

CHAPTER 15

Management of Supply Chain Logistics

Supply chain logistics encompasses all material flows—from the flow of purchased material into a facility, through the manufacturing processes, and out to the final customers. This chapter is focused primarily on the inbound and the outbound flows of material from a manufacturing plant in a supply chain. We are concerned with describing the elements of a supply chain and presenting some techniques for their management.

Improved management of supply chain logistics can lead to improvements in customer service. This can often be done while simultaneously reducing total inventory, transportation, and warehousing costs. This chapter is organized around the following six topics:

- ▲ *A framework for supply chain logistics:* What is the scope of logistics management in supply chains, and how do logistics decisions influence other manufacturing planning and control decisions?
- ▲ *Supply chain elements:* What are the primary activities and tasks in moving material in supply chains?
- ▲ *Warehouse replenishment system:* How are systems for warehouse replenishment designed and operated?
- ▲ *Warehouse location analysis:* How are the number and location of warehouses determined?
- ▲ *Vehicle scheduling analysis:* How are vehicles used for delivery and/or pickup scheduled?
- ▲ *Customer service measurement:* How are customer service measures developed and used to evaluate supply chain logistics performance?

A Framework for Supply Chain Logistics

The detailed systems and models discussed in this chapter are oriented toward the flow of material both inward from suppliers and outbound toward customers from manufacturing. These concepts are also covered in Chapters 14 and 16. Here, a context for

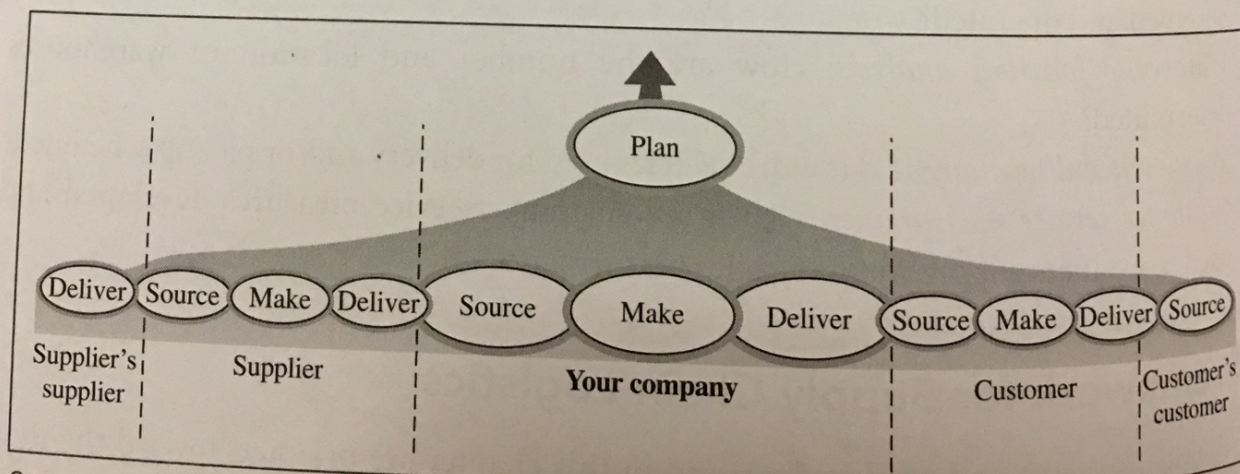
supply chain logistics is developed, and we present an overview of the entire supply chain logistics activity, the need to look at overall costs, and the integrative viewpoint that should be taken by management.

A **warehouse** can be specialized to perform many different types of functions—for example, as a mixing point to achieve transportation economies, as a finishing operation close to customers, and as a bulk break point. However, because we are interested in the operation of warehouses at many different points in a supply chain, we use the term *warehouse* generically to represent the different types of warehouses that exist in practice—for example, branch warehouses, market-positioned warehouses, product-positioned warehouses, distribution centers, and fulfillment centers.

The Breadth of Supply Chain Logistics

One definition of **supply chain logistics** encompasses all material flow decisions, from raw materials to final consumption. The structure of these flows is illustrated in the supply chain diagram shown in Figure 15.1. Dealing with this entire spectrum at once is virtually impossible. However, when portions of the overall flow become rationalized, such as by component-part planning with MRP, it becomes more reasonable to increase the scope of management. Moreover, the materials management organization form applied in some companies fosters improved interactions among material flow-related problems.

Even when the area under study is only concerned with the more limited segment of the outbound flows (i.e., physical distribution), the interactions with other manufacturing planning and control systems are still of critical importance. The outbound flow of materials from the factory is constrained by what is made available by the master production schedule.



Source: Supply-Chain Council, www.supply-chain.org.

Figure 15.1 Supply Chain Processes

The replenishment of warehouse stocks can be considered (often erroneously) to be demand. Without proper system design, it is possible for chaotic factory conditions to be self-induced by the distribution system decisions.

A framework for supply chain logistics recognizes the need for integrative thinking. We know that the MPS has to take into account the demands that are placed on manufacturing by distribution decisions. The need for coordinated design is clear. However, coordination should not stop at the boundary lines of the company. The final demand placed against distribution facilities may be generated by customer purchasing systems. One firm's output can be the other firm's input. A proper view of logistics encompasses linking the decisions made in the firm with both those made by the firm's customers and those made by the suppliers.

The Total Cost Concept

The basic idea in the total cost concept is that costs accrue and values are added by the various stages of product conversion and movement. That is, as raw materials become end products and are moved from manufacturing to the point of consumption, costs are added. The general goal is to minimize the total or overall cost while meeting customer-service goals. This is accomplished by reducing the suboptimization associated with treating each conversion or movement stage independently. If cost performance is improved by some action at one stage, at a more-than-offsetting cost disadvantage at another stage, the action is to be avoided. Further, if an action at one stage, although increasing costs at that stage, will provide a large cost savings elsewhere, it should be taken.

The total cost concept can be exemplified by a series of actions taken by a furniture retailer in New York. A study of customer service provided by retail stores in the New York metropolitan area was undertaken. Each retailer maintained an inventory. In total, for the 40 retailers in the New York metropolitan area, the value of the inventory was about \$3 million.

For an average customer order, the probability that all items desired would be in stock at a single retail store was approximately 25 percent. This meant back ordering, long delivery times, and many other problems. The retailer created one large field warehouse that could be drawn upon by any of these 40 retailers. The retailers, in turn, would no longer carry separate inventories. The value of the inventory in this field warehouse was approximately \$700,000, and the probability of filling an entire customer order from the warehouse stock increased to approximately 0.8. These actions required changes in delivered prices for the furniture, but the retailer no longer had inventory carrying costs. The total cost was clearly reduced. The key is to not permit parochial views of enterprise boundaries and accounting systems to impede progress.

Design, Operation, and Control Decisions

It is clear that logistics decisions can be wide reaching. The impact of some decisions will be felt in more than one functional area of the firm, or even between firms. Making these decisions is not easy. In fact, the difficulties and potential payoffs are highly correlated.

The most basic supply chain logistic design decisions, such as the establishment of the retailer's centralized field warehouse, require top management action. This is also true for other basic supply chain logistics decisions, such as the number of warehouses, their locations, the type of replenishment planning system, and programs for interfirm cooperation.

