineering and procurement staff) that would otherwise be required to play the previously described coordination role. This reduction in overhead is an added reduction in costs related directly to items that can make RBL more competitive overall even if its product prices are higher. In fact, one of RBL's overseas customers claimed that he chose them over stiff competition because he could potentially take a vacation as planned, knowing that any problems that would arise would be resolved by RBL within the supply chain. This capability can be worth a lot to a global buyer.

3.9 Coordinating the Supplier's Role

Should suppliers provide components, or should the OEM make them? Venkatesan ([89]) suggests that often this decision is based on the extent of difficulty involved in the make– buy decision, with parts with causing greater headaches being outsourced. Thus, parts that are complicated or difficult to manage are bought, not made. On the other hand, it is more efficient to manufacture parts that are easier, with long production runs. But such an approach may often end up increasing supply chain costs.

A second issue that may cause a distorted decision arises from the conflicting priorities across decision makers. Often manufacturing managers prefer to fill idle capacity by insourcing, and labor relations managers can point to this decision as a prolabor gesture. In contrast, development engineers for new products often prefer the responsiveness of outside suppliers. They may seek smaller suppliers, who, as part of their entrepreneurial need to satisfy their customers, may be more responsive, provide better product, and deliver faster. Such conflicting perspectives cause the make–buy decision to become highly dependent on the manager making the decision.

Venkatesan ([89]) suggests it is important to determine if a part is a strategic component or a commodity component when making the decision. Three possible criteria for a part to be classified as strategic are (1) The part has a high impact on customer perception of the product and thus provides the most important product attributes; (2) The part requires specialized design and/or manufacturing skills for which there are few alternate suppliers; and (3) manufacture of the part involves technologies that are in a state of flux, thus providing an opportunity to take a clear lead.

One approach suggested is the classification of products into three categories: green, red, and yellow. Green parts are those for which internal capabilities are clearly dominant and have a cost advantage of greater than 15% over that of suppliers. Red parts are those where suppliers have a clear advantage, with a cost advantage exceeding 15%. Yellow parts are those where the gap is less than 15% but a determined effort at improving labor productivity, training, and employee involvement could improve the internal manufacturing competitiveness of the part relative to suppliers.

The main message is the need to balance supply chain costs while deciding on the supplier's role in the purchasing decision.

3.10 Guaranteeing Supplier Quality in Purchase Contracts

Recent newspaper articles focused on lead paint used on Thomas the Tank Engine toys, industrial chemicals in toothpaste, industrial and not pharmaceutical ingredients in children's medicine, chemicals in children's toys that can convert to harmful chemicals when ingested, and contamination of dog food products all indicate that certifying supplier quality in a supply chain is an important component of the purchasing function. However, in the absence of easy-to-perform quality assurance testing, supplier certification and contract incentives play an important role in guaranteeing product quality.

The key issue to be managed in such contracts is the agency effect, as described in the earlier section. The agency effect reflects the fact that only the agent (the supplier) knows the true quality, while the principal (the buyer) experiences the cost of the quality. The associated problem then is similar to the unknown supplier capability discussed in the previous section. Similar to the models discussed there, contracts between the buyer and the supplier can include buyer oversight and buyer-recommended processes that involve buyer costs but may affect supplier costs as well. The optimal contract thus has to account for the extent of buyer oversight and its associated impact on the information rents that have to be paid to suppliers.

3.11 Developing the Scorpio SUV at Mahindra and Mahindra

Mahindra and Mahindra (M&M) is an Indian company that produced utility vehicles, such as the Jeep, in India. The company historically focused on sales to the semiurban and rural markets of India. It also sold to institutional units such as the army, police, paramilitary groups, and other institutional groups. However, as the Indian market opened up to global OEMs, market share started dwindling, and the company decided to focus on selling to the urban consumer. Since it did not have a product targeted to this customer, the company decided to produce a utility vehicle with a carlike feel.

The company's management decided that they did not want to be part of a global OEM's subsidiary but rather wanted to control the vehicle design and distribution. It decided to

> "develop a brand-new vehicle with nearly 100 percent supplier involvement from concept to reality for $120 million, including improvements to the plant. The new Mahindra Scorpio SUV had all of its major systems designed directly by suppliers with the only input from Mahindra being performance specifications and program cost." (Weilgat [90, p. 1])

One of the reasons that global supplier capacity was available in India was the slow growth of the passenger car market and thus the level of unused capacity with top-tier suppliers in India. This slack capacity could be leveraged by the suppliers to provide a competitive product in a short time frame.

> "To keep costs down, many Scorpio suppliers used existing components or components already in development. While much of what drivers see is new, some of the subcomponents are carry-over products from something that was already engineered and tooled." (Weilgat [90, p. 3]).

Costs were also kept low because Mahindra stuck to their original parameters for the project and didn't change specifications or content. In traditional purchasing arrangements competitors come in with different products, and automaker OEMs thus want to add features. Mahindra allowed suppliers to use their expertise, even if it meant using unproven processes. Suppliers also say the program cost them less in investment because they didn't have to constantly change the program. While the project was underway, Mahindra gave many of the suppliers existing Mahindra business so they would not have to wait until the new Scorpio entered production to become profitable.

The result was a product that was completely configured to Mahindra provided specifications, developed for $120 million (which was 20% of the costs faced by a global OEM), sold at retail at a price point between $12.5 thousand and $17 thousand.

> "M&M tied up with the best in the world in their respective areas of the global auto industry. Fukui, Japan, for the press shop; Fuji, Japan, for the dies; Korean company Wooshin for body shop; Fori Automation, USA, for the tester line for final assembly; Durr, Germany, for the paint shop; Lear, USA, for seats and interiors; Visteon, USA, for exteriors; Samlip, Korea, for suspension; and BEHR, Germany, for air conditioning and Renault for gasoline engines. M&M facilitated the development of the supply chain and assembly operations. The vendors set up facilities in and around the factory. The end result was a fully indigenous product with international quality at affordable price." [53, p. 2]

The next few sections will focus on a few abstractions of the procurement problem in an attempt to clarify the buyer's and supplier's roles in the relationship.

3.12 Coordinating Supplier Under Agency Effects

The paper [51] considers the agency effect and provides an example where supplier and buyer coordination affect set-up cost at the supplier. The buyer requires a product from the supplier at a fixed rate D per unit time. Demand is met from finished-goods inventory maintained by the supplier. Shortages are not allowed. Production is assumed to be instantaneous, but there is a production set-up cost and an inventory-holding cost, both incurred by the supplier.

In this context, the buyer is the principal who pays for the work and decides how much to help the supplier. The supplier is an agent who knows specifics regarding production and his capability (which is unknown to the buyer). The set-up cost depends on the buyer's specifications, which in turn, depend on the buyer's resource commitment, $x1$, and on the supplier's set-up capability, ϕ. Thus the unknown supplier's capability creates an agency problem. The agent chooses the production lot size and thus influences buyer costs. The set-up cost will be denoted by $K(x_1,\phi)$. The supplier's decision is the production lot size, x_2. The holding cost is h per item per unit time. The supplier's cost function is $\frac{K(x_1,\phi)}{x_2} + \frac{h}{2}x_2$.

The supplier will choose the optimal lot size x_2 that minimizes his costs. Thus the corresponding supplier cost would be $\sqrt{2DhK(x_1,\phi)}$. Suppose that the setup consists of a number of steps, $N(x_1,\phi)$, that depend on agreed-upon product specifications and supplier capability. In addition, suppose that the cost of each step depends on supplier capability, $s(\phi)$, i.e., $K(x_1,\phi) = N(x_1,\phi) \times s(\phi)$.

The impact of buyer involvement on supplier costs depends on whether the cost relationship between buyer effort and supplier impact is one of substitutes or complements. Figure 3.1 shows an example of complements and substitutes. In this case, if the buyer agrees to specification adjustments that reduce the number of set-up steps, and when the supplier's capability only influences the cost of each step but not the number of steps, the supplier cost decreases faster for a more capable supplier than for a less capable supplier for a given amount of buyer assistance. Such a context is described as a complementary buyer–supplier relationship. In this case, an increase in buyer involvement, an increase in *x,* makes the impact of capability on supplier cost steeper, which increases the cost of information for the buyer.

However, if the supplier's capability influences both the cost of each step and the number of steps, it is possible to generate a substitutes relationship, which allows the supplier cost to improve more for a less capable supplier than for a more capable supplier. Figure 3.2 shows that as the buyer involvement increases, the supplier capability impact on costs becomes less steep. In other words, supplier assistance helps the buyer decrease information-related costs.

Given the description above, buyers would tend to provide more assistance in a substitutes relationship than in a complements relationship. This is the result in [51]. The example above suggests that buyers should consider the tradeoff between involvement with the supplier and its impact on the information rent, i.e., the difference in cost performance across suppliers with different capabilities. If buyer involvement flattens the cost curve across suppliers, that is, decreases cost differences across supplier capabilities, the relationship is one of substitutes, and it may

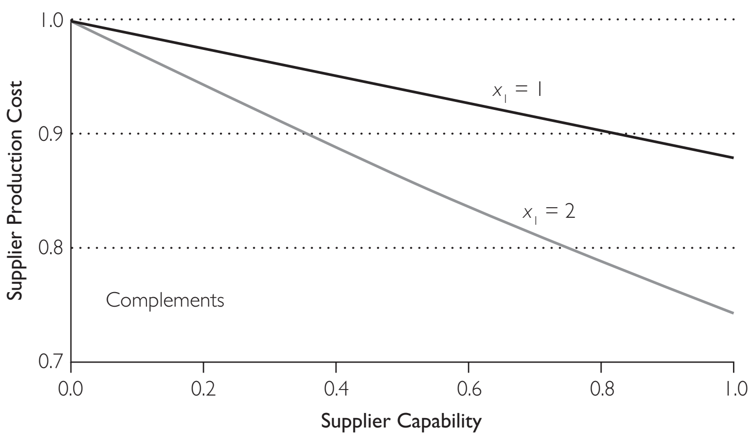

Figure 3.1 Supplier capability vs. production cost for complements

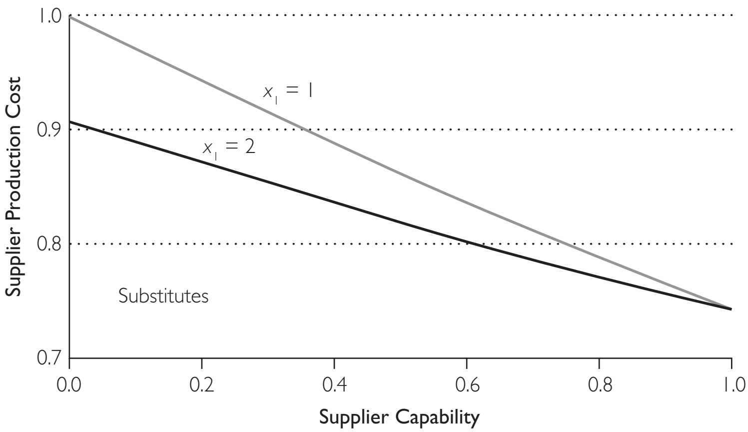

Figure 3.2 Supplier capability vs. production cost for substitutes

be optimal for the buyer to expend effort to decrease supplier costs and benefit from the reduced information asymmetry related to contracting costs. On the other hand, if buyer assistance were to increase the cost differences across suppliers, then it may be optimal for the buyer to withhold assistance because it only serves to increase the cost impact of information asymmetry.

3.13 Competition and Purchasing Impact

Earlier sections in this chapter highlighted the benefit of developing a relationship with a supplier, but such choices are made in a competitive environment. The mere existence of competition may enable better performance to be elicited from suppliers. How does competition across multiple suppliers benefit a purchasing manager? The next few sections focus on this question.

3.14 The Supply Chain Impact of Decentralized Purchasing

Consider a supply chain consisting of a supplier who produces product at a cost per unit of s and then chooses a wholesale price w to sell the product to a buyer. The buyer, in turn, faces a retail demand curve, with the retail price p linked to retail demand q as $p = a - bq$. For the wholesale price to permit retailer incentive, assume $s < a$.

Suppose the supplier and buyer were making decisions independently to maximize their respective profits. The supplier quotes a wholesale price w, and the buyer chooses a retail price p and buys the required quantity q. The supplier's profit is described as $(w - s)q$ while the buyer's profits are $(p - w)q$. Given a wholesale price w, the buyer will choose a retail price $p = \frac{a + w}{2}$ as his profit maximizing retail price, and the associated purchased quantity purchased will be $q = \frac{a - p}{b} = \frac{a - w}{2b}$. Given this purchased quantity as a function of wholesale price, the supplier will choose an optimal wholesale price $w = \frac{a + s}{2}$. Notice that the prices chosen by each member of the supply chain result in a retail price level of $\frac{3a + s}{4}$ and a retail quantity of $q = \frac{a - s}{4b}$.

However, consider a centralized supply chain, with the buyer and supplier maximizing their joint profit. For such a supply chain, the associated retail price will be $\frac{a + s}{2}$ and a retail quantity of $\frac{a - s}{2b}$— decisions made by a monopolist. Note that the retail quantity is $2b$ higher and the retail price lower than in the decentralized supply chain.

3.15 The Impact of Supplier Competition—The Wholesale Price Auction

But what if there were two suppliers, each competing to win the contract. Suppose the two suppliers have production costs of s_1 and s_2, with $a > s_2 > s_1$. Consider a system in which the suppliers first compete on wholesale price, and the buyer chooses the appropriate retail price and quantity. If the two suppliers participated in an auction, then the wholesale price charged to the buyer would be s_2. This wholesale price is always smaller than the best that can be achieved in a decentralized supply chain, i.e., $\frac{a + s}{2}$ because $a > s_2 > s_1$.

Thus, supplier competition to obtain the order results in lower buyer prices than in a monopolistic supplier supply chain. The lower wholesale price increases buyer profits and decreases supplier profits.

3.16 Wholesale Price and Catalog Auctions under Information Asymmetry

Consider the situation where the buyer does not know the supplier production costs, but only knows that the costs are uniformly distributed between $\underline{s}$ and $\bar{s}$. Each of the two suppliers knows their own production cost but only the range of the true cost for the other supplier. All that the buyer knows is that the supplier's cost follows a uniform distribution between $\bar{s}$.

We first consider a *wholesale price* auction. In a wholesale price auction, the buyer announces his purchase quantity, choosing his retail price **before** he knows supplier bids. The buyer has to use his expectation of supplier costs while making the quantity decision. Each supplier has to post wholesale prices in response, and the buyer merely picks his best option. Though suppliers do not know each other's bids because an auction is used, the resulting wholesale price is $\max(s_1,s_2)$. For the suppliers to be competitive, their cost s has to be lower than the wholesale prices that each of them would offer the buyer if they were by themselves, i.e., each supplier's s_j is $< \frac{a + s_i}{2}$ (where $i = 1, 2$) in addition to having $s_i < a$. Assume that $s_1 < s_2$.

After some algebra, it turns out that

$$
\begin{aligned}
q &= \frac{a - 2\eta}{2b} \\
\eta &= \frac{2\bar{s} + \underline{s}}{6} \\
p &= a - bq \\
w &= \max(s_1, s_2)
\end{aligned}
$$

However, under a *catalog* auction, the retailer gets to adjust the purchase quantity in response to the wholesale prices obtained. Thus, the suppliers first compete on wholesale price, and the winning price is s_2. The corresponding retail price is set as $p = \frac{a + s_2}{2}$ with the associated retail quantity determined as $q = \frac{a - p}{b}$. Notice that the associated buyer expected profit is greater than the expected profit obtained under the wholesale price auction. This is because the retailer fine-tunes the purchase quantity to the wholesale price and thus improves overall profitability. Corresponding the supplier's expected profit is lower.

The results discussed in this section suggest the need to adjust the type of auction to extract the benefit of supplier competition as well as compensate for the decentralized supply chain.

3.17 Reserving Supplier Capacity Under Competition

Procurement managers may have to reserve capacity at suppliers before knowing their demand. Suppliers, in turn, face costs to reserve capacity and a cost to execute the order. The costs to reserve capacity are the fixed costs or commitments required to be incurred in advance of the demand realization due to operational lead times.

Given that suppliers have their individual cost structures, suppose these suppliers provide bids to the procurement manager. Each supplier bid consists of a price to reserve capacity (per unit) before demand realization, and a price to execute (per unit) or produce and deliver after demand is realized, subject to the capacity limit that has been reserved. Given a set of supplier bids, how much should the procurement manager reserve with each of the suppliers, and how should the reserved capacity be used when demand is realized? In addition, given the procurement manager decisions, how should suppliers decide on their bids? This specific problem was analyzed by Martinez-de-Albinez and Simchi-Levi ([64]). The remaining part of this section will provide an example to illustrate this auction.

Suppose there are suppliers 1–7 and a dummy supplier 8, whose costs are provided in Table 3.2. These costs are unknown to the procurement manager. Supplier 8 provides any leftover demand and charges the retail product price.

Consider an example set of bids from the seven suppliers, as shown in Table 3.3.

The first step is to use a scatter plot to plot the points with the execution price on the *x*-axis and the reservation price on the *y*-axis. Once this step is carried out, the lower envelope of these points is obtained by moving up as far up as possible such that all points are on or to the right

Table 3.2 The reservation and execution costs for each supplier

Supplier Number	Execution Cost	Reservation Cost
1	0	42
2	10	33
3	20	25
4	30	19
5	50	10
6	65	5
7	80	2
8	100	0

Table 3.3 The reservation and execution price charged by each supplier

Supplier Number	Execution Price	Reservation Price
1	85	20
2	12	31.5
3	76	6.54
4	26	21.6
5	34	18
6	39	18
7	72	3.8
8	100	0

of this envelope. This envelope is called the *convex hull* of these points. In other words, imagine a wind blowing a line made up of a light straw, or a straw line, from the upper right to the origin. The straw line will be pushed until it runs up against a set of points that restrict its movement further. The corresponding structure created by the straw line is the convex hull.

For the example provided earlier, plot the points using a scatter plot (see Figure 3.3) and identify that bids from suppliers 2, 4, 5, 7, and 8 are on the convex hull: they will be termed *active suppliers*. This means that it is optimal for the buyer to reserve capacity only with these vendors.

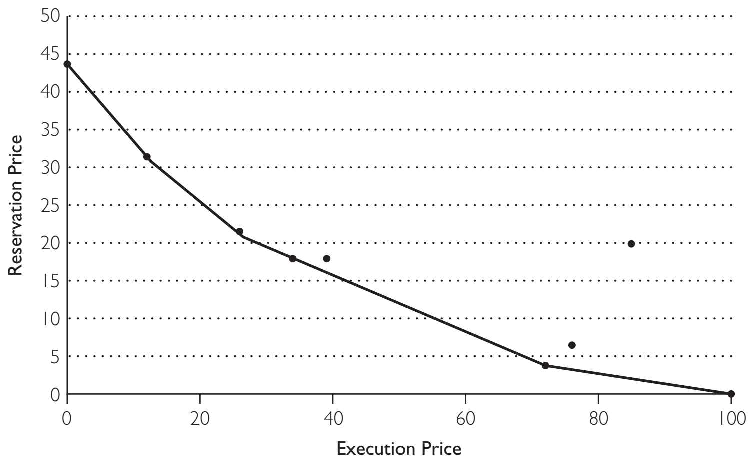

Figure 3.3 A convex hull showing active suppliers

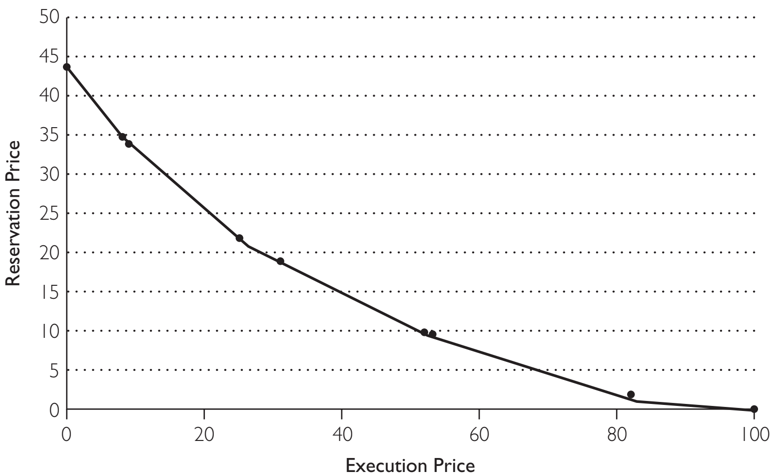

Figure 3.4 A convex hull showing equilibrium bids from suppliers

All the remaining suppliers that are not selected to reserve capacity are termed *inactive suppliers,* as described in [64]. To create a closed envelope, connect the active supplier with the lowest execution price with a point that is defined as having a 0 execution price as the *x*-axis value and the sum of this supplier's reservation and execution price as the *y*-axis value. In this example, this is the point (0,43.5) on the leftmost point of the connected set.