The operation and control of logistics in supply chains tend to be assigned to functional groups. In many companies, these functional groups are separated organizationally. In a growing few, there is a materials management form of organization that facilitates coordination.

A critical dimension of supply chain logistics management is to provide leadership for continued evolution. Once a subsystem is designed and operating, there is a natural tendency to feel that the problem is solved—forever. There is no ultimate weapon, and there is no ultimate supply chain. Improvements are always possible. As more and more subsystems become highly rationalized, transparent, and integrated through databases, new improvement opportunities can be found. To do so, management must devote analytical resources to the study of supply chain logistics within the framework of the total cost concept.

An example of this evolutionary point of view is again provided by our furniture retailer. The New York field warehouse was an unqualified success. This led to the rapid establishment of 12 additional field warehouses in other metropolitan areas. All were successful. However, in a few years, most of the field warehouses were closed down. The reason is that the concept behind their success was applied again. An even larger *regional* warehouse was established adjacent to one of the large Vermont factories. This warehouse provided one- to two-day deliveries to the entire eastern seaboard.

The most important aspect of this example is that management was concentrating on the function of the warehouses—not the warehouses themselves. Some key issues include the following: How quickly must the delivery response be? Who are the customers? What do they really want? How do we reduce lead time variability? What are the costs of stockouts? How do we measure customer service?

Many times the personal prestige of executives can impede evolution in supply chain logistics. The executives who were instrumental in the field warehouse program could not regard their closure as a personal failure. The program was a success, and it led the way to the achievement of even further progress.

An overall framework for supply chain logistics implies the need for evolution and integration. The management of manufacturing must necessarily be integrated with

logistical material flow decisions. So must many aspects of marketing. The objective is continuous and rapid evolution in the understanding and management of the total scope of supply chain logistics.

We now leave this overall focus and turn to more detailed aspects of supply chain logistics. In particular, we address some technical issues of the process. We also provide some examples of application. As we treat individual topics and recognize that each of the supply chain logistics issues is important, we do not, however, want to lose sight of the overall direction implied in the framework of logistics.

Supply Chain Logistical Elements

In this section, we provide general descriptions of some basic elements of supply chain logistics. We deal with the physical attributes of systems for gathering material from suppliers prior to manufacturing, and we are concerned with the distribution of products to customers on the output side of manufacturing. The management and information systems issues are addressed in subsequent sections.

Specifically, we want to identify some of the key characteristics of transportation, warehouses, and inventory regarding both the input of material to manufacturing and the distribution of products after manufacturing. For each of these supply chain elements, the intent is to understand the functions performed. Basically, these elements deal with the place and time utility of the products. Manufacturing provides the form utility.

Transportation

Supply chain logistics is concerned with the movement and storage of products. Achieving the former requires some method of transportation. As shown in Figure 15.2, there are a variety of modes available, and technological change is fairly rapid. Evaluation of transportation alternatives is, therefore, an ongoing need.

For example, there are companies that now move coal and fish in pipelines, automobiles are moved by ship, and many finished and semifinished products are moved by air. The most common modes of transportation are air, rail, truck, pipeline, and combinations of them. Among these modes, however, are alternative ownership/management forms. For example, there are private carriage, courier, common carrier, and contract services; cooperative arrangements; and forwarding agents. Our purpose here is not to discuss these in detail, but to point out the need for having access to someone with expertise in this area. We also want to focus on the key transportation variables and their impact on supply chain planning and control decisions.

One of the prime considerations in product movement is cost. There are substantial quantity discounts for shipping large volumes of products. Specifically, there are large cost

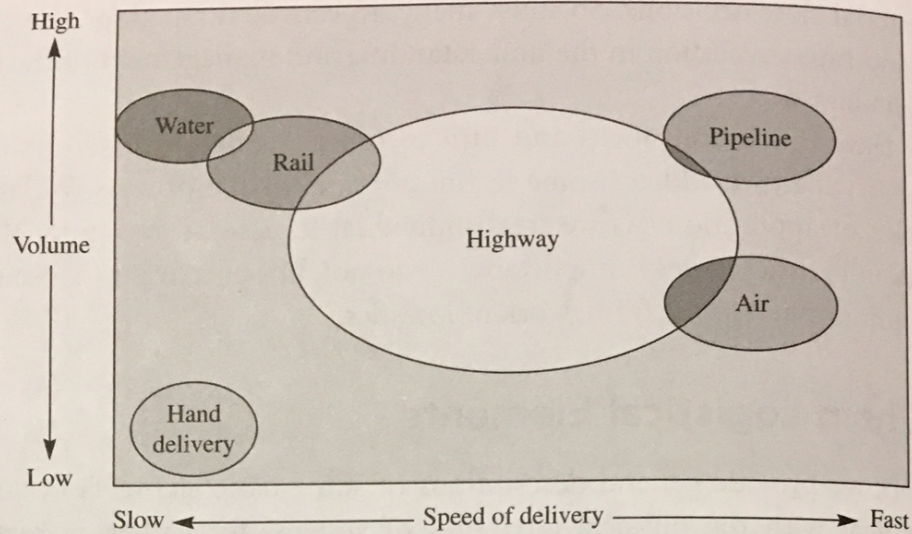


Figure 15.2 Logistics System Design Matrix: Framework Describing Logistics Processes

differences between less than carload (LCL) or truckload quantities and full carload (CL) or truckload quantities. This does not literally mean that a “full” carload must be shipped to get the discount, but that more than some specific weight must be shipped. The extent of freight rate differences is illustrated by Figure 15.3.

Another major variable in the determination of transportation costs is the selection of routing. Several options usually exist for delivering products to multiple customers. Drop privileges, for example, may enable the manufacturer to combine shipments to two or more customers, thereby gaining lower freight rates. Clever combinations of customers into shipping schedules can result in substantial savings. This is illustrated in Figure 15.4, which also shows how the number of alternatives to evaluate for even a simple example can be quite large.

In Figure 15.4, five alternatives are evaluated; the cost from lowest to highest is nearly double. Such extremes are not unusual at all. For companies with private fleets, the vehicle scheduling activities (about which more will be said later) are the equivalent of the routing activities. They can have an important impact on costs.

Figure 15.3 Example Freight Rates for Trucks between Chicago and Los Angeles

Household Effects		Machine Parts	
Weight	Rate (per cwt)*	Weight	Rate (per cwt)*
7,000 lb	\$42	24,000 lb	\$17.78
10,000	37	25,000	9.99

*cwt = Hundredweight or 100 pounds

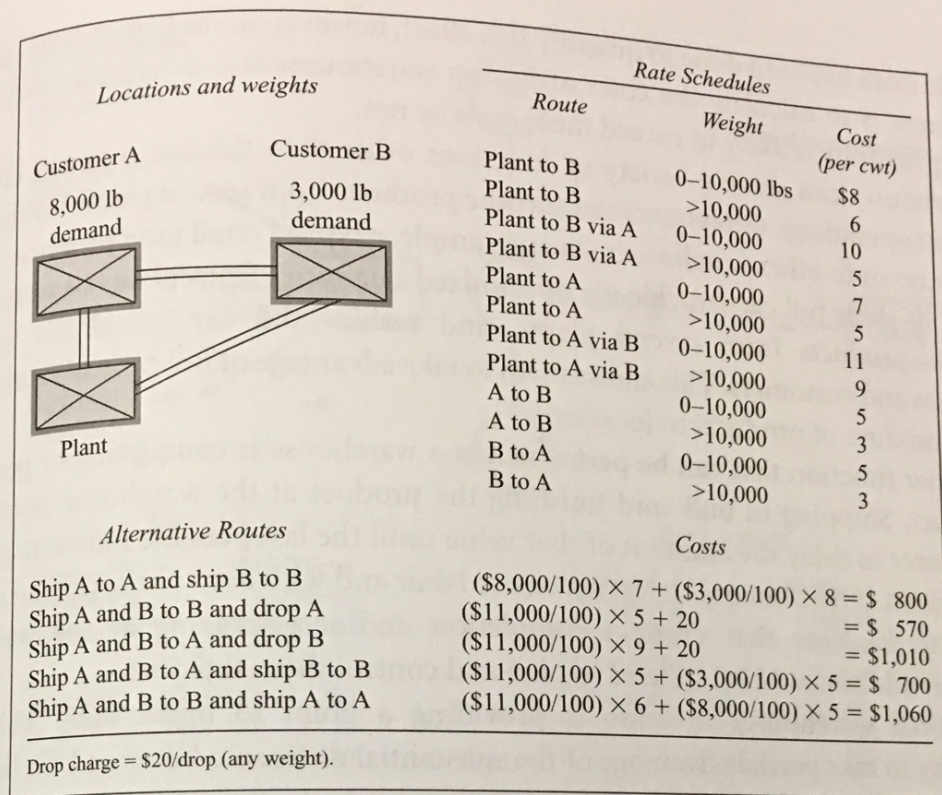


Figure 15.4 Alternative Routing Example to Serve Two Customers

Another aspect of transportation is trade-offs among speed, price, and reliability. In general, the faster a mode, the more costly (e.g., air freight is more costly than trucks). But a more subtle consideration is that of reliability or the variance around the average speed (lead time). Clearly, the greater the variance around the average lead time, the more safety stock or safety lead time is necessary. From a management point of view, safety stock levels are directly affected by the choice of transportation mode and routing, since these will offset the uncertainty in demand during lead time (DDLT).

Warehouses

We have been asked by very serious practitioners why a company should have warehouses. From the customer standpoint, the benefit is in time *and* place utility. That is, the warehouse locates the product closer to the customer in both distance and time. Whether this is worthwhile is a function of the market value of product proximity. Many executives have commented that there is a positive competitive advantage and market response to warehouses located near to the market. We dub this the "warm puppy effect." That is, having a warehouse nearby gives the customers a more comfortable feeling about service.

Very little work has been done to quantify this effect, however, so the best that we can do at the moment is to calculate the costs of having warehouses and determine whether the value of proximity is likely to exceed these costs or not.

Warehouses can serve a variety of functions other than the warm puppy effect. In multiplant operations, warehouses can mix the products from several plants for shipment to customers or to other warehouses. As an example, a typical retail food producer such as Kraft Foods ships full car-/truckloads of unmixed quantities from plants to warehouses, mixes the products from several plants, and reships full car-/truckloads to other warehouses and customers. This allows them to take advantage of full carload rates *and* get the right mixture of products to locations.

Another function that can be performed at a warehouse is completing or packaging the product. Shipping in bulk and finishing the product at the warehouse permits the manufacturer to delay the addition of that value until the last possible moment. It is also possible that it can be done with less expensive labor and with better information on local product needs. Note that product completion and/or packaging at the warehouse necessitates additional MPC systems to plan and control these activities.

One final warehouses function is providing a point to break bulk. This is an opportunity to take partial advantage of the substantial difference between LCL (less than carload) rates and CL (carload) rates for shipping products. By putting a warehouse in a region, the product can be transported into that region at the CL rate, and then can be delivered to customers at the LCL or local delivery rate. Consider, for example, shipment of products from Chicago to the southern California region. An example of two alternatives is given in Figure 15.5. The example shows a potential cost savings of \$720 per week from a Los Angeles-based warehouse. This potential saving can be compared to the cost of operating the warehouse.

Inventory

Several functions of inventory will be mentioned before completing this section on the elements of the supply chain. Some of the marketing reasons for inventory are the maintenance of a full line of products, the provision of adequate display stock, or the provision of full inventory pipelines through the channels to each customer. Let's turn now to some key operational considerations of inventory in supply chains.

Inventory performs a buffering role in supply chains, but much confusion exists over the use of order quantities for buffering against uncertainty. Some firms incorrectly believe that order quantities should be increased when demand becomes less certain (i.e., the forecast error increases). In fact, it is safety stock that should be managed to buffer against increased uncertainty, not order quantities. In general, to increase safety stock, the

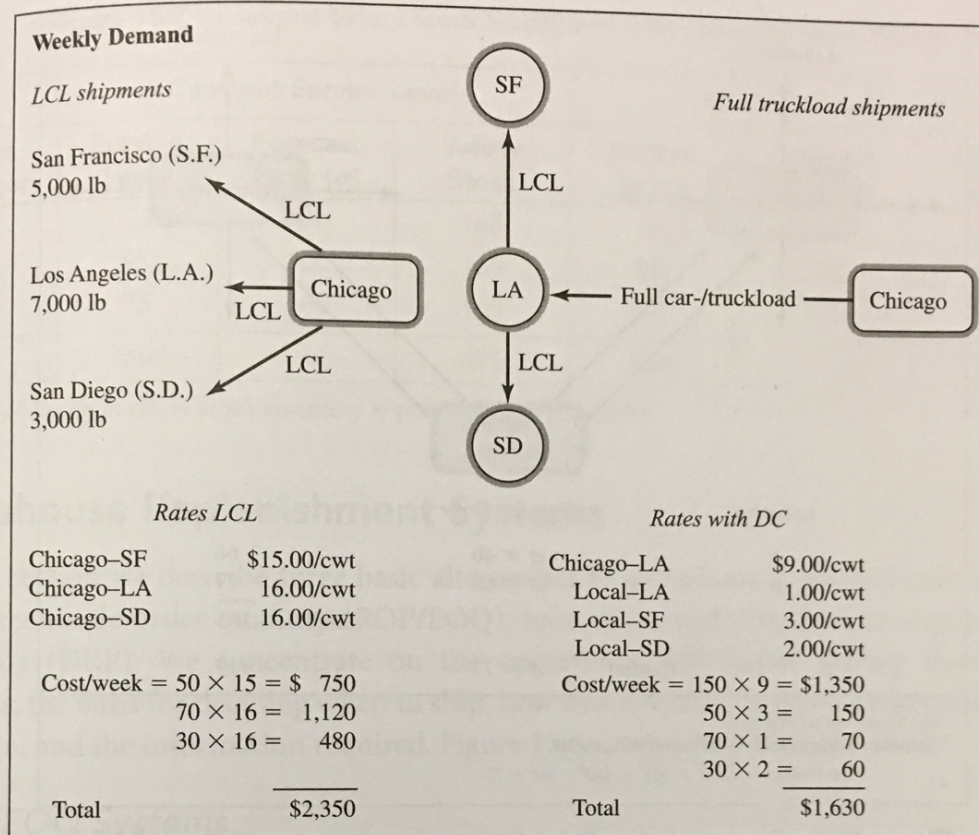


Figure 15.5 Example Cost Comparison: LCL versus Full Truckload, Chicago to California

order point needs to be raised, not the order quantity. Changes in the order quantity should be made as a result of changes in the inventory carrying cost, changes in the setup costs, changes in quantity discounts or transportation costs, etc.