Note that the envelope described above suggests that once bids are obtained from all suppliers, each supplier has an incentive to react to change his bid to become active. As an example, if supplier 1 were to change his bid to offer an execution price of $10 per unit and a reservation price of $33.25 per unit, it would add a point (10,33.25) that would enable this supplier to become active, and thus receive a portion of the buyer's capacity reservation. Thus, competition across the suppliers causes interaction among their bids due to their desire to win and thus impacts the buyer's price.

If the bids are revealed in each round and each supplier responds to adjust his bid, then supplier responses keep adjusting until everyone stops making changes, i.e., the system reaches an equilibrium. This means that the bidding process will conclude when each individual supplier's bid remains the same before and after all bids are revealed. For more details, see [64]. The corresponding set of bids obtained and the associated convex hull is shown in Figure 2.4. This section thus shows how a procurement manager can optimize across supplier bids to choose his cost-minimizing supply strategy.

3.18 Chapter Summary and the 4C Framework

The procurement function focuses on managing order flows and consequent material flow from a supplier to a buyer. The purchasing decision requires choosing supply chain structure through the make–buy decision and the global location of manufacturing and distribution facilities. The capacity level chosen by suppliers is affected by buyer specifications and the extent of buyer coordination. An important issue to consider is the agency problem, which arises because of information asymmetry between the buyer and the supplier. In addition, buyer flexibility and cooperation can often affect supplier costs. Thus, it is important to get the buyer and supplier to commit the right level of resources to maximize joint performance. We focus on buyer approaches to work with suppliers to get the required product or component at a given price, quality, and capability. Purchasing coordination with suppliers can occur through contracts to resolve agency issues through appropriate choice of buyer involvement, use of auctions, and so on. Also, early supplier involvement and staggered model changes both serve as effective tools in managing suppliers. Competitiveness of the purchasing function involves measures such as cost, delivery performance, innovation, inventory levels, and so on. In the presence of supplier competition, buyers can use auctions as a filtering mechanism to improve performance. Solving the agency problem effectively is a key issue when managing suppliers.

CHAPTER 4

Grocery Supply Chains

4.1 Introduction

The dollar value of US retail grocery sales was around $585 billion in 2010 (grocery industry websites), and food and its distribution play a vital role in an economy. The US grocery supply chain has some unique features. Retail chains control a significant portion of the overall market, with the top 20 retailers accounting for 58% of grocery retail sales in 2003 and sales to the top 20 customers by major food manufacturers reached 69% of total sales in 2003. But with the presence of several chains with stores in most markets, retail price competition is fierce, with net margins around 3.5% of sales. Retail price promotions are rampant, with customers expecting the Thursday inserts to provide details of the price promotions for the upcoming week. The industry introduced over 19,000 new products in the food and beverage category in 2009 ([116]).

Manufacturers supply to retail chains through distributors or chain warehouses. Direct store delivery by the manufacturer is used for a few items, e.g., cookies, chips, ice cream, sodas, and so on. For most other products, manufacturers ship in bulk to distribution centers where products are combined with other items and shipped to the store. Capacity constraints to consider include store shelf space capacity, delivery truck capacity, store labor available to put products on the shelf, warehouse product handling capacity, and finally manufacturer plant capacity. There are coordination choices, such as increased frequency of store deliveries, that may increase transport costs but can decrease store inventories. Coordination schemes used in the grocery industry include vendor managed inventory at the warehouse, crossdocking, scanner-based promotions, slotting allowances, and category captains. These schemes aim to balance product availability without increasing retail inventories. Competitiveness metrics in this industry include freshness, variety of offerings, price competitiveness, and customized product assembled on site.

4.2 Chain

The supply chain in the dry grocery industry consists of the following:

1. **Customers:** These are people who shop primarily at the supermarkets. Their purchase quantities are influenced by store promotions, with the extent of impact of pricing depending on the mix of customers shopping at a store. Typically retail promotions may be accompanied by increased purchases as customers stockpile product to gain a low average price over time. The extent of this promotion activity is dictated by store customer characteristics.
2. **Store Inventories and Planograms:** Stores typically decide the amount of shelf space allocated to each item. This layout of products along aisles is called a *planogram.* Stores maintain similar planograms across locations to get customers to become familiar with their product locations. The store replenishes products subject to minimum order sizes (e.g., cases). Store reorders are filled by the distribution center operated by the store chain or by direct store delivery (DSD) by manufacturers (examples include Keebler for cookies, Frito Lay for chips, and Coke or Pepsi for beverages).
3. **Central Distribution Center (CDC):** The CDC receives orders for products from stores, picks orders, and delivers cases of products to stores. The CDC's goal is to minimize delivery costs and CDC inventories. The CDC times purchases from manufacturers in large quantities (truckloads or railcar loads) to manage inventory costs at the warehouse.
4. **Chain Buyers:** Chain buyers focus on managing purchases from manufacturers. Logistics efficiencies may be gained by coordinating purchases across manufacturers or by adjusting the quantities purchased to take advantage of quantity discounts. Further efficiencies may be gained by committing to steady order quantities from manufacturers. Yet other options include backhaul, picking up product from the manufacturer after delivering to stores to save transport costs.

5. **Manufacturers:** Manufacturers have to produce to supply the chain buyer purchases over time. But manufacturers often provide temporary price cuts or promotions to entice chain buyers to stock up. The reason is the belief that once stock is pushed to the CDC, stock pressure will incent the retailer to promote the product at the retail store. Fluctuations in the quantities shipped to the CDC are covered either with manufacturer finished goods inventories or by adjusting the delivery lead time.

4.3 Capacity

A unique feature in grocery supply chains is the impact of retail prices and whole price changes on associated order volumes. An example often quoted is that 40% of the annual sales for a chicken-noodle-soup manufacturer occurs over a two-week period in January when wholesale prices are dropped by 6–8%. To accommodate this large increase in wholesale sales, the company has to manage details such as plant, warehouse, and transport capacities. Providing enough capacity to satisfy this demand requires planning to begin in September of the previous year, with the chicken futures markets reacting to this anticipated surge in demand.

Industry estimates suggest that these volume surges create added costs in the form of premium transport costs, increased plant and warehouse capacity, and associated inventory costs. A 1992 study by Information Resources, Inc. (IRI), an industry analysis company, suggests that these costs can be as high as about 5% of sales or an industry-wide cost of $18 billion [1].

4.4 Coordination

4.4.1 Vendor Managed Inventory

Grocery retailers have to carry store inventory to satisfy retail demand over the supplier lead time to ensure high in stock levels. Thus, retailers have to forecast demand at price levels offered. As discussed in the chapter on coordination, in an uncoordinated supply chain, double marginalization results in a lower retail service level than is optimal for the supply chain as a whole.

Vendor managed inventory (VMI) is a coordinating approach used in the grocery industry. Under VMI, the manufacturer chooses retailer inventory levels. A key feature of VMI is that ownership of the product transfers to the retailer, but decisions regarding replenishment are made by the manufacturer. This scheme, termed *channel alignment* in Lee et al. [62], reduces the number of forecasting steps in the supply chain and thus improves performance and decreases costs. For example, Procter & Gamble (P&G) manages the inventory of its products at Walmart's distribution centers. However, the history of Walmart and P&G wasn't always smooth. In 1985 Sam Walton reportedly called the P&G CEO to inform him that P&G had been awarded their prestigious "Vendor of the Year" award. The call resulted in Sam Walton being transferred five to six times, never reaching the CEO. Since he never reached the P&G CEO, Mr Walton decided to give the award to another vendor ([34]). The follow-up conversations resulted in a transformed relationship, with more frequent data transfers and a VMI relationship between P&G and Walmart. The goods then flowed so quickly through the supply chain that items typically spent eight hours in a Walmart warehouse, were shipped to the retail store within four hours, and were usually sold within twenty-four hours. Other examples include Helene Curtis and Campbell's Soup managing inventories at the distribution center for Chicago retailer Dominick's.

As an example of the impact, analysis of shipment data from Campbell's Soup to a retail chain warehouse showed that after VMI, average lead time decreased from 10.8 days to 3.6 days, and standard deviation of lead time decreased from 3.5 to 2.8 days. Thus, after VMI, on-hand inventory at the warehouse dropped from 3.4 weeks to 1.8 weeks while service levels improved. The reasons for this improvement under VMI included smaller deliveries due to increased delivery frequency and a smaller supplier lead time.

But to make VMI economical, the manufacturer may have to pool deliveries across multiple retailers to optimize costs associated with frequent delivery. In addition, VMI may require the manufacturer to have access to detailed outbound retail shipment information in order to lower manufacturer forecast error and decrease safety stock at the retailer DC required to maintain the desired service level.

4.4.2 Scanner-Based Promotions

Another approach to coordination is scanner-based promotions. Under this approach, the manufacturer announces special discounts for all units sold at the retailer during specific periods. Iyer and Ye [50] study manufacturer costs with and without scanner-based promotions. They show that scanner-based promotions increase the predictability of retail sales for the manufacturer. This is because it becomes profitable for the retailer to schedule retail promotions at times when the manufacturer offers these deals. The associated lift in sales happens at predictable periods determined by the manufacturer, thus improving manufacturer forecasts and decreasing retail order forecast error. This retailer coordination permits manufacturer inventories to be better synchronized with projected retail sales, which decreases costs.

4.4.3 Markdown Money

Markdown money refers to payments by manufacturers to retailers to cover shortfalls in the planned increase in sales due to promotions. For example, some large retailers demand that observed sales be at least 85% of planned sales within 45 days of purchase order issued. For example, suppose a retailer purchased 100,000 units to cover anticipated sales, but only 60,000 pieces were sold. Under the 85% agreement, the vendor would need to provide funds to the retailer to get the 85% sell-through. This may happen, for example, by paying \$0.25 per unit for 85,000 − 60,000 = 25,000 units or \$6,250. For subsequent markdowns to clear product, it may be necessary to take an additional 25% of this markdown, i.e., \$6,250 × 25% = \$1,562. Note that markdown money holds the manufacturer responsible for reasonable forecasts by reducing the incentive to push stocks to the retailer.

4.4.4 Collaborative Forecasting, Planning, and Replenishment

Under Collaborative Forecasting, Planning, and Replenishment (CPFR), the retailer shares with the manufacturer the logic associated with the order, so as to permit store-level monitoring of stock availability and improved performance. Under CPFR, along with a retailer order, retailers submit both retail orders as well as logic for each order. This logic will explain to the manufacturer the reasons for the order placed. A local store may submit information regarding a promotion offered by a competitor in a particular week or a local store closing. Each of these two factors will cause a different effect on the order. In the first case, there may be a drop in store order, anticipating the demand drop due to the deep discounts offered by the competitor. In the second case, there may be an order increase to fill up the pipeline, i.e., to cover demand over the supplier lead time. Note that knowing this logic for the order enables the manufacturer to interpret the pipeline impact of the order.

Often the difficulty of forecasting demand during a retail promotion means that the retailer may order too much or too little. In addition, if the retail pricing information is not communicated to the manufacturer, then a forecasting rule that adjusts orders based on shipments will result in the manufacturer carrying high inventories between retail promotions. Sharing planned retail promotion information decreases these costs and thus improves supply chain profits.

4.4.5 Consignment Inventory

The main difference under consignment inventory is that the manufacturer continues to own the retail consignment inventory until the product is sold to the customer. Thus, consignment inventory is equivalent to the manufacturer purchasing store shelf space and choosing inventory levels to maximize his profits. Coordination is achieved because the supply chain decisions are made by one decision maker. Such an approach is common in the provision of spices; the spice racks in many retail stores are managed by the supplier.

4.4.6 Category Management

Under this approach, the retailer assigns a category manager, usually chosen from among one of the large suppliers to play the role of a category captain. The category captain is provided access to all point-of-sale data for all of the SKUs in the category and assists the retailer in choosing prices, inventory levels, merchandising, and so on, to maximize profits for the entire category.

A study by Seidmann and Sundarajan [79] suggests that with an appropriately designed scheme, category management (CM) can deliver significant benefits to the retailer. Some of the cited benefits include, for example, suggestions by the manufacturer, based on systemwide data, that dropping some SKUs and replacing with others can improve category profits. For example, a study by P&G and Walmart suggested that if Walmart dropped fifty-six SKUs and replaced them with twenty-five others, the retailer and P&G would be better off. Such information regarding the potential benefits of product swapping would be difficult to measure without detailed consumer information of the available with the manufacturer.

There is however, a flip side to CM as described by Steiner [84]. In many locations, the three leading manufacturers were category captains in over 50% of grocery retail stores and mass merchandiser sectors and in 67% of stores in the drug and convenience store sector. It is thus possible that as power shifts to a few large manufacturers, the benefits of CM efficiency may not be passed on to the consumer. It is this issue that has to be monitored, given the level of data sharing required by CM.

4.5 Competitiveness

Grocery retailers compete on many possible dimensions including price, freshness, instock levels, variety, organic products, and service. Walmart's everyday low price (EDLP) pricing policy is one such strategy. To optimize this metric, inventory and variety have to be chosen to guarantee that indeed the prices in every market are at the lowest level. The store-scanned data has to be tied to the inventory system so that replenishments can be triggered as demand is realized.

An alternate strategy is to compete on uniqueness, a strategy used by Trader Joe's. While other grocery stores carry 25,000 to 40,000 items, Trader Joe's stores carry 1,500 to 2,000 items. However the store also introduces about 50 items each week and carries 80% private-label products as well as products that are offered at lower prices than gourmet shops. The international sourcing of items such as cheeses, wines, and desserts enables the store to offer items that are not found at most other grocery stores. Trader Joe's buyers (which number about fifteen) tour the world and develop small suppliers with unique products. The company also has a unique personnel policy that encourages store employees to directly interact with customers, make recommendations, ask about choices, and so on. This interaction increases the perception of service received at the store. By offering nonstandard items that are not available at most other stores, the retailer avoids direct price comparison in establishing customer value. Historically store locations are in strip malls, and the company does virtually no advertising except for the descriptions in the in-store flyers.

Many stores use price promotions to attract customers. The associated hi-lo pricing strategy relies on the fact that store traffic may be influenced by deals on specific items. Customers who come in to the store to buy items on promotion may also pick up items at regular prices. Since most customers determine the reasonableness of store pricing based on monitoring prices for a subset of items, an important capability for the retailer is to identify that customer segment reference item list and thus price competitively for those products. Note that retail price variation creates associated order variance to the distribution center and thus might generate distribution center inventory increases. Synchronizing warehouse inventories with planned store promotions then becomes a key capability to manage the retail chain's profitability.

While grocery stores may compete on different dimensions, retail competition may also affect store pricing, variety, and inventory levels. Balachandar and Farquhar [2] suggests that in an equilibrium environment, there may be situations where a store can earn more by stocking less. They show that when customers are willing to search, competing firms may have the incentive to lower product availability in order to lower the pricing pressures and thus increase their respective profits. In other words, firms can, as in Balachandar and Farquhar's title, "Gain More by Stocking Less."

The aggressiveness of private label and national brands in choosing their respective pricing plans can be affected by the nature of customer preferences across products. Banks and Moorthy [3] describe a model in which there are two customer segments: a brand-loyal segment with a search cost and a price-sensitive customer segment with no search costs. The branded product thus has to defend its brand by appropriate choice of price promotions. They show that as the search costs for the brand-loyal segment increase, the national brand becomes more aggressive in its promotions. The net effect is that the brand-loyal customers may in fact be paying a higher price on average because getting the lower price requires more search. In other words, competitiveness across products may affect their pricing and thus affect supply chain costs.

If competing stores are located close to each other, this may decrease the search costs for customers and thus increase the need for higher-than-normal service levels. Since any stockouts may well result in loss of the entire shopping basket, it may be optimal to carry higher service levels but at lower profit levels, in other words, a prisoner's dilemma outcome, in which all retailers see reduced profits even though they offer higher service levels.

4.6 Grocery Industry Studies

A study by A. T. Kearney [4] tracked the days of finished goods inventory in the grocery supply chain. Imagine that a unit of product is sold at retail, and the lead time it takes for a fresh unit just manufactured at the plant to make its way to the store is recorded. This would require counting the time in inventory at the store, in transit from retail warehouse to store, at the retail warehouse, in transit between the manufacturer warehouse and the retail warehouse, and at the manufacturer warehouse. The estimated values of the days of inventory at each of these locations were twenty-four days at the store, eighteen days at the retail warehouse, six days in transit between the manufacturer and retail warehouse, and thirty-six days at the manufacturer warehouse. The total of days of inventory was thus estimated to be eighty-four days.

What is the industry supply chain cost associated with these days of finished goods inventory? One study suggested that the cost of this inventory is 5% of industry sales. This cost reflects additional investments in property plant and equipment, warehouse capacity and material handling, financing charges for inventories, and additional costs for premium transportation.

A Coca-Cola study entitled "Taking Costs Out of the Grocery Industry Pipeline" [17] suggested using a supply chain perspective to reduce costs and improve performance. The efficient consumer response (ECR) movement was fostered by the Food Manufacturing Institute (FMI) and Grocery Manufacturers of America (GMA). It involved coordination between manufacturers, distributors, and retailers to increase in stock levels of product and product variety without increasing inventory levels. The approach focused on information sharing, joint forecasting, reduced price variation or at least synchronizing retail or wholesale pricing changes with associated inventory positioning, and so on. A corresponding movement in Europe has evolved an industry academic partnership and the *ECR Journal / International Commerce Review,* which features industry and academic articles focused on the Grocery industry.

4.7 Trade Promotions and Their Effect

The grocery industry is famous for the use of temporary price cuts as a mechanism to stimulate sales. The price cuts, also called *trade promotions* or *deals,* encourage large-volume purchases by distributors and retailers and thus permit the manufacturer to push product downstream. Note that pushing product downstream creates "stock pressure" at the distributor or retailer, thus providing them the incentive to lower retail prices and "push" the product to the consumer. Inventory at the consumer's home increases the propensity to consume this item. In short, the grocery supply chain uses product inventory to stimulate product movement downstream and thus (potentially) product consumption.

To understand such pressures, consider the relationship between a retailer and a manufacturer in a supply chain. Assuming that the retailer's warehouse supplies many stores, the demand at the warehouse can be considered to be relatively stable, with a constant rate of D units per unit time. Given an ordering cost and a holding cost at the retailer, it is optimal for the retailer's order sizes to follow the economic order quantity to minimize retailer ordering and holding costs.

Consider the impact of the manufacturer offering a temporary price cut by decreasing the wholesale price by a factor of δ so that the offered price is δc. The retailer now has to decide the quantity Q_d to buy at this discounted price. The tradeoff is the lower cost of goods sold vs the increased inventory costs. Details of this section are from the model in [67].

List of Symbols

s = ordering cost for the retailer per order

c = wholesale price per unit (nonpromotion periods)

h_r = holding cost per day = ic (the product of the annual financing rate and product cost)

D = demand rate per day

In the absence of any trade promotion, the retailer would order the economic order quantity Q as follows:

$$Q = \sqrt{\frac{2sD}{h_r}}$$

Suppose the manufacturer offers a trade promotion, i.e., price reduction, of $(1 - \delta) \times 100\%$ every T periods (where $T > \frac{Q}{d}$). Thus, we have

δ = trade discount factor, i.e., cost during the deal = δc

If a trade deal is offered every *T* periods, how much should this retailer buy?

If Q_d is the amount the retailer buys during a promotion, then the retailer's inventory cost over T days is as follows:

Inventory and ordering costs are

$$s + \frac{\delta h_r Q_d^2}{2D} + \left\{\left(T - \frac{Q_d}{D}\sqrt{2sh_r D}\right)\right\}$$

The total product cost during T periods is

$$\delta c Q_d + \{c(DT - Q_d)\}$$

Therefore the combined cost over the T periods is the sum of the inventory, ordering, and product costs. If this cost is minimized, the retailer purchases the following quantity:

$$Q_d = \frac{Q}{\delta} + \frac{(1 - \delta)Dc}{\delta h_r}$$

Of course, if this quantity is greater than DT, the retailer will purchase DT.

What does this model suggest? First, if $\delta = 1$, then it is optimal to purchase the economic order quantity. In other words, increased purchases are only due to the manufacturer price discount. Next, the model suggests that the magnitude of the discount matters, i.e., Q_d increases as δ decreases, increasing proportional to $\frac{1}{\delta}$. This again is intuitive because as δ decreases, the reduced product cost justifies carrying more inventory to decrease overall retailer costs. The model also suggests that the retailer holding cost vs. product cost matters in determining the response to a given manufacturer price reduction. This reflects the trade-off in decreased product cost vs. increased inventory cost required to avail of the promotion.

The following example provides the details of the calculations and shows how some price cuts by the manufacturer can result in large orders by the retailer while decreasing retailer total costs. The purpose of this example is to show that since manufacturer price cuts and the corresponding inventory effects decrease retailer costs, any changes to this system will require more than just eliminating trade promotions. In addition, the example shows why high inventories might be common in the grocery supply chain as long as trade promotions continue to exist in the industry.