Safety stock is a function of the demand during lead time. The uncertainty is influenced by the choice of transportation mode as well as the variability in demand rate. For each location, then, there is a possible need for safety stock. Each location will also have cycle stock, which is the result of shipping in economic quantities. Although safety stock and cycle stock interact, in this chapter we ignore the interaction in illustrating an important trade-off to be considered in designing the supply chain. This trade-off involves the pooling of safety stock at fewer locations to realize inventory savings.

The impact of pooling safety stocks must be evaluated against the possible advantage (product proximity) provided by a larger number of warehouses. The potential savings in safety stocks are demonstrated in Figure 15.6, assuming a one-period lead time. Providing the service level of 95 percent (the percent of demand that can be satisfied from stock at both A and B) requires 165 units of safety stock, while consolidation at a central location

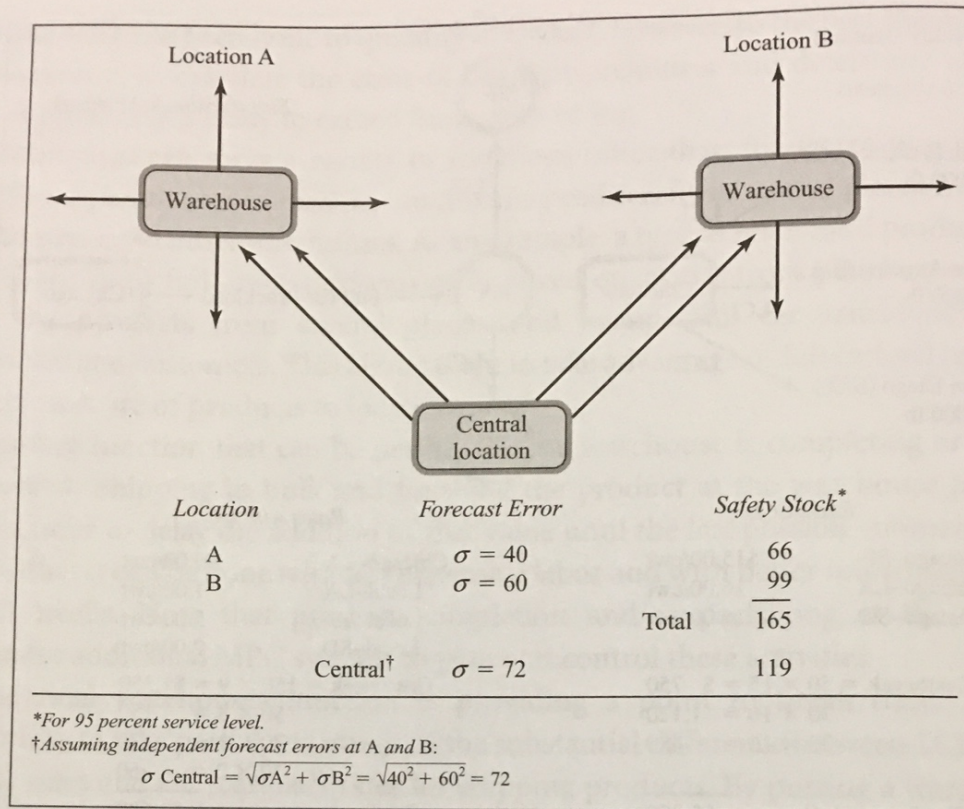


Figure 15.6 Example Safety Stock Savings from Warehouse Consolidation

requires only 119 units. This is the same phenomenon that our furniture retailer capitalized on both in creating the New York warehouse and later in creating the eastern seaboard regional warehouse.

The potential saving from warehouse consolidation of safety stock has led many firms to devise mixed service strategies. Because consolidation locates the inventory farther from the customers, delivery time may be increased. On the other hand, the savings from reduced safety stock may more than compensate for this reduction in service with some categories of products. The mixed service strategy provides different levels of service for different categories of products. Providing, for example, service level of 95 percent for A items, 85 percent for B items, and 70 percent for C items, can lead to substantial savings in inventory, as shown in Figure 15.7. Detailed explanations of A, B, C analysis together with safety stock calculations are topics of Chapter 16.

Thus far, we have discussed the three basic elements of a supply chain: transportation, warehouses, and inventory management. We now turn to the information system used to manage the routine replenishment of supply chain inventories.

Figure 15.7 Example Safety Stock Saving with Mixed Service Level Policy

Item Category	Constant Service Level			Mixed Service Level		
	Service Level	Forecast Error (σ)	Safety Stock	Service Level	Forecast Error (σ)	Safety Stock
A	95%	100	165	95%	100	165
B	95	100	165	85	100	104
C	95	100	165	70	100	53
	Total		495	Total		322

Percent of saving in safety stock inventory = $(495 - 322)/495 = 35\%$

Warehouse Replenishment Systems

In this section we describe three basic alternatives to warehouse replenishment: reorder point/economic order quantity (ROP/EOQ), base stock, and distribution requirements planning (DRP). We concentrate on the operational differences among these three systems: the basis for deciding when to ship, how much to ship, which location makes the decision, and the information required. Figure 15.8 summarizes these issues.

ROP/EOQ Systems

Historically, and perhaps currently, the dominant method for determining the amount to be shipped is the use of an economic order quantity, purchase quantity, or shipping

Figure 15.8 Three Alternative Warehouse Replenishment Systems

System	When to Order/Ship	How Much to Ship	Where Decision Is Made	Information System Complexity
Reorder point/economic order quantity	Warehouse actual inventory reaches reorder point	Economic lot size based on forecast or average usage	Warehouse	Low
Base stock	Scheduled shipment dates	Actual usage in previous period	Central location	Medium
Distribution requirements planning	Projected on-hand balance offset by lead time	Economic shipment quantity based on projected time-phased usage	Central location	High

quantity, and a reorder point to establish the timing of the shipment. As seen in Figure 15.8, the actual inventory balance in the warehouse is used to determine when the inventory reaches the reorder point. Order point calculations are covered in Chapter 16. At that point, an order is released by the warehouse and placed with the central resupply location. Order placement varies from mail forms to Internet-based online communications. Any time delays between order placement by the warehouse and order receipt by the resupply point have to be compensated for with longer lead time.

The shipment quantities are determined, using economic order quantity methodology (described in Chapter 16). The expected demand is assumed to be constant and is based on past averages or a forecast of future demand. The quantity determination can incorporate quantity discounts and transportation economies, if necessary. Both are treated in the same analytical way. Other practical considerations such as full-case, full-pallet, or mixed-product carloads can also be taken into account.

A key aspect of ROP/EOQ replenishment systems is that the decisions are made at the warehouse level. From an information point of view, this means that the central location does not have to maintain inventory records or process detailed warehouse transactions. The complexity of the information system is low. Information handling and decision making are decentralized.