Example: Consider a retail warehouse that faces a weekly demand of $D = 100$ cases per week and is in operation 5 days per week. Assume that the retail holding cost is $h_r = 0.02$ per day per case, wholesale price is $c = \$20$ per case, and the retailer ordering cost is $s = \$80$ per order. The economic order quantity would be the order size and would be

$$Q = \sqrt{\frac{2 \times 80 \times 100/5}{0.02}}$$

$Q = 400$ cases

Now suppose the manufacturer were to offer a trade promotion of $\delta = 0.90$ (i.e., 10% off during the promotion), how much should the retailer buy? From the description earlier, we calculate the quantity Q_d purchased during the promotion as

$$Q_d = \frac{400}{0.9} + \frac{0.1 \times 20 \times 20}{0.9 \times 0.02}$$

Q_d = 2,667 cases. Thus, if the trade promotion is run every 26 weeks, the optimal retailer purchase quantity is 26 weeks of demand or 2,600 units. Thus, for this example, if the manufacturer promotes twice a year, the retailer will only buy during promotions. This will cause a sizeable inventory level increase for the retailer with the order quantity increasing from 4 weeks of inventory to 26 weeks of inventory and the average weeks of inventory increasing from 2 weeks to 13 weeks.

What is the difference in the retailer's total costs in the old system and during the promotion? Using the models presented earlier and the parameters for the example problem, we get the following results.

No Promotion System
Cost per unit time = $408/day
Cost of product = $400/day
Cost of Ordering and Holding = $8/day

Promotion System
Cost per unit time = $384.01/day
Cost of product = $360/day
Cost of Ordering and Holding = $24.01/day

Notice that the total cost per unit time, consisting of product cost and ordering and holding costs for the retailer, decreased from $408 per day to $394.01 per day. This reduced cost is a key driver to the retailer's preference for trade promotions. However, mere analysis of inventory levels will show an average of 13 weeks of inventory at the retailer rather than 2 weeks of inventory as suggested by an economic order quantity. A key takeaway is that in order to understand inventory levels it is necessary, in this industry, to understand manufacturer pricing. It also suggests that any attempts to decrease inventory have to be associated with pricing changes by the manufacturer.

How has the industry responded? There have been two types of industry responses. One approach, typified by Procter & Gamble's approach, is to switch to a lower price for all retailers but to use other means (other than price promotions) to stimulate sales. The other approach, typified by Campbell's Soup and Barilla, is to permit two pricing plans—the original trade promotions or a lower annual price in return for vendor managed inventory. The second approach lets the pace of adoption of manufacturer pricing reflect retailer market conditions. A Harvard case, Barilla Group, provides examples of the impact of a "customers choose" model. The case describes one distributor who chooses to move to VMI and the other who sticks to hi-lo. The impact of intense price competition during the period of trade promotions, increased stocking of competitor products, inability to forward buy in anticipation of price increases, and so on.

4.8 Promotions by the Retailer

The retailer has to deal with various customer segments with different reactions to a promotion. Some customers may stockpile while others may not. The retailer can thus use a retail promotion to move product from retailer warehouse to the customer location depending on the customer segment's propensity to stockpile.

Assume that there are two customer segments with different holding costs that represent the retailer demand base. Customers with high holding costs continue to buy as needed and are unaffected by retail promotions. Customers with low holding costs h_L and stock up according to depth of the promotion. Suppose these customers constitute α% of the total demand rate. Let total demand rate per day be D. Customers who are willing to carry the product will thus buy during a promotion and carry the product.

How can the retailer characterize customer segments based on their propensity to stockpile? An empirical study by Iyer and Ye ([50]) takes data regarding retail sales of soup and provides results of a fitted model. Details of this model are provided in Section 4.9, but the key idea is that the characterization of customer segments, their size and propensity to stockpile, can come from a statistically fitted model to data.

Suppose the retailer were to buy from the manufacturer every k days. Dropping the retail price by \$$X$, will cause the low-holding-cost customers to do a break-even analysis and thus buy $\frac{\alpha XD}{h_L}$ units and stock up. This decreases the retailer's holding costs as long as $h_L < h_r$. Suppose we offer a discount so that the low-holding-cost customers buy for k days, i.e., $X = kh_L$. Then total retailer costs over k days will thus be

$$s + (X\alpha kD) + (X(1 - \alpha)D) + \frac{h_r D k^2 (1 - \alpha)}{2}$$

Any set of parameters that decrease retailer costs will provide incentive for the retailer to promote at retail. Notice that the previous model can permit the retailer to benefit from both customer segments. The low-holding-cost segment will assist in decreasing retailer costs by reducing retailer holding costs from h_r in return for a retail promotion, which will reflect customer holding costs of h_L. The high-holding-cost segment will be willing to pay regular price in return for the retailer holding the inventory. Thus the retailer has the potential to benefit from both customer segments.

Additional details that could be incorporated (and that are in the papers by Iyer and Ye [50],[49]) adjust for the reservation price differences between the two segments. The following example illustrates the calculations.

Example

Suppose the retailer has parameters $s = \$80$, $\alpha = 0.6$, $D = 100$ cases per week, 5 days per week, $h_r = \$0.02$/case/day. Suppose the retailer buys once every 20 days. If the low-holding-cost customers have $h_L = 0.009$/case/day, then dropping the retailer price by $X = \$0.18$/case for 1 day would cause the retailer costs over 20 days to be

$$\begin{aligned} &80 + (0.18 \times 0.6 \times 20 \times 20) + (0.18 \times 0.4 \times 20) \\ &+ (0.02 \times 20 \times 20 \times 20 \times 0.4/2) \\ &= \$156.64 \end{aligned}$$

This is in contrast to the costs without this retail promotion:

$$\begin{aligned} &8 \times 20 \\ &= \$160 \end{aligned}$$

The impact of this promotion is to decrease retailer costs. Note that we showed that dropping the retail price to synchronize with purchases from the manufacturer permits the retailer to flow through part of the purchases so that inventory levels are decreased. In effect, inventory moves from the manufacturer and through the retailer to the low-holding-cost customer.

Why might customers have lower holding cost than retailers? One reason is that customers do not treat their extra space in the home (basements, cabinets, pantry space, and so on) as having commercial value and thus do not incorporate the opportunity cost of that space. Another reason is that customers may not be reflecting the cost of money correctly. Empirical data suggests that customers with low reservation prices do tend to have lower holding costs thus suggesting that they understand the need for the retailer to segment customers through pricing differences.

4.9 Applying the Stockpiling Model to Empirical Data

This section provides details from the paper [50] that illustrate fitting the model described in the previous section to an empirical dataset from 60 stores. Consider a retail environment where customers arriving at a store belong to one of three possible segments, $s = 1, 2, 3$. The three segments have the following characteristics:

1. Segment 1 makes purchases every period to satisfy consumption of exactly one period.
2. Segment 2 does not purchase at the high price level.
3. Segment 3 does not purchase unless the retail price is low, i.e., lower than the average between the highest and the lowest price.

The model was applied to a data set consisting of sales of canned tomato soup over a two-year period for each of 60 stores. The average R^2 across the 60 stores was 76%, suggesting that the customer model was a reasonable representation of the observed sales. In addition, the forecast error (σ) associated with the fitted model parameters could be estimated and included in the description of customer demand. Furthermore, there was a very high positive correlation (around 0.99) between segment reservation prices and their holding costs. This suggested that customer segments willing to pay low prices also seem to be ready to stockpile, as evidenced by their low holding costs.

Table 4.1 Fitted parameters for two sample stores

Parameter	Store 1			Store 2		
	Segment 1	**Segment 2**	**Segment 3**	**Segment 1**	**Segment 2**	**Segment 3**
r_s	1.511	0.5	0.35	1.511	0.5321	0.346
h_s	0.7555	0.05	0.0056	0.7555	0.0337	0.048
c_s	503.3	416.3	375.2	88.8	114.3	672.0

Table 4.1 provides the values of holding costs, reservation prices, and consumption rates for two stores with different characteristics.

The parameter values for the two stores illustrate the different customer environments faced by these stores. While store 1 has a composition across segments of 39%, 32%, and 29%, store 2 has a composition across segments of 10%, 13%, and 77%. Thus we would expect a greater extent of promotions from store 2 than from store 1 due to the much larger size of segment 3 for store 2. Note that the holding cost of segment 3 customers for store 2 is larger than that for store 1. For example, a retail price of \$0.28 would generate a demand from segment 3 in store 1 of 4,502.4 units. This value is obtained as $\left[\frac{(0.35 - 0.28}{0.0056}\right]375.2 = 4{,}502.4$, following the definition in the earlier section. The same retail price of \$0.28 would generate a demand from segment 3 in store 2 of 672 units. This value is obtained as $\left[\frac{(0.346 - 0.28}{0.048}\right]672 = 672$. Thus the size and depth of promotions that are profit maximizing depend on these customer characteristics. Finally, we note that the model forecast error for store 1 is $\sigma_1 = 0.24$. For store 2, the model forecast error is $\sigma_2 = 0.4$. This difference in model forecast error will affect the store inventory level required to provide the desired customer service level for a given store price. The holding cost associated with the safety stock at the stores impacts the choice of the optimal store prices.

As mentioned earlier, the R^2 values ranged from 53% to 87% with an average R^2 level of 76% across the 60 stores. It is clear that the product category (canned soup) affects these parameter levels. For example, we expect the values for customer holding cost to be larger for bulkier products (such as toilet paper) than for canned soup. Similarly we might expect the customer holding cost to be larger for expensive but small-volume products such as analgesics.

4.10 Chapter Summary

A key driver of supply chain costs in grocery supply chains is the volatility in demand created by price promotions. However, price promotions enable multiple market segments to be served and do serve an effective role in this industry. The chain structure of grocery supply chains offers multiple supply locations—from manufacturer plants, to field warehouses, to distributors and cooperatives, to direct store delivery. Capacity in this chain deals with store physical shelf capacity, truck capacity, warehouse capacity, and plant manufacturing capacity. Order lead time is impacted by the interaction between orders and capacity. Often, volatility of demand and lack of synchronization with production implies high levels of inventory across the supply chain. Coordination in grocery supply chains arises through vendor managed inventory initiatives, where manufacturers manage distributor inventory, better synchronization of promotions and production, collaborative forecasting, and so on. Competitive pressures in the grocery industry demand that retailers compete on attributes such as product variety, freshness, service level, promotions, and so on. Given such pressures, effective supply chain management generates a key source of competitive advantage.

With food being an important ingredient of most economies, grocery supply chains typically involve significant volumes of products flowing to match daily purchase and consumption. Grocery supply chains are typically fragmented and involve a large number of SKUs, relative to varied consumer tastes and price points. The competitive nature of the industry generates low net margins at retail and a tremendous focus on cost reduction. Supply chain coordination approaches such as vendor managed inventory, category management, scanner-based promotions, and the like are all focused on improving cost performance. Store shelf capacity and warehouse and delivery capacity coupled with manufacturer and retailer price promotions drive large levels of inventory in the supply chain. The industry has innovated with a tremendous focus on information based coordination and use of radio frequency identification (RFID) devices, for example, to improve supply chain performance in this industry. National and store brands compete to capture the customer sales dollars and influence consumer inventory so as to influence consumption.

CHAPTER 5

Apparel Supply Chains

The US apparel industry generated over $199 billion in annual sales in 2011 [99]. Every season (there may be six to eight each year), manufacturers strive to get product to the retail market in time. Between 80% and 95% of new SKUs are introduced each season. Product that is left over at the end of the season is sold through store markdowns or at outlet stores. Retail gross margins for fashion apparel ranges from 200% to 250%. It is an extremely competitive industry with demand forecasts involving high margins for error, ranging from 100% to 300% of sales.

The *chain* of entities through which apparel flows is globally dispersed in order to be competitive. Effective management of these flows is subject to the long lead times associated with their global sojourn and requires integration of orders with demand information as events unfold. The *capacity* available to manufacture product during the short season is often not sufficient to meet a large surge of demand; thus buffer inventories become the main strategy to maintain service levels. In addition, the historic imposition of textile quotas (which have yet to disappear) necessitates longer order lead times. The choice of the mix of domestic and foreign supplier capacity can thus be a crucial determinant of competitiveness. In this industry, *coordination* agreements between retailers and manufacturers are often necessary to generate incentives to share demand information and provide faster deliveries. Finally, measures of *competitiveness* of this industry vary from being in fashion to being in stock to being value competitive.

5.1 Apparel Supply Chain Challenges

Fashion products, like avant-garde, defy definition. While there is significant disagreement regarding what will be fashionable in a season, at the end of the season there is usually far more consensus regarding what was fashionable. This large shift in uncertainty over a short selling season, combined with very long supply lead times, makes managing fashion supply chains challenging. There are several reasons for the long lead times of supply chains, but the impact is just one or two deliveries per season for many products. Long lead times, high demand uncertainty, and the need for high service levels or the potential for lost sales justify large safety stock for fashion products.

The typical time from design to retail sales for apparel can vary from twelve to eighteen months. Data from the Harvard case "Sport Obermeyer" ([54]) provide an example of a fourteen-month lead time; the Liz Claiborne case ([41]) describes a twelve-month lead time; other examples ([55]) suggest a ten-month lead time. These long lead times reflect the large fraction (over 80%) of new products each season. Typically designers choose the fabric, components of the apparel, styling, and so on, to entice the customer to purchase new apparel every season. Each of these unique features creates lead time challenges, given that the industry has historically been fragmented, with globally dispersed outsourced entities forming the supply chain. In addition, since many of the orders from buyers end up coinciding, the associated congestion for supplier capacity creates lead times. Finally, regions such as the United States and the euro zone impose quotas on the amount of different kinds of fabric that may be imported from a given source country. These quotas create an incentive to order early in order to avoid running out of the country quota. All of these issues result in long lead times in the global apparel supply chain.

A consequence of long lead times is that the retailer has to place orders for the current season without access to data regarding sales of product in the adjacent season or even the same season the previous year. This means that it is difficult to adjust to trends that may arise closer to the start of the season, and that might cause significant demand shifts. How can such shifts affect forecast error? A study commissioned by the trade group Crafted with Pride in the USA ([23]) suggests that a movement from a two-month to an eight-month lead time can increase forecast error from 20% to 55% of the mean demand for fashion products. As an example, Iyer and Bergen ([60]) describe an example in which demand for a woman's blazer at a catalog retailer varied from 1 million units to 10,000 units between successive years.

Thus, fashion apparel products have far greater demand uncertainty during the planning stage, when what will be fashionable is not known, but far more agreement regarding fashion as trends unfold and customer choices become clearer. This trend-spotting feature or trend-following aspect of demand leads to SKUs becoming dogs (low-demand items) or runners (high-demand items) during a season. Notice also that such a broad definition of fashion products suggests that fashion need not refer to apparel alone; books, compact discs, toys, and electronic products all have such runner–dog demand evolution, with a winner-take-all demand structure. This also means that long lead times have consequences that are far larger than the safety stock effect that is usually anticipated. The long lead time also increases the demand variance and thus significantly increases safety stock.

5.2 Chain Structure

The apparel industry supply chain consists of material flow from fiber producers to fabric producers to apparel manufacturers to retailers who supply consumers ([55]). Fiber manufacturing involves large capital expense and research and is a concentrated industry with ten firms providing over 90% of the market. Fabric producers convert the fiber into a variety of fabrics. There are over 6,000 firms involved, and about twelve firms supply 25% of the fabric market. Apparel manufacturing is a fragmented industry, with 70% of the firms employing fewer than fifty people. Apparel manufacturing also involves factors of manufacturing in which the sewing machines might cost less than the annual labor costs to operate the machine. Thus apparel manufacturing has low barriers to entry and low economies of scale. Finally retailing takes place in many different formats: from department stores to branded stores to outlet malls to catalog stores to e-retailers.

Since apparel designers enjoy no intellectual property protection in the United States for the look and feel of their designs, many sell the apparel and not just the design; thus they are involved in coordinating the manufacturing and distribution. Most retailers are part of supply chains of dispersed entities that are spread throughout the world. The locations of supply chain entities are also affected by textile quotas imposed bilaterally by countries. For example, if the quota limit for China has been reached, there is incentive for Chinese manufacturers to produce in Mauritius and ship to the US market. This might involve sending Chinese employees to work in Mauritius in order to manufacture the product. The resulting supply chain thus adds lead time and costs to the end customer, but given the associated expertise and cost advantages, it may also determine supply chain structure.

5.3 Capacity

The capacity for apparel manufacturing is dispersed globally. In addition, apparel manufacturing takes place in smaller firms with little ability to take business risks. Textile quotas historically require early order placement and delivery to guarantee that the volumes shipped to the US market remain within the quota limits. The net effect of uncertain demands and limited capacity is the presence of long lead times.

The nature of capacity, i.e., the mix of automation and manual labor as factors of production, also varies across manufacturing locations. For example, orders accepted by factories in Hong Kong tend to involve more automation and thus higher costs per unit and lower order minimums than factories located in mainland China ([54]). These restrictions on order sizes, influenced by the nature of capacity, affect the particular products sourced in each of the locations. There is also the choice of domestic capacity vs. imported capacity. Studies by the apparel industry trade group Crafted with Pride suggest that for products with high forecast error, which have the potential to decrease closer to the start of the season, it is profitable to source domestic even with higher prices.

The distribution of work across employees in an apparel line can also add to the productivity of capacity. As an example, see the description of the bucket brigade production lines at Champion Industries reported in Bartholdi and Eisenstein ([6]). They summarize the impact of switching from a piece-goods, bundle system to a bucket-brigade system. The key change was to make the work zones flexible and responsive to production rates of individual workers and work content of individual pieces being produced. The system showed significant improvement in productivity (about 15%) over the original system. In addition, the system permitted self-managed work teams to completely handle the manufacturing of the product. This resulted in an observed improvement in quality and productivity.

Finally, as part of a coordination agreement with suppliers, capacity commitment is used to reserve capacity at suppliers in anticipation of demand. But capacity markets are also observed in certain areas of the industry. The Italian apparel manufacturing industry has the *impannatori* or capacity brokers, who mediate between the need for capacity and its availability across the small entrepreneurs in Prato, Italy ([69]). Studies of the Prato markets suggest that in return for the ability to sell capacity, sewing and printing machine manufacturers have increased the extent of investment in modern machinery to levels significantly higher than the rest of the world.

5.4 Coordination

The typical time line from design to retail sales for apparel can vary from twelve to eighteen months. Data from the Harvard case "Sport Obermeyer" ([54]) provides an example of a fourteen-month lead time, the Liz Claiborne case ([41]) describes a twelve-month lead time, and the example in [55] describes a ten-month lead time.

Surveys by major retailers suggest that service levels at various stores are around 70%. Thus one out of three customers does not find the item in stock at a store that carries it. Note that apparel SKUs refer to color, style, and size availability, which requires demand estimates of specific sizes at a location. From a supply perspective, if manufacturer deliveries are of a fixed assortment of product across sizes, then it is clear that any deviation from the average size mix can cause stockouts. Thus, stockout reductions may require coordination between a flexible manufacture of varying sizes (driven by observed store sales) and careful retailer monitoring of inventory levels by size level demand and availability. The additional complication is the impact of fit preferences across customers, ranging from slim fit to loose, baggy fit choices. Such trend effects may add additional complexity to the problem of forecasting demand at the SKU level.

Furthermore, mall traffic has shown modest growth (if any) thus making it critical to maximize each customer who walks through the door.

However, studies show that despite the effort to attract consumers into the store, only around 33% of the customers leave the store having bought something. Surveys of the remaining 67% of the customers who leave the store without purchases show that many of them did not buy items because the specific color or size was out of stock. In such a context, maximizing consumer effectiveness implies managing out-of-stocks carefully.

But planning a high service level well in advance of the beginning of the season does not imply that the consumer will observe a high service level during the season. For example, consider the example where a product's demand is either high or low with probability 50%. Choosing a 90% service level may well imply a 100% service level for low-demand items and an 80% service level for high-demand items. Thus the consumers during the season may observe a high service level for products without much demand: these are the products that are subsequently marked down. However, for products with a high demand, stockouts may be observed. Industry estimates of forced markdowns are about 13% of net retail apparel sales. The corresponding inventory carrying costs are estimated to be 6% of sales. At the same time, stockout-related costs are estimated to be 5% of sales. Thus overall annual apparel pipeline costs estimated to be $24 billion ([55]).

How can coordination schemes improve supply chain performance? One such approach is quick response movement in the apparel industry. Quick response is defined as "a strategy for tying apparel and textile retailing operations to apparel and textile manufacturing operations in order to provide the flexibility needed to quickly respond to shifting markets" ([55], p. 3) Because assortments are planned close to the selling season, after consumer testing and limited introductions to pretest and fine-tune specific color, style, and size options, forecast error is decreased, in-stock products are consequently increased, and markdowns reduced. Such an approach could then provide both improved in stock and lower inventory levels.

In many contexts, there is a need for coordination agreements to implement quick response. Iyer and Bergen [60] provide a set of possible Pareto-improving coordination agreements. One agreement involves the manufacturer offering quick response in return for the retailer improving service level for the product. Another involves the retailer providing a volume commitment across a set of products in return for the flexibility to adjust specific SKU orders. A third describes a wholesale price agreement with a quantity discount as a mechanism to implement quick response. Each of these coordination agreements represent different risk-sharing agreements used in the industry.

5.5 Competitiveness

How do apparel supply chains compete? One approach is to compete on cost, an approach used by Walmart and other department stores. This strategy focuses on developing a cost-efficient supply chain that may require global sourcing with low costs but long lead times. Such supply chains then require large buffer stocks to compensate for demand uncertainty or a focus on predictable demand for basic products with low demand uncertainty. But there are many other dimensions of competition in the apparel industry.