A fundamental disadvantage in the classic ROP/EOQ replenishment system is that the information received by central has been filtered by the individual decision processes at each of the warehouses. That is, the demand being expressed by customers is seen by the warehouses individually. The way in which this demand is transmitted to central is influenced by the parameters of the ROP/EOQ system in use at each warehouse. The problem is often compounded by the fact that the selection and modification of the system parameters are also done by warehouse personnel. There is a natural tendency for amplification. As end-customer demand grows, for example, adjustment of parameters often results in a larger growth in the orders being placed by the warehouses on the central inventory.

Still another problem with the pull orientation of ROP/EOQ systems occurs when the demand on central in a particular time period exceeds the available supply. Some form of allocation is necessary, but without detailed warehouse information, the allocation will necessarily be somewhat arbitrary. In a similar vein, phased withdrawals of products will tend to be uneven at different warehouses. Also, the ability to cross-ship among warehouses will be reduced. The implication is that centralized information can yield more effective distribution inventory management.

Base Stock Systems

There are two distinguishing features of the base stock system. The first is the separation of the information flow on end-item demand from replenishment order data. That is,

information on actual end-item demand is fed back to all stages in the supply chain, including the factory. This feedback allows certain key decisions to be based on data that have had no amplification. The data can be transmitted as received at the warehouse with online communication systems or batched for daily or longer time period processing. The second distinguishing feature of the base stock system is the establishment of a routine replenishment cycle. In its simplest form, the base stock system uses a direct replacement system. That is, the exact amount sold by a warehouse during a fixed time cycle is replenished at the next shipment time.

The base stock quantities for each warehouse are set to cover the maximum expected demand for each item during the lead time necessary to replenish the warehouse. When the next delivery is scheduled to leave for a warehouse, the quantity shipped for each item is the quantity sold since the last delivery plus any adjustments to the base stock level. If, for example, a truck goes to a warehouse on a weekly basis, the quantity shipment would replenish the actual usage in the previous week (if there were no information-processing delays).

The base stock system is predicated on the determination of a shipping frequency to each distribution center. This is seen in Figure 15.8 as the when to order/ship decision. In determining this frequency, a major trade-off is larger shipments made with less frequency, which can reduce transportation costs, versus smaller shipments made more frequently, which can reduce warehouse inventory carrying costs.

Although Figure 15.8 shows the base stock system shipment quantities as equal to the actual usage in the previous period, convenient shipping sizes can also be accommodated. For warehouse replenishment, there will almost always be the issue of pack sizes, full-pallet quantities, etc. This is accommodated by measuring actual demand in the pack or pallet sizes and then use logic that considers current inventory position at the warehouse.

The base stock system incorporates centralized decision making. Rather than having individual systems run by the warehouses determine when and how much to ship, these decisions are made routinely with a single system using data and parameters that optimize the network. The result is better coordination of central inventory resources and multilocation demands. The cost is increased information handling.

An application of the base stock system is the kanban system, which is used in many manufacturing companies (see Chapter 13). It is a base stock system—applied in a manufacturing environment. As a user department actually uses parts provided by a supplier department, the information is passed back to the supplier department. The form of information is empty containers to be refilled with parts by the supplier department and passed on to the user department. In other words, the system is designed to have the supplier department replace the parts the user department just used.

The kanban system *inside* the factory is based on a fixed lot size (the number of items in a container). The periodicity or timing of the replenishment order varies, but lots are so small that, in general, several lots are made in a single day. When the system is applied to

vendors, it is more like the distribution base stock system. The vendor brings in a variable number of items on a fixed delivery cycle. The number of items in a batch is essentially what was just used in production.

Distribution Requirements Planning

The primary distinguishing feature of distribution requirements planning (DRP) is the use of time-phased projected future usage (see Chapter 14 for a detailed discussion of DRP). This means that the determination of when to ship an order is based on a projected inventory position, and the shipment is made in anticipation of inventory availability as opposed to reacting to an actual inventory position. Likewise, the determination of the shipping quantity is made in a similar way from time-phased projected usage information. This means that replenishment can be based on the best estimates of future needs, with possibilities of combining future requirements to fill trucks or railcars for shipment to warehouses. The shipment quantity can be sized using economic order quantity methodology, taking into account transportation costs. These decisions are illustrated by the information shown in Figure 15.8.

An important advantage of using DRP is that decisions can be made at the warehouse, but the time-phased record information for the warehouse items is also fully visible centrally by manufacturing. This can facilitate the coordination of shipment quantities by both the warehouse and manufacturing. As an example, the cross-shipping of products between warehouses is possible when the demand on central exceeds the available supply for a particular time period. A further advantage of DRP is that local information can be taken into account in developing the forecast information. For example, in using DRP at Abbott Laboratories, warehouse personnel knew that many customers order more heavily in the first and third weeks of the month. As a result, these factors could be considered in developing the product forecasts.

The benefits of DRP do come at a cost of a more complex information system. The costs of handling inventory transactions and operating the time-phased DRP system are substantial.

Warehouse Location Analysis

One of the key elements in managing the supply chain activities of a firm is the determination of how many warehouses to have and where they should be located. We consider several approaches to that problem in this section. The basic approach we take is to choose among a set of predetermined alternative locations.

To illustrate the problem and solution approaches, let's assume that some staff group has developed the information (perhaps with regression analysis estimates) shown as

Figure 15.9 Costs for Alternative Warehouse Locations

Potential Warehouse Location	Fixed Cost per Year	Customer Locations										
		Michigan City	Gary	Indianapolis	Lafayette	Kokomo	Columbus	Richmond	Vincennes	Evansville	Louisville	Terre Haute
Hammond	8	10*	22	25	7	4	17	11	5	15	25	22
Indianapolis	7	13	30	20	5	3	14	8	4	11	19	18
Columbus	6	15	32	22	7	4	12	9	3	11	19	17
Terre Haute	5	13	30	22	8	5	17	10	2	12	20	15
New Albany	5	18	40	24	10	7	15	10	4	10	17	17

*Variable cost (in \$000) per year for serving all Michigan City customers from a Hammond warehouse.

Figure 15.9. This figure shows the annual fixed cost of using each of the possible warehouses plus the variable costs associated with serving the customers in particular locations from each warehouse.

Simulation

A useful approach to determining the number and locations of warehouses is **simulation**. One way to do this is to specify a number of warehouses to evaluate—say, two—and randomly choose several examples of two warehouses. Once a particular set of warehouses is chosen, customers are assigned to specific warehouses on the basis of minimum cost, and total annual costs are calculated. For example, a Hammond/Indianapolis set of warehouses would be calculated as follows (in \$1,000 of cost):

$$\text{Fixed costs} = 8 + 7 = 15$$

$$\text{Variable costs (Hammond)} = 10 + 22 = 32$$

(for serving only Gary and Michigan City)

$$\text{Variable costs (Indianapolis)} = 20 + 5 + 3 + 14 + 8 + 4 + 11 + 19 + 18 = 102$$

$$\text{Total costs} = 15 + 32 + 102 = 149$$

Many pairs of warehouses would be similarly evaluated to find a good (but not optimal) set. Next, a different number of warehouses is investigated in the same way—say, three—with random sets of three warehouses chosen for analysis. The end result would be the ability to plot the total annual expected costs as a function of the number of warehouses. Figure 15.10 is an example of such a plot. Once the interesting range of the

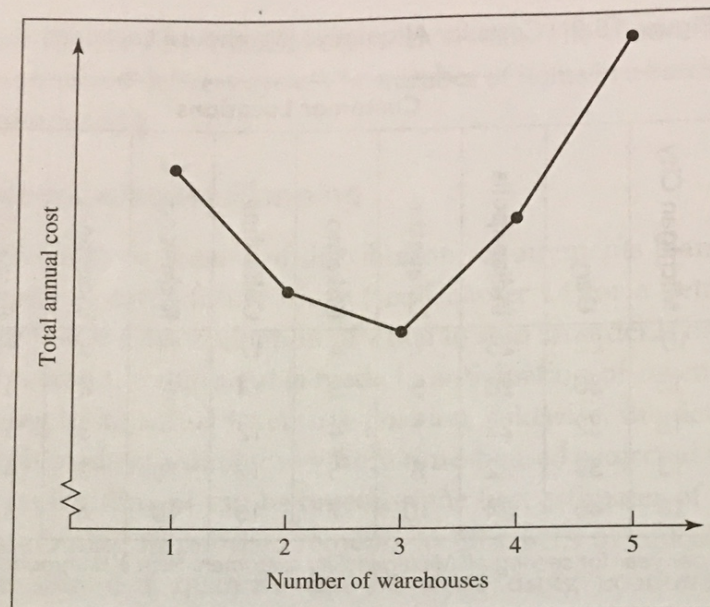


Figure 15.10 Total Annual Cost for Varying Numbers of Warehouses

number of warehouses is determined, more detailed analysis can be made, both in terms of the number of warehouses and location. At this point, management/subjective considerations can also be taken into account.

Heuristic Procedures

Several **heuristic procedures** have been developed to permit rapid determination of good warehouse location patterns. Among these are the *add* and *drop* procedures. The add procedure will be illustrated with the data from Figure 15.11. The procedure starts by considering which single warehouse would serve all the customer locations at the least cost if used *alone*. From Figure 15.11, we see that this is Indianapolis at a cost of \$152K. Once this warehouse is found, the least cost warehouse to *add* to the first one is chosen. Here we see that given that Indianapolis is in place, the cost can be reduced further if we add a warehouse at Hammond. The total cost now is \$149K. Next, the third best warehouse to add to the first two is determined, and so on, until the addition of another warehouse increases total costs. In the example shown in Figure 15.11 the addition of a third warehouse to the combination of warehouses in Indianapolis and Hammond increases costs, so the procedure stops with the two suggested.

Programming Procedures

Neither simulation nor the heuristic procedures guarantee an optimal solution to the selection of warehouses. It is tempting to suggest that all combinations be examined, that is,

Figure 15.11 The Add Procedure for Determining Warehouse Location

Step	Warehouses	Cost	Choice
1	Warehouse	Hammond	Indianapolis
		Indianapolis	
		Columbus	
		Terre Haute	
		New Albany	
2	Warehouse	Hammond	Hammond
	Indianapolis +	Columbus	
		Terre Haute	
		New Albany	
3	Warehouse	Columbus	No choice: costs are increasing
	Indianapolis +	Terre Haute	
	Hammond +	New Albany	

*Final choice: Indianapolis and Hammond.

to completely enumerate all possible warehouse customer combinations to find the best. However, for a typical problem of 100 potential warehouse locations and customers throughout the United States, enumeration of all possible combinations may not be possible.

Exact procedures do exist for optimally solving the warehouse location problem. Branch-and-bound techniques have been made quite efficient and are now feasible for problems of 100 to 200 potential warehouses. The general approach of the branch-and-bound technique is to use the transportation method of linear programming sequentially to bound the solution space. Linear programming techniques alone cannot be applied because of the fixed costs associated with each warehouse. The first step in the procedure is to treat all the fixed costs as variable and solve a transportation linear programming (TLP) problem. The cost of this solution represents a lower bound on costs in that no solution accounting for the fixed costs can be better. If the solution to the TLP problem assigns all customers fully to some of the warehouses that is the solution. If some are only partially assigned, the procedure continues.

The next step is to select one warehouse that is to be constrained as open. This adds the full fixed costs of that warehouse. All other fixed costs are still assumed to be variable. The TLP produces a lower bound to this condition. Next, the same warehouse is constrained to be closed and the TLP solved. Another lower bound is thereby obtained.

The branch with the lowest bound of the two branches (first warehouse open or closed) is then selected for further analysis. Another warehouse is added and again constrained as both open and closed. Lower bounds are obtained with TLP, as before. Again the smaller lower bound path is chosen. The process is repeated until a terminal solution is obtained. A terminal solution is one where all warehouses are either open or

closed. The cost of this terminal solution now becomes an upper bound. That is, it is a feasible solution—any other solution with a greater cost can be ignored.

All branches for which lower bounds were calculated but not explored en route to obtaining the first terminal solution can now be compared with the upper bound. Any branches that have a lower bound greater than the upper bound can be omitted from further consideration. Those that are lower have to be evaluated. The evaluation proceeds either until lower bounds are achieved for the branches that exceed the current upper bound or until a terminal solution is reached. If the cost of the terminal solution is lower than the current upper bound, it becomes the new upper bound.

This basic approach has been augmented to reduce the computational effort. For example, in the problem shown in Figure 15.9, it is possible to quickly determine that the optimal solution will use the Hammond warehouse because Hammond can most cheaply serve Michigan City and Gary. The next best alternative to serve these two customers would add \$3,000 and \$8,000, respectively. This is more than the fixed costs of the Hammond warehouse.

Vehicle Scheduling Analysis

In this section we treat **vehicle scheduling**. We assume a given supply chain system involving the replenishment of customer inventory and a given set of customer locations. We then determine how vehicles should be best scheduled to achieve the supply chain objectives. Here, the customer may be manufacturing plants served by a supplier, a set of warehouses served by a manufacturing plant, or a set of customer locations served by a warehouse.

The problem typically formulated is to determine the order in which customers will be visited by delivery/pickup vehicles, often called the *route*. Other questions include determination of the proper number of vehicles, the frequency with which each customer should be visited, and the times to be associated with the stops along the route.

Our approach to vehicle scheduling is to first present a discussion of the *traveling salesmen* problem. This provides an analytical framework. We then suggest methods for solving the problem.

Traveling Salesman Problem

The traveling salesman problem is one of those easily stated but difficult to solve problems on which mathematicians thrive: Given a set of cities, warehouses, or customers to be visited, what is the least-cost method of visiting each of them, starting from and returning to a given point (the central facility)? An example is shown in Figure 15.12, where there are five warehouses to be visited from a central plant.