The multibillion dollar Spanish retailer Zara focuses on being synchronized with trends by adapting, in real time, to consumer suggestions: the focus is on speed of supply and product availability over selected periods. The company has stores all over the world, owns large sections of the apparel supply chain, and manages the entire chain to speed innovation and product availability. One secret is the constant flow of customer requests and information from stores to the design studios as well as constant flow of product from plants to stores, with planned replenishment. Zara sources the fabric from all over the world (e.g., Italy, China, Japan, India). But it owns its own machines that cut the fabric in batches. The layout of templates is optimized within each roll of fabric to minimize scrap. Independent sewing shops in Europe and Morocco do most of the stitching. The apparel comes back to Zara where it is ironed, packaged, and grouped by store. Zara contracts with independent trucking companies to distribute the products to stores. The retail stores worldwide are solely owned by Zara. Customers expect fresh assortments every time they visit the store and do not expect products to be in stock for a long time. This creates an urgency to buy and consequent expectations of in-stock levels. By controlling most steps in the supply chain, Zara is able to respond faster to market trends.

Zara represents a mainly vertically integrated supply chain with intense coordination between levels. Store managers pass along customer requests to designers, who then incorporate customer suggestions into new designs that are manufactured and delivered frequently to stores. This coordination enables faster cycle times, under two weeks from start to finish. Capacity for cutting, packing, and delivery is managed directly by Zara. The sewing capacity is subcontracted but managed by Zara. Is the Zara supply chain competitive? The company has a market value that is significantly larger than most firms in the apparel industry. Success comes from significant control of assets as well as an intense coordination of information flows throughout the supply chain.

Another approach to compete is a focus on customized apparel. Such an approach is offered by Lands End with its custom direct pants. Such customization may create longer lead times and issues with handling returns of customized products, especially noteworthy in an industry where returns could run 30% of volume.

Another competitive offering is guaranteeing that if an item is not in stock, either the item or delivery (to the customer's home address) will be free. Under such a scheme, the retailer's product margins, anticipated customer demand (given such guarantees), or supplier delivery lead-time improvements are expected to cover the additional costs.

In addition, competition across stores gets stores to provide higher service levels than individually optimal, and thus they obtain lower profit levels in order to retain customers. Under competitive conditions, customer service level extends to offers of returns at full credit, thus increasing the forecast errors and inventory underage or overage levels. Competition across stores also forces higher levels of product variety and lower levels of customer loyalty as customers start following trends to determine shopping preferences rather than looking to the brand or designer to make apparel choices.

5.6 A Conceptual Model of the Apparel Inventory Decisions

Consider the demand model faced by an apparel buyer. Suppose this demand becomes more predictable as the season approaches. A conceptual approach, using a specific example adapted from [35], may incorporate current information to improve demand forecasts. Suppose demand at the end of the season can be classified into two possible demand levels, dogs and runners. These groups of items have increasing average actual demand levels and associated mean and variance. Next, suppose probability distributions are fit to the ex post demand from each category as shown in Figure 5.1. The associated mean and standard deviations for dogs are 4.5 and 3.35, and for runners, 27 and 16.43.

While the products can perhaps be classified accurately as dogs or runners at the end of the season, the buyer's classification of product category is often imperfect at the start of the season. Thus, for example, if a buyer classified a product as a dog at the start of the season, there may be an 80% probability that the item ended up being a dog and a 20% probability that the product ended up being a runner. Similarly, if a buyer classified an item as a runner at the start of the season, there may be a 65% probability that the item ended up as a runner and as a dog, 35%.

The demand distributions described for each planned classification are obtained by taking the probability that the product actually belongs to a segment and multiplying it by the probability of that demand being realized (from Figure 5.1). In other words the demand distribution for an item classified as a dog is a weighted mixture of the two possible

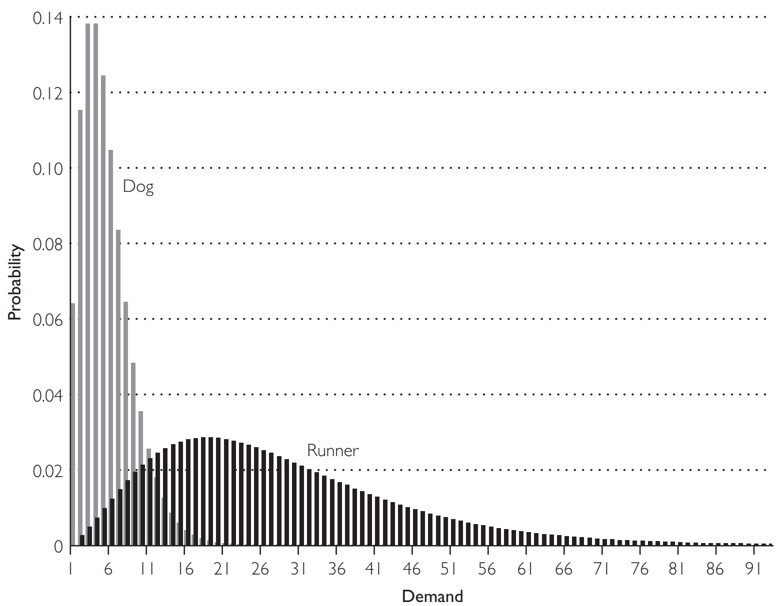

Figure 5.1 Demand distribution by ex post classification

distributions, as in Figure 5.2. Similarly, Figure 5.3 shows the distribution for items classified as runners.

Thus the actual mean for a product classified as a dog is 9, and the associated standard deviation is 12. The corresponding means and standard deviations associated with items classified as runners are 19.13 and 17.14, respectively.

The preceding example shows that, given the buyer's inherent difficulty in classifying the product, the forecast error associated with classifications is large. For example, an accurate classification of a product as a dog would have a forecast error (standard deviation/mean) of 3.35/4.5,

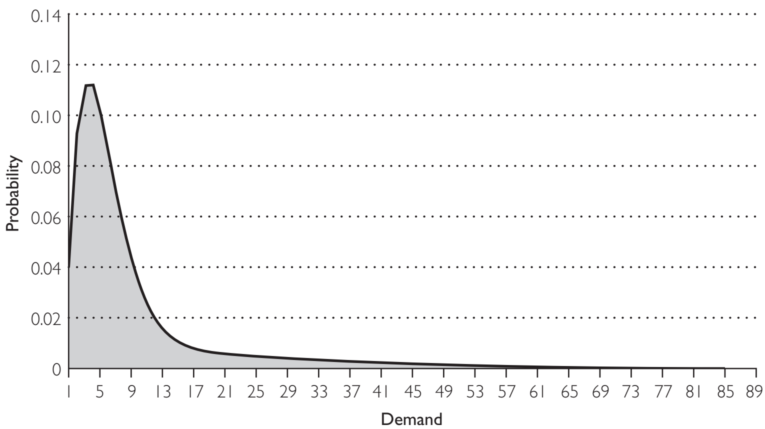

Figure 5.2 Demand distribution for planned dogs

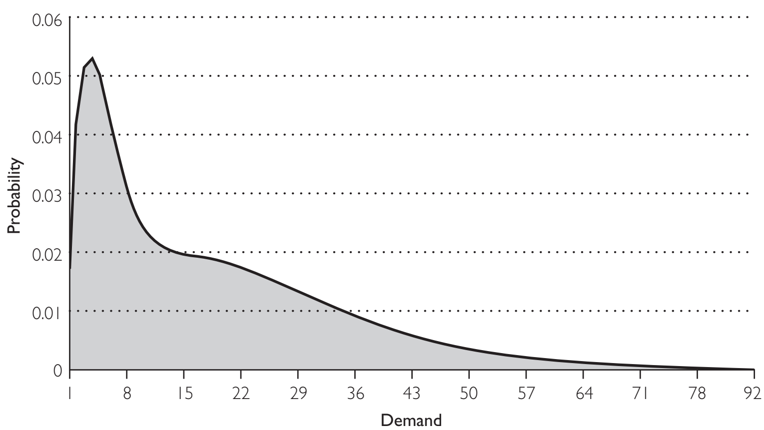

Figure 5.3 Demand distribution for planned runners

or 0.75. However in the presence of inaccurate classifications, the standard deviation of a product classified as a dog changes to 12/9, or 1.33. This greater ratio of standard deviation divided by the mean suggests the need of a larger level of safety stock and associated inventory costs. Of course, the major difficulty in accurately classifying a product is the lag between the forecast decision and actual demand data due to the long procurement lead time before the season.

5.7 Using Recent Observed Data to Improve Forecasts

How can the approaches described earlier be improved if there is access to more current data regarding season demands? One approach is to use Bayesian updating ([35]) to improve demand forecasts. To understand this approach, consider the classification of products and their associated actual demand distribution as in the example in the previous section. Before discussing details of the approach, consider how collected data can be used to project season demand for a product.

One of the features of the apparel industry is the existence of stable percent-done curves. The percent-done curve provides an estimate of the percent of total demand that is realized at different points during the season. An example is shown in Figure 5.4.

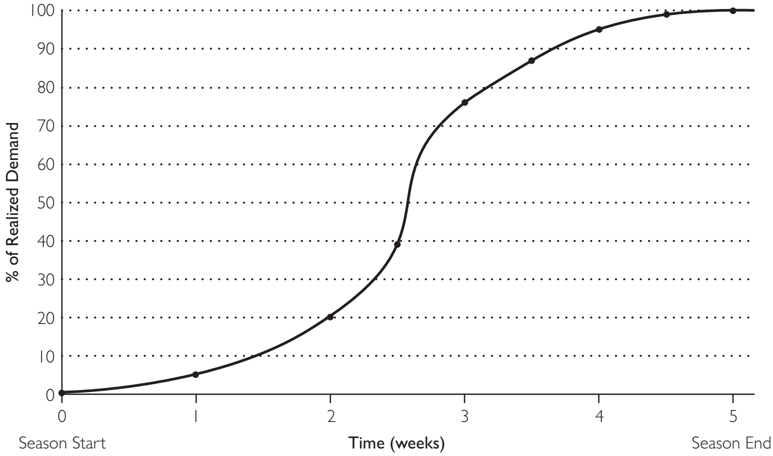

Figure 5.4 Percent-done curve

In Figure 5.4, the x-axis shows the time from the start of the season to the end of the season. The y-axis shows the percent of total season demand observed at different points in time. The y-axis thus varies from 0% to 100%. Thus a demand of five units, observed over two weeks, translates into 20% of the season demand and thus suggests a $\frac{5}{0.2}$ or a 25 unit season demand projection. This ability to project season demand based on observed selling rate over shorter time periods permits early demand data to be used to improve demand forecasts. Given an observation of demand data, the buyer can revise the weights or probability that the product belongs to a segment.

As an example, suppose that a product had been classified as a runner, but the early demand projection suggested a demand level of 25 units. Then the Bayesian updated weights for that product are obtained as follows:

$$P\left(\frac{Runner}{Demand = 25}\right) = \frac{P\left(\frac{Demand = 25}{Runner}\right)P(Runner)}{P(Demand = 25}$$

Using the data provided earlier, the calculations would be

$$P\left(\frac{Runner}{Demand = 25}\right) = \frac{0.0251 \times 0.65}{0.0164} = 0.998$$

Thus, given a revised demand estimate of 25 units, the revised weights for that product being a dog or a runner are 0.002 and 0.998. Note that the effect of the new data is to increase the probability that the item will be a runner. This change in estimates reflects the incorporation of observed data in the Bayesian updating procedure. Thus, as data are received during the season, the weights get updated, the associated demand distribution converges to the actual product classification, and forecast error decreases.

5.8 Buyer Forecasting Processes Commonly Used

What is the consequence of long procurement lead times? Note that the retailer has to place orders without access to data regarding sales of product in the adjacent season or even the same season of the previous year.

This means that it is difficult to adjust to trends that may arise closer to the start of the season and that might cause significant demand shifts. How does a buyer in a fashion product environment make purchase decisions given the long lead times? There are numerous descriptions of the process; a typical one was described earlier in this chapter. Buyers are provided all historical background information regarding past products. Buyers then use the information to create a description of product demand if the product is a runner or a dog.

The buyers' meeting then makes a consensus determination regarding demand for the product. Usually the meeting results in buyers providing input regarding why they think demand will unfold at a particular level. Since the goal is to get the product demand right, the consensus decision often ends up close to the mean of all of the buyers estimates. This estimate from the buyers' meeting is then used to determine the amount to order for the upcoming season.

One key problem is that, when one examines the relationship between buyer estimates and observed season demand, the scatter plot is often skewed towards optimistic forecasts. One of the causes for such optimism by buyers is that they are often loathe to run out of product given the high product margins. Thus, rather than examining the process as one of demand forecasting, they end up trying to prevent inventory levels from being too low, thus denying themselves the upside benefits of higher sales levels.

In addition, many buyers are provided access to databases of customer purchases where each SKU is cataloged based on over 1,000 attributes. This permits the buyer to check sales of products with zippers, products with a particular color palette, products with particular fabric types, and so on. The goal of the buyer is to perform the appropriate data mining of product sales, identify opportunities by flagging upcoming trends and then get ahead of the curve by positioning inventory of the correct type, anticipating demand for products. For catalog stores and department stores facing long lead times, often the earliest season sales data may come from Miami or San Diego, where seasons begin earlier than in the rest of the country.

Given the processes used by buyers in practice, improving the apparel supply chain requires a healthy combination of statistical processes and buyer judgment. The approaches outlined in this chapter provide such a scheme.

5.9 A Model of the Profit Impact of Quick Response

If decisions regarding purchase quantity are made closer to the start of the season, then better demand information is available, resulting in lower forecast error. Figure 5.5 provides results obtained by the industry trade group called Crafted with Pride in the USA. Their study used fifty buyers across the industry and had them forecast demand for fashion products and basic products at different points in time before and during the season. The graph shows how the forecast error varied with time and across product type for a fashion product. As the season approaches, there are many entities that provide sources of information. Fashion shows all over the world showcase upcoming trends. Fashion consulting services provide their judgments regarding the upcoming season, while color consultants project popular colors for the upcoming season. Fashion magazines highlight specific features and designs. All of this information gradually defines the fashion trend for the season.

In order to illustrate the need for coordination agreements to implement quick response, consider the example of a retailer Assort that sells women's dresses. The first analysis will use a long lead time relationship between a manufacturer and Assort. In this relationship, the retailer has

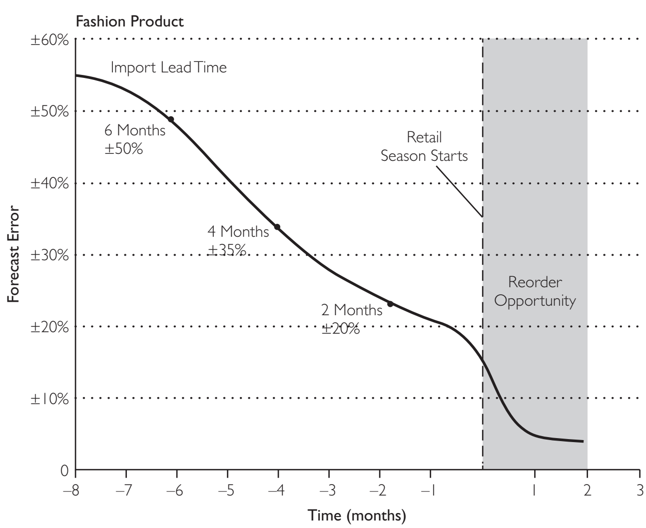

Figure 5.5 ***Forecast error vs. time***

access to historical data and uses that data to project possible demand levels for products.

Assume that analysis of the historical demand data for reported products has indicated that demand through the season can be divided into two groups: low and high demand. The set of dresses in the low demand category is observed to have demands whose distribution is uniform between 1 and 5. The set of dresses in the high demand category is observed to have demands whose distribution is uniform between 4 and 8 units. Notice that there are some dresses whose categorization is not perfect. This reflects the uncertainty regarding whether they are high observed demands in the low category or low observed demands in the high category. Note that the best that the sales managers can do for the products is categorize them into these categories. (As an analogy that does not allow for overlap, in most classes, there is a range of performance scores that warrant the same final letter grade.)

The role of the buying team is to assess, about eight months in advance, when the order is placed, the probability that demand for a product is from each of the possible categories. For this example, assume that the best estimate is that demand for a particular dress will be either low or high with a 50% probability.

These dresses are bought for \$100 and sell for \$200. If Assort runs out of dresses, the future profit impact is estimated to be \$200. Dresses that are held through the fashion season incur a holding cost of \$20. Those dresses that do not sell during the season are sold off to an outlet store for \$40.

Under this system, what should be Assort's optimal order size and associated expected profit, if orders have to be placed eight months in advance?

Answer: Given these costs, note that Assort will estimate the optimal service level to be

$$\frac{r + g - c}{r + h + g - s}$$

where $r = 200$, $c = 100$, $h = 20$, $s = 40$, $g = 200$. Thus the optimal service level is 78.9%.

Note that we are provided the conditional demand distributions, i.e., demand realizations depending on whether the product is in the low or high demand category. The buyer's estimates have also assigned a 50% probability that the product being considered for the upcoming season falls in the low or high category. Thus, for example, the probability that the demand is for 1 unit is equal to

Probability (Demand = 1 unit) = (Probability (Demand = 1/Low Category) × Probability (Low Category)) + (Probability (Demand = 1/High Category) × Probability (High Category))
= (0.2 × 0.5) + (0 × 0.5)
= 0.1

Thus the forecasted demand distribution, eight months in advance, is

Demand	*Probability*
1	0.1
2	0.1
3	0.1
4	0.2
5	0.2
6	0.1
7	0.1
8	0.1

With this demand distribution, and to attain the optimal service level, the inventory of dresses purchased is 6 units. Associated with this inventory purchased, Assort's expected profit is as follows:

(–100 × 6) + (Purchase Costs)
((0.1 × 200 × 1) + (0.1 × 200 × 2) + (0.1 × 200 × 3) + (0.2 × 200 × 4) + (0.2 × 200 × 5) + (0.1 × 200 × 6) + (0.1 × 200 × 6) + (0.1 × 200 × 6)) + ((0.1 × 20 × 5) + (0.1 × 20 × 4) +
(0.1 × 20 × 3) + (Expected Revenue)
(0.2 × 20 × 2) + (0.2 × 20 × 1)) + (Expected salvage – Holding Costs)
((–0.1 × 200 × 1) + (–0.1 × 200 × 2)) (Expected Penalty Costs)
= 216

The associated manufacturer revenue is 100 × 6 = \$600.

5.9.1 *Quick Response: Retailer Impact*

Consider the quick response (QR) approach. Under this scheme, the manufacturer has to receive the order only four months in advance. The retailer can collect data regarding sales of similar products at points closer to the upcoming season before placing an order. Intuitively, the ability to order closer to the season increases the possibility that more recent trend information or economic conditions can be used to better forecast demand. For this example, assume that data regarding demand for similar product enables the retailer to further refine the demand distribution estimates. **What will be the impact of QR on the retailer?** (For now, assume manufacturer prices remain the same.)

Answer: Under QR, the retailer collects four more months of demand. Assume that the demand (d1) during these months follows the same distribution as demand during the upcoming season, i.e., the outcomes belong to the same demand category. What might cause such a relationship? Perhaps styles, color, or patterns link products from different seasons. Thus, assume that the retailer observes a draw from the demand distribution for the adjacent season. Depending on the value of this observed demand, Assort will adjust demand estimates as follows, using the Bayesian approach for updating weights (Section 5.7):

Demand	*Probability*
$1 \le d1 \le 3$	P(Low) = 1, P(High) = 0
$4 \le d1 \le 5$	P(Low) = 0.5, P(High) = 0.5
$6 \le d1 \le 8$	P(Low) = 0, P(High) = 1

Thus, the observed demand changes the conditional weights (last column above) placed on each of the two demand distributions. As before, we can then derive the optimal inventory policy and associated expected profit for the retailer as follows:

Demand (d1)	*Probability*	*Inventory*	*Expected Profit*
$1 \le d1 \le 3$	0.3	4	$144
$4 \le d1 \le 5$	0.4	6	$216
$6 \le d1 \le 8$	0.3	7	$444
Total Expected Profit			$262.80

Thus, the retailer's profit increases from $216 to $262.80, an increase of 22%.

What is the expected quantity purchased from the manufacturer under QR?

$$(0.3 \times 4) + (0.4 \times 6) + (0.3 \times 7) = 5.7 \text{ units}$$

Thus manufacturer revenues decreases to $570, a drop of 5%.

It is clear that since the retailer-expected profits increase while the manufacturer revenues decrease, manufacturer profits decrease (if costs were to remain the same). This QR is not Pareto improving without coordination agreements. This suggests the need for agreements between the manufacturer and the retailer to implement QR.

5.9.2 *Quick Response: Service Commitment*

Since QR without any agreements does not benefit the manufacturer, coordination agreements may be necessary. One possible agreement is that the retailer commits to a higher service level, say 100% in this example, in return for the manufacturer providing QR.