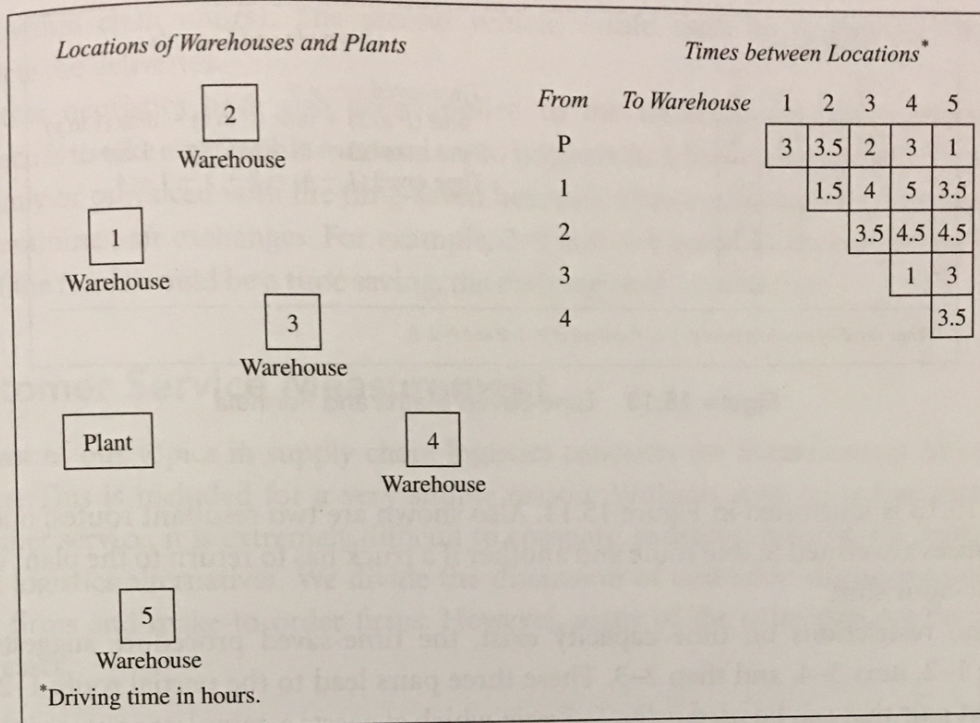


Figure 15.12 Traveling Salesman Example

Solution Methodologies

The traveling salesman problem can be formulated as a zero-one integer programming problem. Optimal solution approaches include branch-and-bound procedures similar to those discussed for the warehouse location problem and dynamic programming. Producing optimal procedures becomes computationally costly as the size of the problem goes up. That is, as the number of customers or warehouses to visit in a schedule increases, the computational costs rise geometrically.

Heuristic procedures have been devised for this problem that produce reasonably good results in far less time than the optimal procedures. One widely used heuristic is based on the *time-saved* concept. The basic consideration is the time or distance that would be saved if two warehouses were visited in a single tour, as opposed to visiting each separately. For the example shown in Figure 15.12, a matrix of time saved can be constructed. Figure 15.13 provides this information.

The time-saved matrix can be utilized for several purposes. But let's first start with the determination of the route. The most desirable combinations to put on a route are those that save the most time. Because a route that goes from 1 to 2 (or vice versa) would save the most time, it is selected first. The application of the heuristic to the entire set of data in

Time Saved					Formula and Example	
	2	3	4	5		
1	5*	1	1	.5	Time saved $x - y =$	
2		2	2	0	time (P to x) + time (P to y) - time (x to y)	
3			4	0	Time saved (1 - 2) = 3 + 3.5 - 1.5 = 5*	
4				.5	Time saved (3 - 4) = 2 + 3 - 1 = 4	

*Time saved by traveling from P-1-2-P instead of P-1-P and P-2-P.

Figure 15.13 Time-Saved Matrix and Formula

Figure 15.13 is illustrated in Figure 15.14. Also shown are two resultant routes; one if all warehouses are visited in one route and another if a truck has to return to the plant within an eight-hour shift.

If no restrictions on time capacity exist, the time-saved procedure suggests first pairing 1-2, next 3-4, and then 2-3. These three pairs lead to the partial route 1-2-3-4. The next pair that can be used is the 1-5 pair, which suggests a complete route would join 5-1 so that the complete route would be P-5-1-2-3-4.

The addition of the eight-hour time constraint is readily included in the time-saved heuristic. In Figure 15.14, pairs would be combined until the constraint was reached, and then a new route would be started. The first route would be P-1-2-P using eight hours (there is no warehouse that can be visited from warehouse 1 or 2 with return made to the

Figure 15.14 Application of Time-Saved Heuristic

Rank of Pairing by Time Saved		Unconstrained Route	Eight-Hour Constraint Route
1-2	5	1-2	P-1-2-P 8 hours
3-4	4	3-4	P-3-4-P 6 hours
2-3	2	1-2-3-4	
2-4	2		
1-3	1		
1-4	1		
1-5	.5	5-1-2-3-4	
4-5	.5		P-3-4-5-P 7.5 hours
2-5	0		
3-5	0	P-5-1-2-3-4-P	P-1-2-P, P-3-4-5-P

plant within eight hours). The second vehicle would then be routed P-3-4-5-P to complete the deliveries.

Other heuristics have also been applied to the traveling salesman problem. One approach is to take any feasible tour and try to improve it. A feasible tour could be generated randomly or produced with the time-saved heuristic. One improvement procedure would be to examine pair exchanges. For example, 2-3 and 3-4 could be exchanged for 2-4 and 4-3. If the result would be a time saving, the exchange would be made.

Customer Service Measurement

The last of our topics in supply chain logistics concerns the measurement of customer service. This is included for a very simple reason: Without some objective measure of customer service, it is extremely difficult to compare, measure, and control many supply chain logistics alternatives. We divide the discussion of customer service into make-to-stock firms and make-to-order firms. However, many of the principles are the same in both cases.

Make-to-Stock Companies

In this section, we consider firms that ship from an inventory to customers (or provide an inventory for customers). We look at the difficulty of defining and measuring customer service.

A major issue in measuring customer service for the make-to-stock firm concerns delivery timing. Among firms shipping from factory inventories to retail centers, warehouses, or customers, many feel that customer service should be assessed in terms of the speed of delivery. That is, after a customer places an order, how soon is it delivered? This leads to policies like one-week or overnight delivery. This fixed delivery time implies levels of inventory and/or capacity that should be thought through carefully before setting the policy.

An alternative measure of customer service is the consistency of delivery. This is related to available-to-promise logic. Make an honest promise—then keep it. This is not common, but the emergence of manufacturing planning and control systems is making it more possible. It still is not as popular as the fixed response ideas—such as next-day delivery.

Our experience indicates that there is no one best measure. *All* firms state that they are very concerned about customer service, but we find firms falling into two major groups. The key difference is whether they have unambiguously defined and measured customer service. One group of firms does not systematically measure and does not have

unambiguous definitions of customer service. Among the second group, those who do have definitions and measures, there tends to be very different measurements.

Once the issue of when (promise date or response time) has been resolved, there is still the issue of how to measure service in terms of *what* is delivered. Again, there are a number of different measurements used for this aspect of customer service. One common measurement is the percent of the items demanded in any period (i.e., a year) actually supplied from stock when demanded. A related measure is the percent of demand satisfied from stock during the reorder cycle. The measure reflects the notion that the exposure to stockouts occurs between the time the replenishment order has been placed and the time the delivery arrives in inventory. Another measure is the percent of the line items in an individual customer order that have been filled out of inventory. Still another measure is the percent of the customers for whom all line items were filled from inventory.