What is the impact on the manufacturer and retailer under this scheme?

Answer: We will have to change the inventory purchased after observing demand to guarantee a 100% service level. We will thus get the following results:

Demand (d1)	*Probability*	*Inventory*	*Expected Profit*
$1 \leq d1 \leq 3$	0.3	5	$140
$4 \leq d1 \leq 5$	0.4	8	$170
$6 \leq d1 \leq 8$	0.3	8	$440
Total Expected Profit			$242.0

The associated manufacturer revenue is

$$100\,((0.3 \times 5) + (0.4 \times 8) + (0.3 \times 8)) = 710.$$

Thus the manufacturer and the retailer are better off with this agreement than in the original system because it is Pareto improving.

How do we implement this increased service level?

Consider two different newspaper advertisements that can be interpreted as enabling monitoring of these agreements. In the advertisement for Enzo Angiolini shoes, the retailer told the public that if the shoes were not in stock at the store, then customers would be mailed a free pair (either from another store or from the manufacturer). Note that this guarantees a 100% service level. In the second advertisement for Dockers pants, the manufacturer guaranteed that the pants will be shipped within a fixed number of days or provided free to the customer. Again, the customer is assured a 100% service level. Clearly, in this case, the customers play the role of monitoring agents and guarantee compliance.

How does this higher service level help the manufacturer? In a retail store that carries products from hundreds or thousands of manufacturers, additional service can range from such commitments to store personnel getting the inventory for the customer or providing free product. This extra servicing of manufacturer products provides the incentive for the manufacturer to implement QR.

Where are the retailer's increases in expected profit coming from?

Answer: Consider the service level in the old system and the new QR system with a 100% service level.

Demand (d1)	*Probability*	*Old System Service Level*	*QR System 100% Service Level*
$1 \leq d1 \leq 3$	0.3	100%	100%
$4 \leq d1 \leq 5$	0.4	80%	100%
$6 \leq d1 \leq 8$	0.3	60%	100%

By choosing the assortment of dresses closer to the season, Assort faces a lower forecast error. This enables the retailer to have fewer stockouts, the manufacturer to have higher revenue, and the customer to have a higher service level. All of this is accomplished without a decrease in retailer profits. In addition, customers would see a higher in-stock level that is uniform across products and thus get better service.

Note that providing a 100% service level in the old system would have decreased retailer profits to $170 because of the increased holding and salvage related costs.

Thus QR allows the customer service level to be increased without decreasing retailer profits.

This shows that improving lead times and enabling decisions under a lower demand forecast error may require coordination agreements between members of the apparel supply chain. Once such coordination agreements are established, the access to manufacturing capacity closer to demand enables improved competitiveness of the apparel supply chain. Notice that all four Cs played a role in improving the supply chain.

5.10 Chapter Summary

The US apparel industry had $199 billion in sales in 2011. The industry has high gross margins (200%–250%), long lead times (ten to fourteen months), and six to eight fashion seasons each year. There is a large percent (80%–95%) of new products each season and large demand forecast errors due to the fickleness of fashion trends. Given demand volatility, the industry has seen a tremendous number of retail and manufacturer closures in the past decade.

The global apparel supply chain is dispersed, with production at cost-competitive locations. Regulations and expectations regarding production processes require continual rethinking of production locations to match supply locations with consumer price and ethical expectations. One approach, followed by competitive chains such as Zara, is to have a significant level of vertical integration. Other fashion manufacturers, such as Liz Claiborne, leverage a collection of independent suppliers with close coordination and longterm relationships.

Since manufacturing capacity is located far from the demand points and is often not sufficient to meet a large surge of demand, buffer inventories become the main strategy to maintain service levels. The quick response (QR) movement in the fashion industry focuses on coordination agreements between retailers and manufacturers, along with information sharing, to incentivize shared demand information and provide faster deliveries. Retailers and manufacturers use different measures of competitiveness, including being in fashion, in stock, and value competitive.

The retail environment continues to increase in competitiveness, offering new formats such as e-retailing and mass customization. As competition increase, pressures for increased in stock without the corresponding increased prices have created the need for careful integration of the supply chain operation with the marketing divisions.

CHAPTER 6

Spare Parts

6.1 Spare Parts and the Four CS of Supply Chain Management

In many industries, the provision of spare parts and associated services represents a significant component of supply chain profits. Some studies [23] estimate US sales of spare parts and after-sales services to be 8% of the annual gross domestic product (GDP) or $1 trillion. Others [28] suggest, for example, that in 2001, General Motors earned relatively more profits from its $9 billion in after-sales revenues than it did from $150 billion in car sales. Another estimate [124] suggests that the total cost of ownership of a product may far exceed the amount spent on the initial product purchase and may vary between five and twenty times the original product cost. The main conclusion from these studies is that managing spare parts supply chains and related services after a product is sold may have a significant impact on both primary demand as well as on profits.

Consider the architecture of the spare parts supply chain. Demand flows from specific customer locations, where breakdowns and thus demands for specific spare parts and service occur, to dealers, regional distribution centers, central distribution centers, and manufacturing plants. Parts flow in response to these demands, with lead times decreased by forward positioning inventories. The capacity to service demand requests depends on the availability of parts at each of the levels of the supply chain as well as on the availability of associated servicing capacity. Design of the product can assist in increasing this capacity by permitting replacement of entire modules, thus decoupling product repair from the lead time for diagnosis and repair of the module. Coordination of maintenance information and product design updates with product usage data and management of the associated spare parts inventory can improve supply chain performance. In addition, coordinating the pricing and service guarantees with adjustment of the associated service capacity enables service guarantees to be met with high probability. Competitiveness metrics in aftermarket can range from speed of response to minimizing the cost of response to an offer of ironclad performance guarantees to offer of product on a pay-as-you-use basis, which moves the responsibility for product availability to the manufacturer.

The next sections provide a set of specific problem contexts along with a description of an adjustment of the supply chain architecture that improved performance of the supply chain.

6.2 Managing Spare Parts at the US Coast Guard

Chapters on coordination provides a description of the spare parts inventory supply chain at the US Coast Guard (USCG) [27]. We summarize the specific features of the spare parts system and the changes made to improve performance. The main supply chain support for air assets for the Coast Guard is the Aircraft Repair and Supply Center (ARSC) located in Elizabeth City, NC. Aircraft failures in the airstations are often tracked to part failures. Those parts are replaced with working parts from field inventory at the air station and the salvageable broken components are shipped to ARSC for repair. In turn, ARSC replenishes field inventory.

Figure 6.1 shows a supply-chain view of the aircraft service activities. Data are tracked in two separate databases: Aviation Computerized Maintenance System (ACMS) and Aviation Maintenance Management System (AMMIS). The ACMS database stores individual part-level serial number tracking and history of repairs and planned maintenance. The AMMIS database tracks flow of the broken part as it is repaired. In the original system, these two databases did not communicate ([27]).

Item Managers (IMs) at USCG were responsible provision of service parts, with an IM responsible for a group of parts. Typically, IMs used a part's demand history and treated demand for a part as an independent event. They chose a sufficient inventory level to satisfy demand, using ad hoc rules, developed through years of experience, to run the system. Officers at the USCG wanted to devise a scheme to use ACMS maintenance information to improve performance.

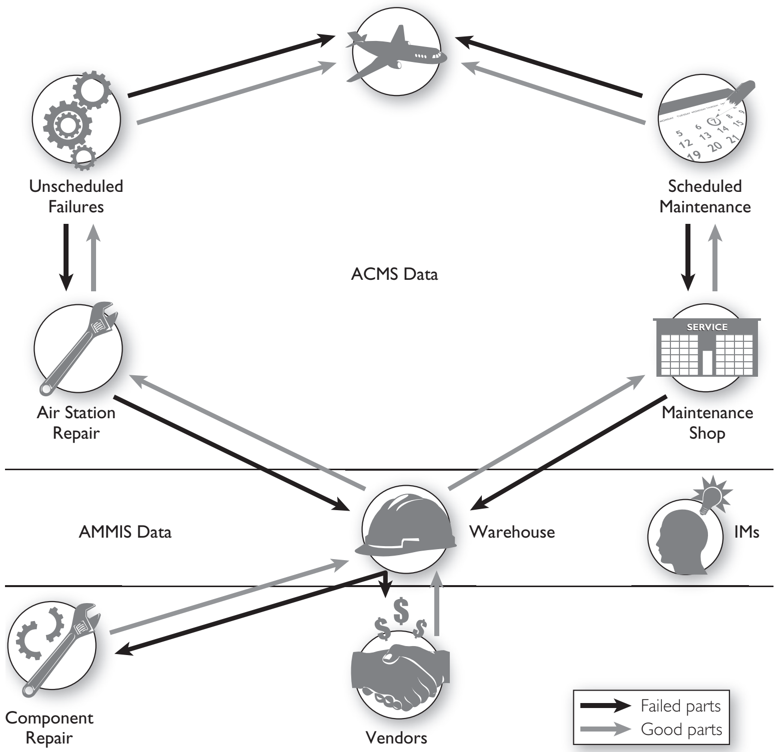

Figure 6.1 A supply-chain view of service–parts flows at US Coast Guard

Figure 6.2 summarizes the approach described in [27]. While several details are skipped, the key step is to incorporate part age information in the replenishment policy used by the IMs. This was implemented using an age-trigger mechanism that would signal when a part's age crossed a certain threshold. The idea was to use the number of parts whose age exceeds a certain threshold as a signal to forecast impending demand and thus adjust the level of inventory. The approach synchronized inventory with forecasted upcoming demands, thus adjust the level of inventory. The approach synchronized inventory with forecasted upcoming demands, thus decreasing costs while improving service.

The inventory policy tracks the number of old and new parts in the system, and the age threshold is optimized to account for marginal costs of shortage and holding and repair lead time. As Figure 6.2 shows, we anticipate the demand for old parts and trigger advance orders for these

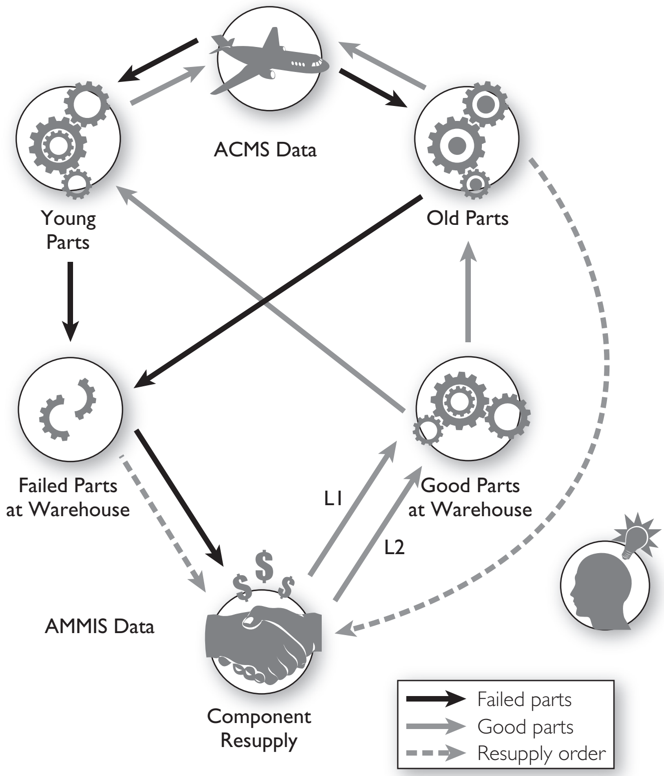

Figure 6.2 An integrated supply-chain view based on analysis at US Coast Guard

parts directly with the suppliers. For failures of young parts, we wait for failure to generate a replenishment order. If failures of old parts are more predictable, then triggering advance orders for these parts has the potential to decrease expected residence time for parts in the system and thus decrease overall inventory costs.

An outline of the specific adjustment of the inventory is as follows. Suppose the observed demand is correlated with the advance signals regarding the number of old parts. The observed correlation for different age thresholds is shown in Figure 6.3. Consider a model where the part age signal and the observed demand over supply lead time follow a joint bivariate normal distribution. Each period, once the part age signal is observed, the conditional distribution of actual demand during lead time can be generated. For any given service level, the associated inventory level is obtained.

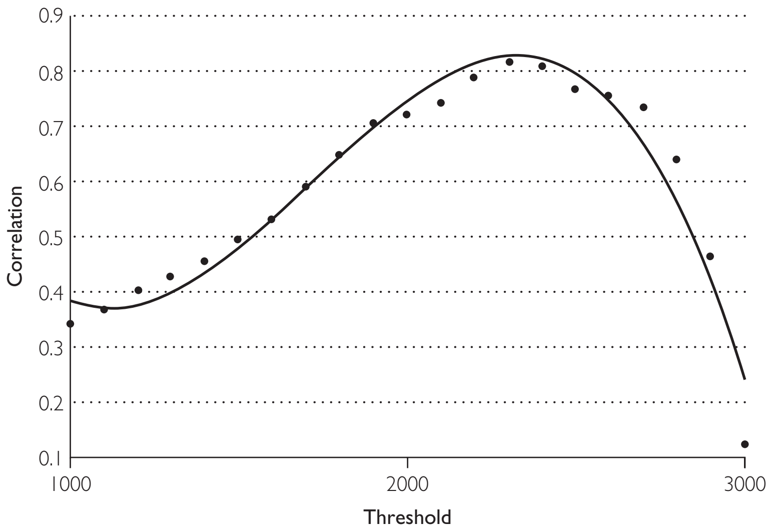

Figure 6.3 Correlation between signal and demand for different thresholds

The paper [27] provides details of the application using data from USCG. The projected benefits from using this approach were an increase in service for the same budget and a decrease in costs to provide the current level of service. The key idea—coordinating part use and thus part age with the associated demand forecast—can permit part inventory to be adjusted proactively, thus improving performance. In contrast, a purely replenishment approach would have decreased part inventory if demands are not observed for a while. Note that this is the opposite of the idea that was implemented, because low observed demands suggests that the parts being used on aircraft were getting old, thus increasing the likelihood of high demands soon. This difference in perspective generated improvement in supply chain performance.

6.3 Spare Parts at Saturn

Cohen et al. [18] describe the management of the after-sales parts availability at Saturn, a division of General Motors. They report that, in 2000, Saturn had the highest off-the-shelf parts availability across all brands. As a result, customers of Saturn return for repairs and scheduled maintenance for many more years than other automobile owners.

Demands for automobile parts can be triggered by a car crash or other repair incident, routine maintenance, a do-it-yourself project, or the needs of a non-Saturn repair-service provider. Repairs can occur at scheduled times (due to planned maintenance) or at random. The parts required for a repair would not be known until the car was diagnosed at the shop. Customers, however, prefer to wait for no more than one day to receive their repaired car back.

The usual part-procurement process for Saturn is as follows [18]: If the part was out of stock at the retailer, the order would go to a "pooling group," consisting of nearby retailers who may be able to supply the part from their inventory. If the pooling group cannot supply the part it would be ordered from the DC or from the supplier. Inventory at stocking locations would be visible in real time to all entities to determine part availability with all costs of part transfers borne by Saturn. The stocking and replenishment decisions at locations would be revised based on daily sales data by location.

Two key issues were managed to ensure high in-stock levels [18]. (1) Product criticality: There may be differences in necessity of the parts for function of the car. For example, a failure of an engine part might be serious, while a failure of a radio part is less serious. Thus it may be important to determine the cost to the customer associated with product failure and thereby the value of the component's uptime. (2) Decisions regarding a centralized or distributed service strategy: Under a centralized strategy, the goal is to achieve the highest turnover at lowest cost, with point-of-sale data used to forecast sales and thus choose inventory levels. Under a distributed service system, the goal is to determine customer need and obtain the part. In such a case, forecasting may depend on estimates of part reliability and the local installed base of cars. Coordination across locations to obtain parts plays an important role in managing performance.

As described in [18], the main challenges in the auto parts supply chain are (1) intermittent parts consumption with very low turns, (2) enormous disparity across part costs, (3) great variety across models, with hundreds and thousands of SKUs worth billions of dollars in inventory across the supply chain, (4) variable value of delivered service based on the severity of the failure, (5) lack of dealer interest in becoming efficient inventory managers and failure to see the connection between providing good service and selling cars.

6.4 Supplying Product in the Chicago School System

Eisenstein and Iyer [33] provide a description of a project to improve supply availability in the Chicago Public School System. The supply chain consisted of a warehouse that supplied products to 600 public schools. The products included engineering and educational supplies. Engineering supplies, also called Class A, included toilet paper, paper towels, rock salt, and so on, and accounted for about 50% of dollar value of the warehouse shipments but 1% of the items and 70% of the shipment volume. Educational supplies, also called Class B, accounted for 99% of the items, 50% of the dollar volume, and 30% of the physical volume. In the original system, all items shared a common truck capacity to minimize waste shipment space. Each school had a scheduled delivery once every two weeks.

At the start of the project, schools had observed poor-on-time delivery of products. The planned delivery lead time of two weeks was often replaced by an observed lead time of three weeks and a maximum of up to eight weeks. Figure 6.4 shows the original distribution of delivery lead times. Figure 6.5 shows the fluctuation in volume of loads across days as a line graph and as a histogram with the truck capacity indicated. Figure 6.6 shows the same volume each day relative to the available trucking capacity. It is clear that there are many periods when the loads exceed truck capacity and thus result in the lead times observed in Figure 6.4.

The project [33] describes a new system in which truck capacity was split so that deliveries of engineering goods, whose demands were predictable, were done once every two weeks. However, delivery of hard-to-predict educational supplies was done overnight, via the school's internal mail system. This synchronization of delivery lead times to part demand characteristics improved system performance. The reorganized system observed faster delivery without any increase in truck capacity and reduced costs by over $150,000 per year.

Notice that the new system replaced the single supply chain with two separate supply chains, each with its own product and delivery characteristics. In Chapter 4 on capacity, we described conditions when splitting capacity may improve the system. In the same chapter, we also discussed

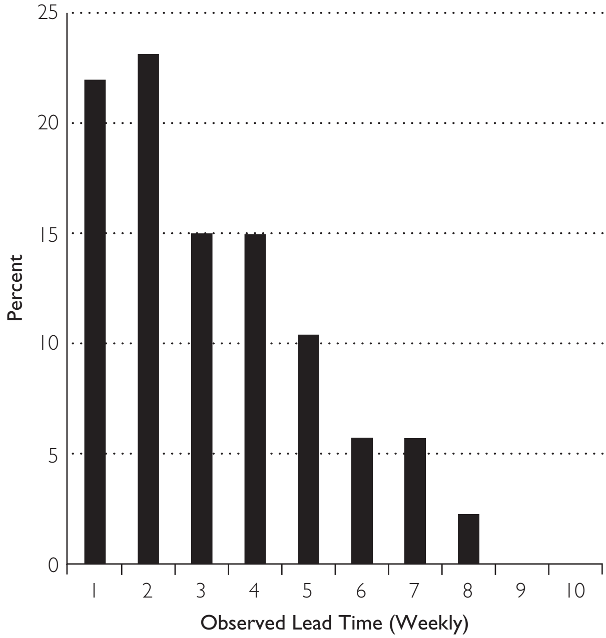

Figure 6.4 Lead times originally observed by schools

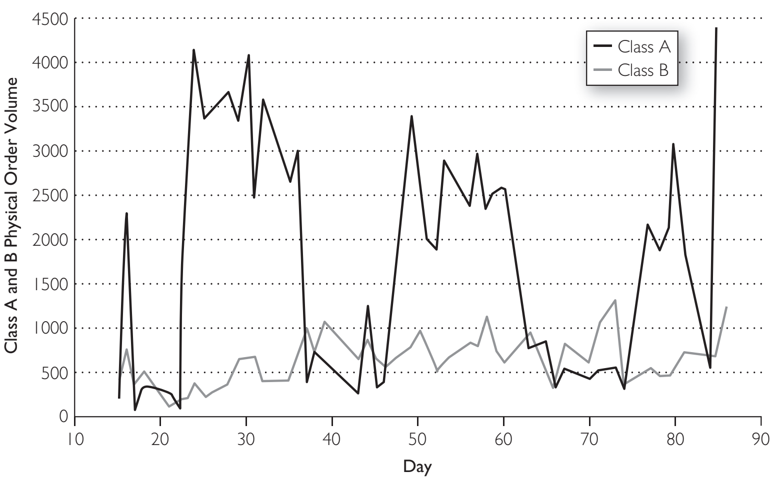

Figure 6.5 Demand volume fluctuations over time

how offering different lead times for different products may improve system performance. The application at the Chicago Public School system is such an implementation.

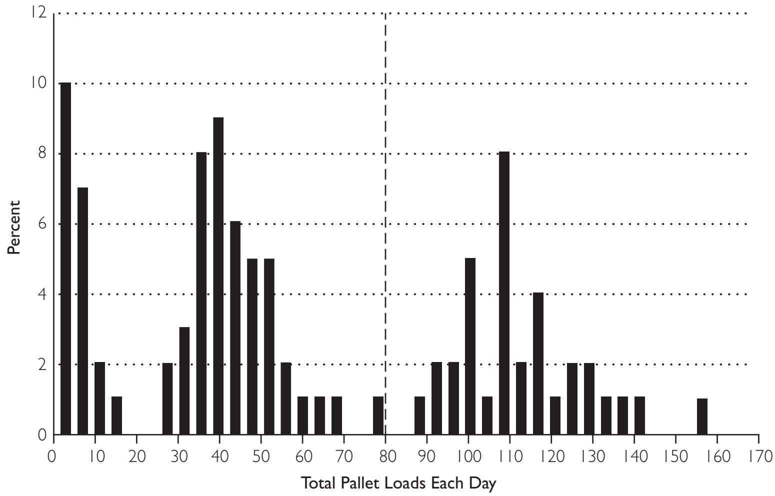

Figure 6.6 Capacity in pallet loads compared to trucking capacity

6.5 Locating Safety Stocks at Eastman Kodak

Graves and Willems [48] provide an example of a network model to determine safety stocks in a supply chain at Eastman Kodak. The supply chain involves a high-end digital camera in which the camera, procured from an outside vendor, came with lens, shutter, and focus functions. The imager, circuit board assembly, and many other parts were assembled and tested. The final product was then moved to a distribution center and shipped against demands. The parts in the camera were classified into two groups, one with a lead time of under 60 days and the other set with a lead time of over 60 days.

The model (described in Section 6.18) determined the optimal safety stock levels at each location to minimize the overall holding costs. In this example, individual functional areas added constraints. Marketing determined that the service time for the customer should be five days. The assembly group required safety stock of the imagers to be held at the assembly plant, thus setting the lead time for imager to zero. The effect of these constraints was to increase the safety stock by 8.7%. The optimal solution held no inventory at the distribution center and generated a cost of holding safety stock of $78,000. The product flow team also used to model to evaluate the effect of adding other constraints such as both manufacturing and distribution holding safety stock and quoting zero service times. This increased costs to $89,000. Another policy examined was only the distribution center holding safety stock. This changed the cost to $81,000 and was used as the solution acceptable to management. The authors state that the model use coincided with an improvement in delivery performance from 80% to 97% while worldwide finished goods inventory decreased from $6.7 million to $3.6 million and worldwide raw material inventory and work in process inventory decreased from $5.7 million to $2.9 million between 1995 and 1997 at one assembly site [48].

6.6 Volvo GM Heavy Truck Corporation

Narus and Anderson [90] describe a study of Volvo GM Heavy Truck Corporation and its dealers. An important source of revenue for Volvo GM is its sales of repair parts for its commercial trucks. However, in the mid 1990s, dealers reported high stockout rates even though inventory levels of spare parts were rising. Dealers complained that lack of consistent service was causing lost business as customers replaced Volvo parts with generics.

Analysis of the demands faced by dealers showed that customers placed orders for two reasons: scheduled maintenance and emergency roadside repairs. Since scheduled maintenance was predictable, the necessary parts could be ordered ahead of schedule and managed. But demands for emergency repairs were not predictable and required a different supply process. Volvo GM, working with FedEx Logistics Services, set up a warehouse in Memphis, TN, and stocked it with truck parts. All emergency repair requests were shipped out by FedEx, for delivery either overnight or the same day. Parts are picked up at the airport or are delivered to the roadside repair site with delivery charges paid for by customers. This dual delivery approach for the supply chain enabled Volvo GM to eliminate three warehouses and decrease total inventory by about 15% while increasing service level and substantially decreasing stockouts.

6.7 Okumalink

Okuma America is a machine tool builder with a warehouse in Charlotte, NC. Okuma's customers require any of thousands of possible spare parts to repair a broken machine tool. Okuma guarantees shipment within 24 hours for all parts manufactured in Charlotte. If the part is not shipped within 24 hours, the customer gets the part for free.

Okuma requires each of its forty-six distributors to carry a minimal number of machine tools and selected repair parts in inventory. A shared information system keeps distributors informed about the location and availability of all tools and parts throughout the system. If a distributor does not have a part, he can check to find the closest location with the part. The item can then be shipped directly to the customer plant site for availability the next day. Since all inventories are posted on the information system, called Okumalink, distributors can arrange exchanges of parts electronically. This decreases the inventory and handling costs for all distributors while offering forty-eight potential paths for items to be shipped to the customer, i.e., Okuma's two warehouses and the forty-six distributors. The low stockout rates increases the customer confidence in spare part availability and potentially benefits the initial sale of Okuma machine tools to customers.

6.8 Service Differentiation for Weapon System Service Parts

In the mid-1990s, the US military moved the management of consumable service parts from the individual services (Navy, Army, Air Force, and Marines) to the central Defense Logistics Agency (DLA). The goal was to take advantage of economies of scale, inventory pooling, and efficient inventory expenditure allocation to reduce costs while increasing readiness. Deshpande et al. [26] provide an empirical study of observed service differentiation using a data set from the DLA.

The supply chain for parts consisted of inventory held at the ships and bases in the field, called *retail stock,* that was replenished by wholesale inventories managed by the DLA. Choice of the wholesale inventory level required balancing the goals of maximizing readiness with the goal of minimizing holding and investment costs. Since part demands differed in their importance in supporting readiness, choice of inventory levels for parts required judging the part's importance by requesting agency. A part's importance is measured based on its essentiality to the weapon system and its criticality in the overall mission. The four essentiality codes used in the project were (1) Very High Criticality—the weapon is inoperable without the part, (2) High Criticality—the part affects personnel safety, (3) Medium Criticality—the missing part degrades effectiveness but does not render the weapon inoperable, and (4) Low Criticality—the missing part does not affect the weapon operation. Similarly, a part's criticality code is based on the importance of its system application (high, medium, or low). Thus, the combination of the criticality and essentiality determines the weapon system indicator codes.

The goal of the DLA was to set inventory levels to provide better service (i. e., higher fill rates and shorter response time) for parts with higher levels of criticality and essentiality. When the DLA descided to pool all inventory, a key problem was that different agencies had different Weapon Standard Industrial Codes (WSIC) for the same part. In such a case, the DLA rounded all codes so that the part was assigned the highest WSIC across all agencies. Note this may imply that pooled inventories and associated costs may be higher than a separate inventory system [19].

The study [26] provides an estimate of the benefit of developing processes to differentiate access to inventory based on the WSIC codes of the demand-generating entity. This approach adjusted the inventory deployment based on threshold levels, so that when inventory levels were low the inventory was reserved for demand with high criticality. Such an approach enabled an improvement in service based on criticality for the same level of pooled inventory.

6.9 Aftermarket Service For Products

Data presented in [124] show that the original cost of the car represents about 20% of the total cost of ownership. The customer's cost of ownership includes financing, repairs, a rental car during repairs, gas and so on. This suggests that a manufacturer might want to consider the customer's total cost of ownership when designing and building the car. The corresponding data for locomotives shows that the total cost of ownership of a locomotive is twenty-one times the cost of the locomotive. This suggests that the service contracts and usage issues associated with a locomotive will have a significant impact on product demand. Similarly the total cost of ownership of a personal computer is over five times the cost of purchase and includes network maintenance, software updates, and so on.

What strategies can the manufacturer adopt to decrease total cost of ownership? The following suggestions are four different approaches observed in industry [124]:

1. Embedded Services: Honeywell Aerospace, a manufacturer of flight control and avionics devices, realized that embedding real-time diagnostics in an airplane could permit a continuous monitoring of the performance of many important components. When the aircraft lands, this real-time monitoring permits pinpointed maintenance, thus decreasing aircraft turn-around time and costs while increasing reliability. This improved maintenance at decreased costs decreases the total cost of ownership for the airline. Such an approach requires changes in the original product design but delivers decreased repair costs, thus offering Honeywell a stream of revenue associated with diagnostic tools, repairs, and so on.
2. Comprehensive Services: GE Locomotive services recognized that in addition to the locomotive itself, track maintenance, scheduling, credit, spare parts, and maintenance all comprised the total cost of ownership of a locomotive. GE offered credit availability through GE Capital and also offered to lease locomotives at competitive rates. GE also offered software support and guaranteed up time of the engines, paying for standby engines that could be pulled into service if a problem arose. The impact was that the GE solution was competitive from the perspective of total cost of ownership and thus enabled both growth and increased profitability.
3. Integrated Solutions: Nokia realized that an important issue with cell phone providers was both provision of the cell phone as well as choice and upgradeability of the equipment associated with managing customer calls. Nokia came up with a list of standard plug-and-play equipment that were guaranteed to work seamlessly with all the Nokia-certified equipment. This confidence in the continual provision of certified equipment enabled its customers to purchase Nokia products, knowing that the total cost of ownership could be optimized.

4. Distribution Control: Coca-Cola realized that the quality of service offered for its products is significantly affected by the performance of its bottlers. Distribution control by Coca-Cola required purchase or control of downstream bottling and distribution facilities to ensure product servicing and availability. This distribution control permitted Coca-Cola to manage the retailers cost of ownership and thus decrease total costs.

Many products follow the "give free razors to generate future cartridge sales" model. Sales of generators, tractors, printers, airplane engines, machine tools, and so on, all generate a significant portion of their margins from providing spare parts after products are sold to customers. This suggests that managing the supply chain of service parts can have a significant impact on the total cost of ownership.

6.10 Caterpillar Logistics Services

Caterpillar Logistics Services [75] provides a twenty-four hour shipment guarantee for over 620,000 parts anywhere in the United States. If the part is not delivered within forty-eight hours, it is provided free of charge to the customer. The current delivered service for parts within forty-eight hours exceeds 99.99%. By carefully planning the location and quantity of inventory for different spare parts and by planning original part designs to maximize commonality with existing parts, Caterpillar can potentially convince buyers to choose a Caterpillar product. This is particularly true with earth-moving equipment, where an inoperable machine can cause significant costs due to work delays and schedule disruptions.

How does Caterpillar organize the system to provide this service? Data from Caterpillar presentations show that service level from the dealer was 81% immediately; service level from the nearest depot was 83% within twenty-four hours, and service level after a system wide search was 98% within forty-eight hours.

Note that this overall service level in forty-eight hours is obtained by considering the decision tree of what happens if the demand is not satisfied immediately and within twenty-four hours or within forty-eight hours. The probability demand is satisfied immediately is 81%, so 19%

of the time the transaction may go to the depot. For that 19%, the depot can satisfy inventory 83% of the time. Thus the percent of transactions that have to go to a nationwide search is $(1 - 0.81 - (1 - 0.81) \times 0.83) = 0.0323$. Of this fraction, 98% is located and delivered within forty-eight hours, thus providing an overall service level of $1 - (1 - 0.81 - ((1 - 0.81) \times 0.83)) \times 0.02$, which is equal to 99.9994%.

Schmidt and Aschkenase ([105]) claim that detailed coordination across network strategy, data management, inventory management, and reverse logistics contribute to the supply chain performance. Between 1983 and 2004, Caterpillar managed to cut its inventory levels by more than 50%, while maintaining high fill rates. It can be argued that this service parts performance has a large impact on the original purchase decision, too. Some of the processes honed by Caterpillar Logistics Services are as follows:

1. Forecasting: Knowing part demands historically and the location of customers who purchased products, Caterpillar can forecast the potential demand by part by location. The quality of the demand forecasts enable positioning of inventory (similar to the USCG example) in anticipation of part demands.
2. Managing Part Retrieval: Once demands are received at the warehouse, the order picking system should be able to pull parts while minimizing material handling. This requires automated warehousing, efficient warehouse management systems, efficient put away and retrieval.
3. Competitive Service: Note that the performance guarantee enables Caterpillar to convince customers that parts required for any broken products will be provided quickly. Availability of equipment is critical since downtime of earthmovers and other heavy equipment can result in project delay penalties, and costs can be substantial.
4. New Products Development, Expansion of Product Lines, and Benefits of Service Support. If new products are designed with many parts in common with existing products, then the service guarantees can be extended to new products without much increases in costs. This provides incentives to design new products to maximize commonality of parts with existing products.

5. Shared Resources: Caterpillar manages over 700,000 square feet of warehousing space and ships over $500 million of client product. CLS manages Logistics for Land Rover Parts which has 52% parts turnover in UK, 20% in Europe, 28% in the rest of the world. The customers are 57% private, 27% military (29 armies), and 16% commercial fleet.

6.11 Unconditional Service Guarantees

Hart [57] discusses the concept of unconditional service guarantees. The best example of an unconditional service guarantee is the one provided by Bugs Burger Bug Killer (BBBK) an exterminator company based in Florida. BBBK offers the following guarantee: (1) The customer does not pay until all pests are eliminated, (2) if ever dissatisfied with BBBK's service, the customer receives a refund of up to twelve months of BBBK's service plus fees for another exterminator of their choice, (3) if a customer spots a pest on the premises, BBBK will pay for the guest's meal or stay, send a letter of apology, and pay for a future meal or stay, (4) if the facility is closed down due to pests or rodents, BBBK will pay all fines and lost profits and an additional $5,000. In short BBBK says that if the customer is not satisfied 100%, they don't owe anything.

In [57], Hart describes some important features of a service guarantee:

1. Unconditional: Examples of unconditional service guarantees include LL Bean's guarantee of "100% satisfaction in every way." This includes full credit for returns even ten years after purchase. Caterpillar Logistics offers guaranteed delivery in forty-eight hours or the product is free. Okumalink offers shipment within twenty-four hours or the product is free. These guarantees are easy to state, easy to understand, and are devoid of caveats.
2. Meaningful: Bennigan's fifteen-minute lunch service provides a meaningful measure. The amount of the penalty should correspond to the inconvenience associated with the delay; thus, Domino Pizza's delivery in thirty minutes or $3 off was considered more reasonable to customers than a free pizza for deliveries after thirty minutes.

3. Easy to invoke and collect: Cititravel's low price guarantee only required identification of the source of the lower fare, with the company following up and providing the guarantee. A recent experience with tire insurance by the author started with the tire dealer invoking every possible reason why the car owner was at fault for the unusual tire wear. In addition, the insurance required that a sheet of paper be stored in the car, despite data in the store computer that showed the insurance was purchased. In other words, the guarantee is weakest exactly when the customer needs it.
4. Breakthrough service: The guarantee should be significant enough to capture customer attention. FedEx's absolutely, positively ontime or your money back was a significant service improvement. Payouts against this guarantee provide quick feedback regarding the number of times the guarantee is not met and thus enable process adjustments in response.

The concept of unconditional guarantees is particularly relevant when it comes to spare parts provision. Examples such as Caterpillar Logistics and Okuma satisfy the requirements for a good service guarantee, providing such guarantees force careful system design to ensure consistent delivery.

6.12 IBM Spare Parts

IBM's Optimizer [14] is a system for optimizing spare parts required by installed population of IBM products that exceeds tens of millions. The system tracks 200,000 part numbers and 15 million SKUs. It is used by over 15,000 customer engineers (CEs) that call in part requests. The parts may be delivered to the customer site before or after the CE arrives, the CE may use parts stored on the customer premise, or the CEs may carry a limited number of parts. The system was intended to minimize the overall inventory and transport cost while maintaining the part availability level (PAL) as specified by the service contracts.

The Optimizer model started with modeling the impact of individual part availability on the availability of a set of parts, all of which may be required to fix a customer's problem. The associated service level is called the technology component group's (TCG) service level. The model then identified that the demands at a higher echelon, or inventory level, can be classified into (1) demands generated by part failures in customer machines supported by one location, (2) emergency demands not satisfied at a lower echelon, and (3) replenishment requirements to restock lower echelon locations. Developing demand from these building blocks enabled insights into demands that were from a combination of replenishment orders and emergency orders. The implemented model enabled the system to adjust inventory levels to synchronize with impending demand, service guarantees, and product architecture, thus permitting either lower costs or increased service levels at the same cost.

6.13 Estimating the Impact of Echelon Stock

The goal of this section is to develop intuition regarding the optimal inventory location point in a supply chain. The concepts will be illustrated with a numerical example.

Consider a supply chain with two spare-parts demand stations that face a daily demand for a part that follows a normal distribution with a mean (μ) of 50 and a standard deviation (σ) of 25. Assume that the parts stations face a replenishment cost (K) of \$125, a holding cost (h) of \$0.2/day/part, a backorder cost (b) of \$5/day/part. Also, suppose each station faces a supply lead time (L) of 3 days to be replenished by the central warehouse. The corresponding service level *see* $\frac{b}{h + b} = 0.96$ and the associated $Z_{ser} = 1.77$.

If each parts station were to operate a (Q, r) policy, they would each maintain a reorder level r as follows:

$$r = (\mu \times L) + \left(Z_{ser} \times \sigma \times \sqrt{L}\right)$$
$$= (50 \times 3) + \left(1.77 \times 25 \times \sqrt{3}\right) = 226.64$$

Also, the order quantity Q would be calculated as

$$Q = \left(\sqrt{\frac{2 \times K \times \mu}{h}}\right)$$
$$= \left(\sqrt{\frac{2 \times 125 \times 50}{0.2}}\right) = 250$$

The central warehouse processes orders received from the parts stations. Suppose the costs for the central warehouse are also $K = 125$, $h = 0.2$, $b = 5$, and $L = 3$. The central warehouse is replenished by vendors and serves as a consolidation point.

Using an Excel worksheet, simulation of the orders received at the central warehouse generates an average demand across 100 periods of $\mu_c = 101.07$ and the standard deviation, $\sigma c = 141.57$. With this mean and standard deviation, and using the same formulas as before, the corresponding values of reorder level and order quantity at the central warehouse are as follows:

$$
\begin{aligned}
r_c &= (\mu_c \times L) + \left(Z_{ser} \times \sigma_c \times \sqrt{L}\right) \\
&= (101.07 \times 3) + \left(1.77 \times 141.57 \times \sqrt{3}\right) = 737.12 \\
Q_c &= \left(\sqrt{\frac{2 \times K \times \mu_c}{h}}\right) \\
&= \left(\sqrt{\frac{2 \times 125 \times 101.07}{0.2}}\right) = 355.43
\end{aligned}
$$

Again, using an Excel spreadsheet, simulation of the expected costs across 100 iterations and 100 periods yields an expected cost per day at the central warehouse of \$166.26, an expected inventory level each day of \$658.99.

Note, however, that the orders received by the central warehouse follow a "lumpy" pattern with demands bunched up with erratic intervals in between. This lumpiness reflects the batch sizes of orders placed by parts stations. But orders received by the central warehouse display a negative serial correlation across time, i.e., if we receive an order from a parts station at time t, there is a much smaller probability of receiving another order from that same station in period $t + 1$.

Suppose we maintain the value of QC as equal to the economic order quantity at the warehouse, i.e., we set

$$
Q_c = \left(\sqrt{\frac{2 \times K \times \mu_c}{h}}\right)
$$

$$
\left(\sqrt{\frac{2 \times 125 \times 101.07}{0.2}}\right) = 355.44
$$

While the details are beyond the scope of this book, examination of the demand stream at the central warehouse shows that it is possible to decrease the inventory (in this case by 34% in simulations) and associated costs (by about 26% in this example) by taking into account the demand structure. This example illustrates the need for careful analysis of the inventory policies at an echelon of a distribution system that faces a demand that reacts to the costs and demands experienced by the lower levels of the distribution system.

6.14 Variance of Orders Faced by an Echelon

In this section, we discuss a simple model that shows the variance of order sizes arriving at an echelon of a logistics system. Suppose we have N inventory locations, each facing a demand rate of D_I units per day and a batch size of Q_I. These locations place orders that arrive at an echelon. The goal is to obtain the mean and variance of orders arriving at the echelon.

Note that location i places orders once every $\frac{Q_i}{D_i}$ units of time. Thus the probability that the echelon observes an order from location i on any given day (p_i) is $\frac{D}{Q_i}$ We assume that $Q_i \geq D_i$). Thus, from location I, the echelon receives an order of size Q_i with probability p_i and an order of 0 with probability $1 - p_i$. The associated mean and variance across the N locations are as follows:

$$\text{Mean demand at the echelon/day} = \sum_{i=1}^{N} Q_i p_i.$$

$$\text{Variance of demand at the echelon/day} = \sum_{i=1}^{N} Q_i^2 p_i (1 - p_i).$$

6.14.1 Numerical Example

For the model described earlier, with $N = 2$, daily demand for a part that follows a normal distribution with a mean (μ) of 50 and a standard deviation (σ) of 25. Assume that the parts stations face a replenishment cost (K) of \$125, a holding cost (h) of \$0.2/day/part, a backorder cost (b) of \$5/day/part. Also, suppose each station faces a supply lead time (L)

of 3 days to be replenished by the central warehouse. The corresponding service level $ser = \dfrac{b}{h + b} = 0.96$ and the associated $Z_{ser} = 1.77$.

The corresponding values of $Q_1 = Q_2 = 250$ and $p_1 = p_2 = \dfrac{50}{250} = 0.2$. This yields the values

$$\mu_c = (250 \times 0.2) + (250 \times 0.2) = 100$$
$$\sigma_c = \sqrt{(250^2 \times 0.2 \times (1 - 0.2)) + (250^2 \times 0.2 \times (1 - 0.2))} = 141.42.$$

Thus the echelon faces a demand with a mean of 100 units and a standard deviation of 141.42 units. Notice that the increased standard deviation of demand at the echelon reflects both order uncertainty as well as the lumpiness caused by the batched ordering from locations.

6.15 Inventory Levels Accounting for the Impact of Part Substitution

This section provides a numerical example to illustrate the inventory impact of part substitution on inventory levels and costs. Consider a retail location that sells two products. Product 1 costs \$5, and product 2 costs \$10. Product 2 can perform all the functions of product 1 and more. The retail selling price for product 1 is \$10 and the retail selling price of product 2 is \$13. Demand for each product is normally distributed each period with a mean of 50 units and a standard deviation of 25 units. Holding cost per unit per period is \$0.20 per unit per period, and the backorder cost is \$5 per unit per period. Each period the retailer places reorders from a supplier and faces a lead time of 4 periods for delivery. These data are captured in Table 6.1.

Table 6.2 shows the effect of decreasing the inventory of the first product and increasing the inventory of the second product by the corresponding quantity, in other words changing the inventory mix. Note that increasing product 2 inventory allows the retailer to increase expected profit from \$435.52 (under substitution) to \$452.35, when the standard deviation is 25. This happens because of the flexibility of product 2 to satisfy its own demand as well as product 1's demand.

Table 6.1 Impact of substitution on expected profits

Standard Deviation	Expected Profit (No Substitution)	Expected Profit (Substitution)
10	496.44	500.57
15	468.82	476.25
25	420.69	435.52
35	370.72	389.48
40	340.44	360.92

Table 6.2 Impact of substitution on adjusted inventory

X	Expected Profit (substitution)
0	435.52
10	441.29
20	447.73
30	451.98
40	452.35
50	450.69

Consider the impact of the following retailer scheme: *If the location were to run out of product 1, offer the customer product 2 for the price of product 1.* Note that when the demand standard deviation is 25 units, the effect of substitution is to increase expected profit from $420.69 to $435.52. This increase in expected profit is realized because of the opportunity to get both revenue for product that could be potentially backordered as well as associated savings on the backorder costs in the presence of the alternate to substitute product demand.

Thus permitting substitution may help both decrease inventories and increase service levels in a supply chain.

6.16 Prioritizing Demands to Improve Inventory Levels

Consider the school system example provided at the start of the chapter and the example from Volvo truck division. In Section 6.4, the more variable demand products were offered a shorter lead time while the less variable orders were offered a longer lead time. Such an approach can decrease overall inventory levels because the safety stock associated with a lead time depends on both the demand variability and the lead time. But how can such a matching of demand variability to lead time be accomplished?

It is clear that the cost associated with inventory depends on the variance of demand during lead time. In such a case, the larger the demand variance, the greater the effect of lead time on safety stock. Now suppose orders to a facility came from two sources that differ in their demand variability. Suppose we provide priority to the higher demand variance orders and low priority to the low demand variance order; what is the impact? Note that, as shown analytically and illustrated with a numerical example in Chapter 4 on capacity management, if one set of orders receives a priority, the lead time for those orders will decrease. But, since the capacity level is unchanged, the lead time for the lower priority orders will increase. Thus, priorities are one mechanism to offer differentiated lead times across order streams and thus improve supply chain performance for spare parts.

The following example appears in Chapter 4, and is reproduced here for convenience. A manufacturer services two products sold by retailers, with demand for each of the two products being $m_1 = 140$ units per day and $m_2 = 60$ units per day, and demand standard deviations of $\sigma_1 = 125$ units and $\sigma_2 = 25$ units. The batch size for both products is 100 units. Thus, the order batch rate from each product would be $\lambda_1 = 1.4$ orders per day and $\lambda_2 = 0.6$ orders per day, respectively, for a total arrival rate of 2 orders per day across both products. Given the batch size, suppose the set-up time for an order is 0.1 days, and the processing time per unit is 0.003 days. The corresponding service rate for any order batch of 100 units is 2.5 orders per day or $\left(\frac{1}{0.1 + (0.003 \times 100)}\right)$.

Notice that if both products were accessing capacity in order of arrival, they would both face the same lead time of 2 days. The corresponding impact on their safety stock would be 363.05 units for the first product and 72.61 units for the second product (obtained using the equation $Z\sigma\sqrt{L}$). Thus the total inventory across both products would be 435.66 units.

However, suppose product 1, which has a higher variability, is given priority over product 2. Then the new lead times, using the formulas provided in Chapter 4, would be $L_1 = 1.12$ and $L_2 = 4.03$ days. With these lead times, notice that the corresponding safety stock for the first product would be 272.55 units, which decreases from the earlier case, while the safety stock for the second product would be 103.15 units, which increases from the earlier case. Note that the total inventory across both products is now 375.72 units. This decrease in inventory reflects the benefit of tailoring access to the supply chain based on product demand characteristics. Notice that giving priority to the more variable product permits its lead time to decrease, thus decreasing the safety stock for that product. But clearly this comes at a cost to the less variable product, whose lead time increases but at a slower rate.

In other words, it may be worth reconsidering how products or orders get access to capacity. Tailoring the access to capacity based on product characteristics can improve the overall supply chain performance.

6.17 The Benefit of Geographic Postponement of Critical Parts

Express delivery companies, such as FedEx, offer services such as critical parts supply. This service stores critical parts for OEMs at one of FedEx's hubs. As soon as there is demand for a part, FedEx will schedule to get it delivered to the desired location based on the promised guarantee. The transportation mode used may vary from a next flight out from a regular airport to a FedEx same-day shipment to a next-day shipment. While premium transport is an expense, such services permit geographic postponement and thus an opportunity to pool demand risk across locations.

To estimate the benefit, let Δ be the additional cost per unit for premium transport. The benefit of a centralized location with express shipping is justified if we have $hZ\sigma(N - \sqrt{N}) > \Delta\mu$. As the premium paid for express shipments declines and the value of such service guarantees increases, geographic postponement increases in value to the OEM.

Typical products that use such services include expensive but light parts, pharmaceutical products that are time sensitive, repair facilities for critical equipment, and so on.

6.18 Strategic Safety Stock Positioning

Graves and Willems [50] describe an approach to set safety stocks in a supply chain in order to provide the desired customer lead time. Their approach provides a conceptual basis to consider location of service parts inventory across a supply chain to optimize overall performance. The data for a sample five-stage serial supply chain is shown in Figure 6.7, with the supply chain details in the stage description row.

The supply chain is described along with production times, maximum demands over time, and costs. If for a location i, the inbound service level is S_{i-1}, the production time is T_i, and the outbound service level is S_i, then the net replenishment interval is $S_{i-1} + T_i - S_i$. In order to guarantee that demands up to a certain service level (*ser*) will be satisfied, the safety stock level that has to be maintained is $Z_{ser}\sigma\sqrt{S_{i-1} + T_i - S_i}$. A key result is that at each location i, it is optimal to have either $S_i^* = 0$ or $S_i^* = S_{i-1}^* + T_i$. This result implies that each location either carries no safety stock and is a pass-through location or that it decouples that stage from the result of the network upstream by providing a zero service time.

Next consider the possible locations of the zero service time across the five nodes in the network. This generates 32 possible service-time combinations involving the positioning of the zero service-time locations. Given these zero service-time nodes, in order to determine the requires safety stock, start from the first node (on the left) and set the service time equal to 0 (if specified) or to $S_{i-1} + T_i$ otherwise. Assume that $S_0 = 0$. Thus, for example, if all service times were set to 0, the requires safety stock would be the sum of the safety stocks required to provide 0 service time, which is the sum of the safety stock values in Figure 6.7, as can be seen in the last column of the first row with service time values in Figure 6.8. On the other hand, if the service times for all nodes are nonzero except for node 5, then the service times will be set as 20, 25, 28, 29, and 0 respectively. The associated lead time to be covered by

STAGE	1		2		3		4		5
	Purchase Parts	→	**Build Subassembly**	→	**Produce Assembly**	→	**Ship to DC**	→	**Ship to Retailer**
Holding cost %	15.00		15.00		15.00		15.00		15.00
Production Time	20.00		5.00		3.00		1.00		3.00
Stage Incremental Cost	20.00		25.00		45.00		10.00		10.00
Cumulative Cost	20.00		45.00		90.00		100.00		110.00
Z (service level)	1.64		1.64		1.64		1.64		1.64
Sigma	20.00		20.00		20.00		20.00		20.00
Service Time	0.00		0.00		0.00		0.00		0.00
Safety Stock	441.36		496.53		769.22		493.46		940.16

Figure 6.7 Data for a sample supply chain

safety stock is 29 + 3, which includes the preceding stages' lead times as well as stage 5's production time of 3 periods. Thus the holding cost of safety stock is $0.15 \times 110 \times 1.64 \times \sqrt{29 + 3}$ or 3070.55, which is the holding cost (15% of cumulative cost through stage 5) times safety stock required to provide a zero lead time to the end customer. Figure 6.8 provides the holding cost of the safety stock for the 32 different possible settings of service levels across the five nodes in the network.

From the data in Figure 6.8, notice that the optimal configuration of safety stocks can be identified for each possible lead time constraint by identifying the lowest cost safety stock cost (last column) for a given commitment of retailer lead time (in stage 5). Figure 6.9 provides the safety-stock-related cost associated with positioning inventory across the supply chain for different retailer lead time commitments. As expected, longer retailer lead times enables significant safety stock reductions. If the retailer can wait for the entire supply chain lead time of 32 days, notice that no safety stock need to be held anywhere in the supply chain, thus driving the safety stock holding cost to zero.

SERVICE TIME					SAFETY STOCK COST
1	2	3	4	5	
Purchase Parts	Build Subassembly	Produce Assembly	Ship to DC	Ship to Retailer	
0	0	0	0	0	3140.73
0	0	0	1	0	2792.72
0	0	3	0	0	2864.96
0	0	3	4	0	2374.01
0	5	0	0	0	3131.11
0	5	0	1	0	2783.10
0	5	8	0	0	2861.89
0	5	8	9	0	2321.68
20	0	0	0	0	3313.11
20	0	0	1	0	2965.10
20	0	3	0	0	3037.35
20	0	3	4	0	2546.39
20	25	0	0	0	3783.63
20	25	0	1	0	3435.61
20	25	28	0	0	3597.50
20	25	28	29	0	3070.55
0	0	0	0	3	2200.57
0	0	0	1	4	1707.11
0	0	3	0	3	1924.80
0	0	3	4	7	937.89
0	5	0	0	3	2190.95
0	5	0	1	4	1697.49
0	5	8	0	3	1921.73
0	5	8	9	12	441.36
20	0	0	0	3	2372.95
20	0	0	1	4	1879.50
20	0	3	0	3	2097.19
20	0	3	4	7	1110.28
20	25	0	0	3	2843.47
20	25	0	1	4	2350.01
20	25	28	0	3	2657.34
20	25	28	29	32	0.00

Figure 6.8 Data for a sample supply chain

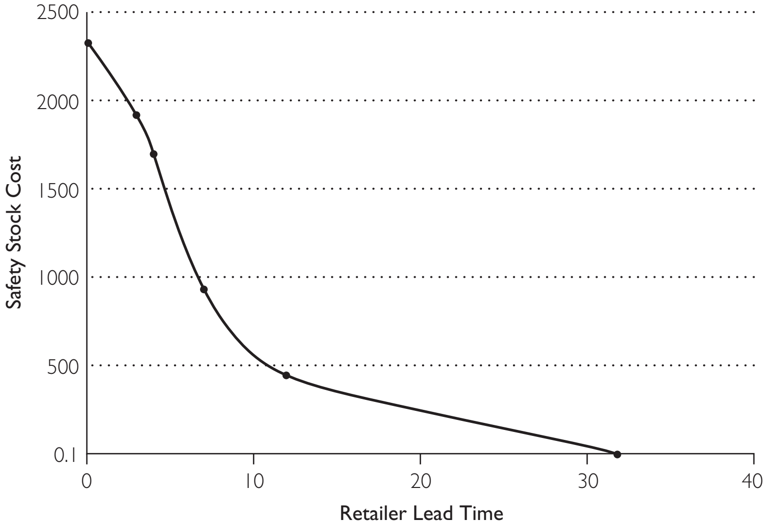

Figure 6.9 Optimal safety stock vs retailer lead time

6.19 Chapter Summary

Managing the supply chain for spare parts requires choosing an inventory location to satisfy demand where the primary product is being used and carrying sufficient inventory to ensure the required service level. Capacity of the intermediate warehouses, dealer capacity, and plant manufacturing capacity interact with demand and inventory to determine supply lead times, a key competitive metric for the aftermarket. Segmentation of the nature of the aftermarket demands from stable maintenance related demands or orders to replenish inventory to unpredictable breakdowns, and customizing the delivery mode and lead time to demand characteristics can improve supply chain performance. Coordinating maintenance information with inventory and repair decisions can enable reduction in inventory levels and costs and an increase in service levels. Competitive metrics include guaranteed delivery lead times, guaranteed product uptime, and improved life cycle costs.

CHAPTER 7

Reverse Logistics

The total value of products returned by US consumers is estimated at $100 billion annually. The management of reverse supply chain, i.e., flows from the consumer back to the manufacturer, is also increasingly important as producers are held responsible for the cradle-to-grave impact of their products on the environment. Increased emphasis on building sustainable products that minimize their impact on greenhouse gases, landfills, and water usage implies that production and destruction costs have to be considered beyond their flow from the manufacturer to the consumer. Some products can be reused in other markets (refurbished engines or used clothing), others can be reshipped (products returned to stores or catalog companies), and other products may require breakdown and remanufacturing (printers). In each of these cases, anticipating the reuse of the product suggests a new set of possible product design and assembly choices.

The reverse supply chain is inherently more complicated and involves less control than the primary movement of product out to the customers. Collecting product back from consumers requires intermediaries to play a key role. These could include the consumers themselves, city garbage pickup, collection centers, and so on. The capacity of collection is distributed across many intermediaries and thus impacts stability of supply. Coordination between participants has to include issues of regulatory compliance, e.g., new regulations regarding use of recycled content require companies to ensure availability of recycled material to produce primary product. Coordination across manufacturers to standardize the composition of packaged product or designs can increase the success of reverse supply chains by simplifying aggregation of returns. In some industries (such as batteries), effective recycling is key to ensuring availability of minerals such as lithium, given their restricted supply relative to projected demand. Finally, competitive metrics such zero waste, reduced greenhouse gases, and 100% recycling, are used by companies as part of product attributes to attract demand.

In reverse supply chains, each individual product has to be assessed, separated, treated, and then reused as is, salvaged, or recycled. Consider the typical flow of products back to the manufacturer. Some fraction of the products sold are returned. Of the returned product, some are in perfect, unused condition and so can be resold as soon as they are available for the market. Of the remaining fraction of product, some can be remanufactured and put back into the market. However, if these return steps are delayed, the product moves closer to the end of its life cycle, when its demand will run out. Luk et al. [11] suggest that products whose value loss over time is low should be matched with an efficient reverse supply chain, while products with a rapid falloff in value require a speedy product recovery, which may be achieved by being matched with a responsive value chain. The efficient supply chain can use a centralized approach to process returns, thus reducing costs to manage the reverse supply chain while potentially increasing the time to get the returned product ready for resale. However a decentralized supply chain can adjust the speed of product pickup and thus permit trade-offs between speed of product recovery and marginal value of product.

The next few sections will describe interesting and effective reverse product supply chains.

7.1 Recycling Used Disposable Kodak Cameras

The single-use FunSaver camera by Kodak had between 77% and 86% of recyclable components by weight ([14], [29]). The product was designed and manufactured so that the customer could not reload the camera. This ensured that only Kodak film would be used on the camera. The components of the camera included an alkaline mercury-free battery and electronics showing the number of times the circuit boards had been recycled. All parts were color coded for recyclability.

The reverse chain started with the consumer, who purchased the camera from a retail store and used it to take pictures. Given the camera design, unexposed film remained in the camera, and the consumer took the camera with the completed roll inside to a store to be developed. The store removed the film cartridge, developed the pictures, and delivered them to the customer. The retail store was paid $0.05 per unit core fee to send the camera to the recycling center. The battery was reused by some other supply chain.

At the recycling centers, Kodak removed the lenses from the returned cameras, reground them, and reused them in a new camera. At Out-Source, a state-sponsored organization in New York that employs handicapped people, covers and lenses were removed. The polymer covers were ground up into pellets, and the paper and cardboard were recycled. The chassis, camera mechanism, and electronic flash were tested, inspected, and reused. Those components that do not pass inspection were ground up and used as raw material. By using parts that snap together as opposed to being welded, Kodak could resell its FunSaver 35 camera components up to ten times, thus lowering the component costs and retail prices.

The disposable camera supply chain requires a careful design to incentivize the customer to take the finished camera to a retail store, coordination agreements to incent the retail store to return the product to the manufacturer, a counter to track use of the components, simple snap design to separate components, sufficient capacity of subsidized labor to break apart the camera, and a competitive pricing model to recover component cost over multiple product generations. In short, all the Four Cs of supply chain management had to be planned carefully to ensure an effective reverse supply chain for the FunSaver cameras.

7.2 Used Clothing Supply Chain

The flow of used clothing from the United States to the rest of the world is described in [101]. The United States accounts for 40% of the world trade in used clothing, representing 7 billion pounds of clothing exported between 1990 and 2003. Used clothing is donated by consumers throughout the United States as an act of charity (with associated federal tax benefits), thus the input costs for the used clothing supply chain are zero. Since the volume of donated clothing is far greater than US demand, this clothing now enters a reverse global supply chain, traveling from the

United States to primarily Africa. The clothing is sorted into different sets with associated price points in order to appeal to potential global market segments. Notice that even if the final retail price is lower than original product cost, this reverse chain can be profitable, since it only has to cover transportation and margin requirements from supply chain participants.

The chain of flows starts with clothing collected by nonprofit charitable groups such as Goodwill and the Salvation Army. Usable clothing is selected and makes its way to the Goodwill or Salvation Army stores. The remaining product gets sold, by weight, to a secondary layer of the supply chain, involving companies such as Trans-Americas Trading Company. These companies identify valuable apparel that has significant market value. Used clothing brought in by trucks is emptied into a conveyor belt where workers sort it by type: apparel made of cotton, skirts, men's pants, household materials, and jeans. Some products such as T-shirts are sent to a group of people called "miners and graders," who separate the clothing based on potential value. Vintage clothing such as band T-shirts (e.g., the Grateful Dead's New York tour) may have a high value, so they are separated. On the other hand, 30% of the clothing is sold at $0.05 a pound and is used as wiping rags. For such a purpose, the plain white T-shirt carries a lot more value than a colored T-shirt. If the T-shirt is too covered with paints or prints, it may only fetch $0.01–0.02 per pound and is classified as "shoddy." Shredded shoddy is used in automobile doors, carpet pads, cushions, and so on. Another group is T-shirts that are sold by weight at $0.60–0.80 per pound, where each pound consists of about three T-shirts.

The bulk of the T-shirts are shipped to traders in Africa who then create paths to consumers. Tanzania is the largest importer of used clothing from the United States. The exported T-shirts are separated into over thirty different groupings and sold in bulk at prices that are between $0.60 and $0.80 a pound [101]. The implied wholesale price of a T-shirt is thus $0.25, which is less than the price of the raw material used to make the T-shirt. Retailers buy these T-shirts in bulk and separate them into single items that can sell for retail prices between $0.50 and $1.50. The author [101] estimates that 90% of the value of a bale would come from 10% of the items in it. However, at retail, dynamic pricing may be needed based on time of day, market volumes, time of month, and so on to adjust the retail prices to willingness to pay.

But what is the impact of all of this used clothing? It is very difficult for the local African textile industry to compete with the economics of this supply chain. As a result, the local apparel industries in many African countries have been devastated. What started off as a noble gesture of charity is transformed by the global supply chain to have the opposite impact in another part of the world.

7.3 Dupont Film Recovery Program

Dupont's Film Recovery program targets three markets: offset printing, medical services, and electronics ([73]). Dupont's focus on film recovery from the hospital X-ray film market was a result of the Environmental Protection Agency's Superfund liability standard, which makes site owners as well as parties involved in generating, managing, or arranging delivery liable for environmental impact.

Dupont authorizes 350 independent local collectors to pick up and consolidate used film from hospitals, clinics, and print shops and ship them to its reclamation centers. In addition to picking up used film, these collectors recover silver.

Dupont guarantees a 25-day cycle, which is a key parameter. Collectors are also offered the option of Dupont purchasing the silver and reselling it or simply using the reclamation services for a fee. Similarly the generators of the recycled material can work directly with Dupont or go through a third-party collector. The reverse supply chain thus aims to recover the silver, reimburse the customers within a promised lead time, and permit customers to decide a convenient alternative to collect the associated funds.

7.4 Home Depot

At Home Depot stores, old pallets are backhauled by trucking companies to Advanced Pallet Recyclers (APR) ([73]). APR collects, shreds, and composts the pallets, creating two products—Enviro Mulch 2000 and Root Mulch. These brands are sold in Home Depot stores in bags marked with the environmentally friendly label.

Home Depot and Mindis Recycling have also created the Recycling Depot. This depot provides small contractors with a convenient alternative to disposing of materials from renovation jobs, such as aluminum window frames, water heaters, and electrical wires. Customers receive cash for the items they bring, based on current market prices. Mindis hopes that the plumbers and electricians who shop at the Home Depot will bring valuable scrap metal, such as copper wire and pipes, to the Recycling Depot.

7.5 Returns of Clothing at a Catalog Retailer and Their Impact

For catalog companies, returns of clothing by consumers can be significant. In many cases, returned unopened product volumes may be significant enough that they have to be taken into account in the initial inventory purchase in order to manage profitability. Eppen and Iyer [35] describe returns and reuse in the context of a catalog company that purchased inventory at the start of the season but had opportunities to receive, process, and reship returned items.

Consider a context where products are shipped out against demand, but v% of the product is returned. Of this v%, a fraction u return quickly enough to be reshipped, while $(1 - u)$% return too late to be reshipped or are damaged and cannot be reshipped. Thus out of each round of outbound shipped product, uv represent the returns that can be reshipped. Thus, if the system starts with initial inventory y, it can really be used to ship out $\frac{y}{1 - uv}$ demands. Similarly if a demand x is shipped, then the realized demand is $x(1 - v)$. Typical rates quoted in the example in [35] are a 36% return rate (v) and a 30% reusable return rate (u).

If the per-unit costs are as follows, (1) end of season salvage value of s per unit ($s < c$), (2) holding cost of h, (3) revenue of r, (4) goodwill loss of π, and (5) product cost of c, then the optimal decision y is obtained as

$$\Phi\left(\frac{y}{1 - uv}\right) = \frac{(r(1 - v) + \pi - (h - s)v(1 - u)) - c(1 - uv)}{(r(1 - v) + \pi + ((h - s)(1 - v)))}$$

Note that the ability to reuse returned items permits a lower initial inventory because of multiple opportunities to sell the product. Of course, this suggests that schemes that enable items to be returned quickly, i.e., increasing *u*, can improve system profitability.

7.6 Surplus Inventory Matching in the Process Industry

A typical problem in the steel industry concerns the allocation of orders to leftover surplus stock ([71]). The problem of matching unique customer requirements to existing inventory is termed the *surplus inventory matching problem*. The surplus stock arises because orders may be canceled after units are produced, because produced units are below acceptable quality levels, or because surplus units had been intentionally created to reduce customer lead times. While this problem is described from the context of steel mills and paper mills, the problem can be framed in a more general form, e.g., as dealing with leftover trucking capacity or production capacity.

The two key issues to consider are the assignment restrictions when an order is allocated to a surplus inventory item, i.e., geometric considerations and quality attributes and processing constraints when a set of orders are earmarked for an inventory item. While orders are allocated to surplus inventory, a goal is to do this allocation while minimizing the wasted product in order to avoid leftover product that has low possible value. One approach is to require that all orders be satisfied while minimizing the leftovers for the chosen slabs from inventory. Kalagnanam et al. [71] report on solution of real-life problems in a steel plant. The deployed solution was used daily in the mill operations and generated savings of the order of $3 million per year.

7.7 Chapter Summary

As sustainability becomes an important supply chain attribute, manufacturers are being forced to find mechanisms to reuse or recycle used products. We have considered examples of reuse (Kodak cameras, returned clothing and donated T-shirts) and recycling (Dupont's silver and Home Depot's pallets). The supply chain and product design have to be organized to manage the Four Cs of the return flows effectively. The return flows impact choices of participants in the supply chain (retailers or the customer returning product), coordination of incentives for intermediaries, sufficient capacity to process returned product in a timely manner so that its value is repatriated and effective use of the competitive benefit of operating in a sustainable manner.

CHAPTER 8

Humanitarian Logistics

Humanitarian logistics deals with delivering aid and thus relief to people in situations caused by natural or manmade disasters. Over 35 million people in the world depend on emergency relief to survive in any given year. To envision the supply chain management challenge, imagine the television or newspaper coverage of a hurricane, tsunami, earthquake, civil war, forced migration, drought, or postwar reconstruction activity. In all of these cases, the goal of the supply chain effort is to focus on the management processes involving planning, ramp-up, sustainment and ramp-down to rapidly deal with the contingency ([94]). Many of these efforts are temporary and last only as long as it takes to stabilize the system and turn it over to local government or development agencies.

Every year, over $6 to $8 billion dollars are spent on relief efforts. During the past 30–40 years, the number of nongovernmental organizations (NGOs) involved in relief efforts have gone from 938 in 1972 to over 26,000 in 1999. Though the distribution of funds is concentrated, with twenty NGOs receiving 75% of the funds, many smaller NGOs are involved in the distribution of aid to actual people, the "last mile" of aid provision. NGOs have started to depend on public funding, and public funds often focus on specific projects and places that are of interest to the donating country. In addition, the public's attention is focused on emergencies that attract a lot of television coverage; thus, for example it was easy to generate $225 per person in need in Kosovo but only $18 per head were generated for Sierra Leone or Somalia.

In many complex emergencies, the humanitarian relief problem evolves quickly and unpredictably. There are usually significant life-and-death consequences associated with inadequate relief supplies. The associated locations may have poor infrastructure and poor telecommunications, and have political constraints. In such environments, effective supply chains can significantly increase the odds of success. The overall goal of the humanitarian logistics activity is to restore the capability of the system, at least to the level prior to the catastrophe, and leave development to other entities.

8.1 Chain Structure

Humanitarian supply chains involve many separate entities, both government and nongovernment, that ensure flow of product to the disaster victim. As described earlier, the lastmile service is provided by hundreds of NGOs and other entities. Funding for such relief may be provided in the form of in-kind or cash donations. The role of the supply chain is to match the supplies with demands and get the products to the destination location as effectively as possible.

In some cases, even establishing a chain of entities may be complicated by the need for permission from the sovereign government. There is also the need to sometimes work with local defense forces. Finally, as will be discussed in Section 8.5, these chains have to be created while respecting the humanitarian space expectations of the specific event.

8.2 Capacity

Often, at the location where the disaster has occurred, the infrastructure and leadership may be temporarily destroyed or significantly affected. For example, during the earthquake in Haiti, a significant portion of the United Nations leadership as well as several government entities were destroyed or diminished. In addition, there may be a shortage of trucks, ships, airplanes, and landing and docking facilities. Neighboring countries may not have adequate agreements to permit an adjustment in the mode or paths of flow.

In situations where the capacity is depleted, prices may increase significantly in the absence of coordination. Temporary difficulties with adding to the capacity add to pressure to the supply chain. Finally, the capacity and security of warehousing facilities end up being a key concern.

Another capacity constraint is the information technology capability. Recent efforts by Telecoms San Frontiers (in Sri Lanka for example) suggests that adding to wireless or telecommunications capability may boost an important weak link in the supply chain and act as an externality for everyone involved.

8.3 Coordination

Coordination in the humanitarian supply chain involves working with bitter political enemies, military forces, local authorities, and NGOs. Given shortage of logistics assets, there is a need to prioritize and allocate tasks, deploy personnel, attract donor funds, indulge the mass media, and deliver relief. Another aspect of humanitarian logistics is that, in addition to bilateral aid provided directly by donor countries, frequently there are several NGOs such as the Red Cross, Doctors without Borders, World Vision, in addition to the United Nations–related entities such as the World Food Program, The World Health Organization, and the United Nations Humanitarian relief. As all these organizations rush in to provide relief, there are several basic steps to be managed, which include permissions from the host country to let individuals arrive, managing congestion, and managing the coordination with the military or security groups. How should this coordination be accomplished?

The United Nations Joint Logistics Committee (UNJLC) is a coordination body within the UN system whose goal is to coordinate logistics across independent agencies, UN, governmental, and nongovernmental. The mission of the UNJLC is summarized as "coordinate but not implement" i.e., facilitate the performance of other mission specific entities but allow them to do their own work. Over the years the UNJLC has played a key role in resolving conflicts and bottlenecks in several contexts, as the following examples illustrate. These examples are available as cases published by Professor Luk Van Wassenhove and colleagues ([103],[81],[102]).

When relief organizations were rushing in to provide aid in Afghanistan, a landlocked country, many organizations attempted to enter the country through Uzbekistan and load supplies on barges down the river.

The hundreds of relief organizations, each operating independently, created such chaos that the Uzbek government shut down access to Afghanistan. The UNJLC played the role of "traffic cop," debottlenecking the situation by establishing a regular barge schedule and smoothing the flow of aid through the Uzbek entry point. This role of scheduling across independent relief organizations actually increased capacity available and decreased lead time for everyone. Such a coordination role can be considered as coordination by command, i.e., a centralized scheduler who plays the role of an externality that delivers value to all parties, coordinating the system and improving performance for everyone.

When relief organizations were pouring into Rwanda, the World Food Program (WFP) was shipping in food for hungry Rwandans while the UNJLC was shipping Rwandan refugees out from the war stricken area. Given the floods, the main mode of transport was air. WFP was flying in food and flying out empty; UNHCR was flying in empty and flying out full. The UNJLC coordinated the schedules across the two agencies so that WFP aircraft flew back with refugees while UNHCR aircraft flew in food supplies. The adjustments in flight schedules had to take into account loading issues at both ends, food and refugee arrival at each end, safety and security, and so on. But coordination enabled improved utilization and higher capacity at about the same cost. Such coordination is coordination by consensus across the relief organizations.

In Afghanistan, the UNJLC website provides security and weather updates, logistics shipment needs (similar to a college campus ride board), road conditions, and so on. The ensuing coordination is left to individual agencies who use this information to seek out interested parties to share resources. Such coordination is minimal, left to individual agencies, and thus is coordination by default.

The previous examples show three forms of coordination: coordination by command, i.e., a centralized approach; coordination by consensus, i.e., cooperative, Pareto-improving solutions; and coordination by default or no coordination except perhaps information sharing. In Section 8.7 we discuss possible reasons for each form of coordination. A complete theory that matches optimal coordination type to situation context remains a research topic at this point.

8.4 Competitiveness

There are several separate performance measures, almost a different one used by each donor. Some donors focus on the bottom line of getting the job done, others focus on specific efficiency measures (e.g., percent truck utilization, inventory turns, fraction of women and children receiving assistance). Often the recipient country has to spend an inordinate amount of time generating reports for each separate donor. While competing performance measures may be part of receiving aid, it does constrain funds usage effectively at the recipient location.

While there are several possible measures of performance of a humanitarian relief supply chain, one approach, suggested by Fearon [37], is to compare an actual outcome with the counterfactual outcome. In such an approach, the question is whether the humanitarian intervention did in fact improve the system in terms of lives saved, diseases avoided, crop failure averted, market functionality maintained, and so on. But other suggestions focus on the success of the appeal coverage, lead time between donation and delivery of aid, financial efficiency and assessment accuracy. Each of these metrics focuses on the process of forecasting the aid required and garnering the resources and then efficiently delivering the aid while respecting the planned humanitarian space.

But the issues are substantial, and the following list provides examples that suggest that choosing metrics can have an impact on solutions, some innovative and some that have unintended consequences:

1. In the past, plastic jerry cans were air dropped to regions where refugees accumulated to permit them to collect water and transport it to their camp site. In an effort to efficiently transport a large number, collapsible plastic containers were used. However, these collapsible containers required careful cleaning to prevent bacteria from accumulating at the folds of the cans. Cleaning required the use of chemicals such as potassium permanganate that changed the water's color to a purple hue. As refugees avoided this cleaning step, the food and water shortage evolved to a severe medical crisis for the population. Clearly the supply chain solved one problem while generating another.

2. In the past, severe malnutrition required delivery of milk powder or other enriching powdered nutrition that had to be mixed with water. Contamination of the water supply made disease a problem and thus prevented effective treatment of the malnutrition. An innovative entrepreneur in France came up with Plumpy-Nut, a paste made of peanuts and milk power that could be squeezed into a child's mouth without addition of water. This innovation enabled a substantial reduction in the malnutrition soon after use. ([117])
3. Often, aid delivered is focused more on what donors have to offer rather than what is required. Soon after the 2004 tsunami in Asia, several loads of ski parkas and sweaters were shipped to Sri Lanka, a country where the weather seldom gets significantly cold. The ski parkas were often used as diapers and the donated clothing used as play things by children, rather than providing relief. One may argue that, by clogging up the delivery system with such ineffective aid, these donors compounded the problem ([5]).
4. Often effective delivery of purified water involves setting up of large purification plants in the field. But this effective approach also requires aggregation of large numbers of frail and disease-ridden people in close quarters. This increases the prospects of spreading disease and thus hampers possibility of providing effective relief.
5. In El Salvador, most of the poor population felt that aid was being diverted to the richer sections of society and abetted by the people in power at the time. There was the need to create a new entity that would permit coordination between the different groups. Despite efforts to keep the process neutral, the opposition managed to convince voters that their party played a key role in aid distribution and thus won the elections held soon after. The ex post facto analysis may as well have concluded that some of the humanitarian principles were violated, even though aid delivery itself was acceptable.
6. In Indonesia, the government troops were battling local guerillas in Banda Aceh. When aid arrived to this badly devastated region after the 2004 tsunami, the government troops were affected far more than the guerillas in the mountainside. But the government did not want the international media and US Marines to appear on their soil and interact with these guerillas. The denial of permission to

international military to offer assistance clearly complicated the efficiency of the associated relief supply chain.

7. In Ethiopia, aid groups brought in cooking oil as part of a food program. This oil competed directly with local producers and drove them out of business. The longterm consequence was a prolonging of the disaster.

8.5 The Humanitarian Space

What distinguishes the humanitarian supply chain management problem is that the deployment of the supply chain is the need to operate within a humanitarian space also referred to as the *humanitarian triangle.* The humanitarian triangle consists of three issues [118]: (1) "The first principle, humanity, implies that human suffering should be relieved wherever it is found" (p. 12); (2) "the second principle, neutrality, implies that relief should be provided without bias or affiliation to a party in the conflict" (p. 13); and (3) "the third principle, impartiality, indicates that assistance should be provided without discrimination and with priority given to the most urgent needs" (p. 13). Clearly each of these issues has to be weighed against its impact on the relief supply chain. The principle of humanity focuses on maximizing the number of people who benefit from the relief effort. But the principle of impartiality focuses on a weighted benefit, i.e., that of impacting those most in need of relief. Clearly each of these metrics might result in very different choices and deployment strategies. As an example, in the relief efforts following the floods in Rwanda, it is only after the relief organizations arrived at the scene that they realized the location of people most in need, which was in the border areas. From an evaluation perspective, the relief supply chain may have failed the impartiality test. Similarly, when relief efforts started following the hurricane in El Salvador, the ruling party was supported by the wealthy segments of society, while the guerilla army was supported by the poorer segments of society. Providing relief required coordination across both segments. The principle of neutrality required preventing any perceptions, apparent or real, that would benefit one or the other political parties.

8.6 An Illustrative Model

The following is an attempt to translate the impact of these principles on the running of the logistics system. The model is simple, but it could be made to reflect more realistic situations.

Consider a situation in which a logistics manager has an inventory level of food (I) that has to be distributed at a port. We are planning on how to distribute the food over a planning period T. (Think of T as the replenishment interval if we want to imagine this as a rolling horizon problem.) There are two population groups P_1 (in location L_1) and P_2 (in location L_2). L_1 is located at a distance (time) of T_1 from the port, and L_2 is located at a distance (time) of T_2. Assume that $L_1 << L_2$. Now suppose that the demands in each location over the period T are greater than the inventory available. Also, the benefit per unit delivered in P_1 is b_1, while the benefit per unit delivered in P_2 is b_2, where $b_2 > b_1$. Assume that given the transport assets available, the food can be moved at a constant rate to either location. Finally assume that the existing political situation has two powerful parties, each representing P_1 and P_2. However, whoever is successful in delivering the food will gain the upper hand politically.

Suppose the goal is to distribute the food as quickly as possible. If the food is distributed at a constant rate, since L_1 is closer, less will be in the pipeline and thus more food will be distributed over a fixed time period. Thus a plan to assist the largest number in a fixed time (humanity) will deliver all of the food to L_1.

Now suppose the goal is to distribute food so as to generate the greatest benefit. The focus is less on the quantity delivered and more on the benefits realized. This tips the focus to L_2. If all of the food is shipped to L_2, then we will deliver less food (as food will be stuck in the longer pipeline) but realize greater benefits from the food distributed. This will give us the principle of impartiality as being maximized by delivering all of the food to L_2.

Now focus on the principle of neutrality. Under the delivery to L_1, we tip the political power to P_1 party. Under the delivery to L_2, we tip the political power to P_2. If we want to do neither, but preserve the existing political climate, it is best to divide up the food and distribute (perhaps) half to P_1 and half to P_2. Note that given the differences in transport time, we will have to deliver $\frac{I - T_1 - T_2}{2}$ to each location. We will ship $T_1 + \frac{I - T_1 - T_2}{2}$ along the path to location L_1 and $T_2 + \frac{I - T_1 - T_2}{2}$ along the path to location L_2 in order to deliver equal amounts to each of the population centers P_1 and P_2. This will maintain the principle of neutrality.

8.7 Decisions

Coordination in the context of humanitarian supply chain management involves the delivery of relief in a cohesive and effective manner and involves (1) strategic planning, (2) gathering and managing information, (3) mobilizing resources and assuring accountability, (4) orchestrating a functional division of labor, (5) negotiating and maintaining a serviceable framework (6) providing leadership by injecting discipline without unduly constraining action [66].

Strategic coordination (SC) deals primarily with (1) negotiating access to affected populations, advocating respect for humanitarian principles and law and liaising with international political and military actors (including the UN system); and (2) setting the overall directions and goals of the UN humanitarian program, allocating tasks and responsibilities, ensuring correspondence between resource mobilizations and priorities, monitoring and evaluating the system-wide implementation. Tactical coordination (TC) tasks include managing (1) administration providing common services, communications, security and common logistics and (2) substantive decisions regarding deployment to specific sectors, geographical areas, choosing and prioritizing delivery to beneficiary groups, etc.

The three classic steps in any contingency are ramp-up, sustain, and ramp-down. During each of these phases, coordination activities can be described as consisting of reducing conflicts and bottlenecks and prioritization/scheduling. As discussed earlier, the varying nature of the scope activities suggests different management strategies over the life cycle. It is clear that there will be multiple agencies with individual missions, capabilities and metrics, separate donors, and so on.

Furthermore, the choices made by the owners of the system (governments, ministries, other countries, etc.) create the humanitarian space in which the relief efforts have to operate. In addition, information may be local and decentralized (e.g., local security, truck rates, contracts, quality of service) or centralized (e.g., weather conditions, road network, satellite images). The resources may be available centrally or donated by agencies and operated by private agents, the military, or individual relief agencies.

8.8 The Life Cycle of a Contingency Plan

During ramp-up, the humanitarian space is not clear. The deployment requirements are urgent, and some donors make use of speed of deployment to determine who gets resources (i. e., the early bird gets the worm). Sometimes the CNN effect results—few agencies are there early, and information is fragmented. However, starting the process requires several one-time tasks to be completed with respect to permissions to operate, taxes on imports, licenses for operating vehicles, rules regarding ownership of goods, clarifications regarding laws, visas, landing rights, customs and religious observances, and so on. There may also be infrastructural needs such as Air Traffic Control (ATC) requirements, bridges, and port clearance from neighbors. The region may be suited for centralized coordination because of the small number of entities involved and the critical nature of the congestionrelated issues.

During the sustainment phase, the individual agencies want to operate efficiently but may still require assistance such as security info, weather information, sharing of resources, help with breaking up cartels, assistance with persistent problems involving interpretation of laws, and coordination with military. Since many parallel efforts may be in operation, with each agency having its own supply chain processes, it may be appropriate to coordinate by consensus.

Coordination between agencies is helpful during ramp-down, when there is a need to identify local groups to continue operations, coordinate with the military for exit, decide how much development activity will continue, take actions to prevent mission creep, and so on. Since many entities may be involved, and each may be planning a hand-off to an appropriate local entity, it may be best to permit independent coordination with just information exchange.

8.9 Chapter Summary

The chain structure in a humanitarian logistics context is complex and consists of donors, collection groups (often NGOs), transport companies, aid groups at the destination, warehouses, relief camps, and recipients. The number of possible NGOs involved may be several hundreds, and the aid may be flowing in both through a pipeline as well as through bilateral efforts. Often the "last mile" of delivery requires coordination with local NGOs. The capacity of the local affected population to receive airplanes or ships, store products, and transport them to affected areas, as well as the level of skill of personnel are often key sources of complexity. Large demands on transport by several independently acting NGOs may create congestion and price increases and compound delivery problems. In addition, security concerns may add to the difficulty as well as the coordination problems with the military. The coordination choices made may include centralized coordination, coordination by consensus, and coordination by default. The nature of the coordination may depend on the stage of the contingency. Finally the metrics of performance vary greatly, including output measures of delivery effectiveness, truck utilization, and distribution of aid by population segments (e.g., women and children). In some contexts, significant portions of the aid are offered to the NGO who is first on the scene. Such metrics create a focus on speed at the cost of coordination or effectiveness. Given the increasing number of catastrophes, as well as the significant numbers of people depending on such aid, effective humanitarian supply chain management may well offer both intellectual challenges as well as personal satisfaction.

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Supply Chain Logistics and Applications

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