One has to be careful in selecting among these measures. The objective is to provide customer service—to measure how well one is doing and to continually look for improvement, both in the service provided and in the measurement used. If a completely responsive production facility were available, no customer service issue would ever arise. All orders would be shipped upon order receipt. While clearly unrealistic for most products, there are some instances where it is competitively necessary to provide such service. For example, some firms have a customer service policy of “immediate” delivery of spare parts. Again, one must recognize that this measure is going to fail for some customers unless the normal demand can be postponed, so the manufacturing facility can literally make the spare part immediately.

All of these measures signify different aspects of trying to satisfy customer demand. It is not always possible (or even desirable) to satisfy all demands. Moreover, many actual delivery requirements vary. For this reason, variable specifications may be in order, depending on the customer served.

Make-to-Order Companies

The primary customer service consideration in a make-to-order (or assemble-to-order) firm is the ability to meet promised delivery dates. Thus, measuring performance against these promises is as important in the make-to-order as it is in the make-to-stock firm. The timing issue is also critical in the make-to-order firm. One key dimension of timing is the time from order placement until delivery. An important element of this is the manufacturing lead time. If insufficient time exists, some promises will have to be made on the basis of previously forecast volumes. Managing that requires an effective MPC system.

Customer service measurement in the make-to-order firm is somewhat complicated by the fact that customers often change desired delivery dates. In measurement then, one issue is whether the change was made by the customer or the manufacturer. Should performance be measured against the assigned date or the revised date? Against both?

The implications of the necessity to control and measure against delivery promise dates underscores the need for close coordination between order entry and master production scheduling. Many make-to-order firms have a simple policy of six weeks (or some other such period) delivery for every order. If this were correct on the average, it means that in 50 percent of the cases delivery could have been sooner, and in 50 percent of the cases delivery will be late. It is the function of the master production scheduling activity to monitor the capability of the shop to deliver. This ability to monitor the customer promising capability through the available-to-promise logic means that the delivery date can be specified on the basis of actual shop capability, and the supply chain logistics function can deliver to the customer against a date that was feasible from the shop's standpoint and agreeable to the customer.

We see then that customer service measurement is critical to assess supply chain design choices. It is also intertwined with other manufacturing planning and control (MPC) system functions. Good master production scheduling makes for better customer service. Good execution systems make for an attainable master production schedule. MPC system strengths can support new and exciting changes in supply chains.

Concluding Principles

Several technical and managerial principles are discussed in this chapter:

- ▲ The role and contributions of each element of a supply chain's logistics must be determined and managed.
- ▲ Management must provide the integration for the elements of these systems and evaluate alternatives in terms of total cost.
- ▲ The information from distribution requirements planning systems should be used for planning product deliveries.
- ▲ The design of warehouse systems should incorporate the locational (warm puppy) effect on sales.
- ▲ The vehicle scheduling activities must be coordinated with customer service requirements.
- ▲ Customer service objectives and standards must be set and monitored. These should reflect the types and classes of customers and products.

APICS/CPIM Certification Questions

1. A warehouse can perform which of the following activities?
 - I. Finishing operations (e.g., packaging)
 - II. Bulk break point for shipments to customers
 - III. Mixing point for shipments from multiple plants
 - a. I only
 - b. I and II only
 - c. II and III only
 - d. I, II, and III
2. Suboptimization is likely to occur when stages of the supply chain are considered separately.
 - a. True
 - b. False
3. Which of the following best ranks the transportation options from slowest to fastest?
 - a. Rail—pipeline—highway—air
 - b. Rail—highway—pipeline—air
 - c. Pipeline—rail—highway—air
 - d. Pipeline—highway—rail—air

Handwritten note: A box labeled 'ARHPA' with an arrow pointing to option b. Next to it, handwritten text reads: 'Rail 1st, Highway 2nd, Pipeline 3rd, Air 4th'.
4. In general, shipping full loads will be less costly (per unit) than shipping partial loads.
 - a. True
 - b. False
5. Warehouses offer which of the following benefits to customers?
 - I. Faster deliveries
 - II. Lower costs
 - III. Better product availability
 - a. I only
 - b. II only
 - c. III only
 - d. I and III only
6. When demand becomes less certain, the firm should take which of the following actions?
 - a. Increase order quantity
 - b. Increase order point
 - c. Decrease order quantity
 - d. Decrease order point

7. In the following example, what is the safety stock savings from using a mixed service level? (Select the best answer.)

Item Category	Constant Service Level			Mixed Service Level		
	Service Level	Forecast Error (σ)	Safety Stock	Service Level	Forecast Error (σ)	Safety Stock
A	95%	100		95%	100	
B	95	125		90	125	
C	95	100		85	100	
		Total			Total	

- a. 10%
☒ b. 15%
 c. 20%
 d. 25%
8. In the following example, what is the safety stock savings from centralizing safety stock to a single location (assume demand is equal at each warehouse)? (Select the best answer.)

Warehouse	Service Level	Forecast Error	Safety Stock
A	95%	100	
B	95	125	
C	95	75	
		Total	

- a. 20%
☒ b. 40%
 c. 60%
 d. 80%
9. The economic order quantity (EOQ) calculation makes which of the following assumptions?
- I. Constant demand
 - II. Non-zero lead time
 - III. No quantity discounts
- ☒ a. I only
 b. II only
 c. III only
 d. I, II, and III

10. Base-stock systems reduce or eliminate the problem of amplification.
☒ a. True b. False
11. Base-stock system order quantities are set to cover
 a. Minimum expected demand during lead time
☒ b. Maximum expected demand during lead time
☒ c. Average expected demand during lead time
 d. None of the above
12. The use of kanbans is an example of a base-stock system.
☒ a. True b. False
13. Distribution requirements planning (DRP) systems allow input from local decisions but maintain centralized control.
☒ a. True b. False

Questions 14, 15, and 16 refer to the following information:

Costs for alternative warehouse locations (all costs are in \$100's)

Potential Warehouse Location	Fixed Cost per Year	Customer Locations						
		Des Moines	Ames	Fort Dodge	Rock Rapids	Davenport	Sioux City	Dubuque
Ankeny	90	250	200	275	400	350	375	325
Spencer	50	325	275	250	200	475	250	350
Cedar Rapids	75	275	250	300	425	300	400	200
Iowa City	60	300	275	325	450	200	500	225
Council Bluffs	45	250	275	275	250	450	300	400

14. What is the expected cost (in \$100) if the firm places warehouses at Ankeny and Iowa City? (Select the best answer.)
 a. \$1,500
☒ b. \$2,000
 c. \$2,500
 d. \$3,000
15. Using the "add and drop" location heuristic, what would be the third warehouse added?
 a. Spencer
 b. Iowa City
☒ c. Ankeny
 d. Cedar Rapids

16. Using the "add and drop" location heuristic, what is the lowest warehousing cost (in \$100)? (Select the best answer.)

- a. \$1,500
- ☒ b. \$1,750
- c. \$2,000
- d. \$2,250

Questions 17, 18, and 19 refer to the following data:

From Plant	To Warehouse			
	1	2	3	4
1	2	2.5	3	4
2		5	2.5	5.5
3			5	4
				3.5

17. Of the four following round-trip options, which results in the shortest travel time?

- a. P-1-2-3-4-P
- b. P-1-3-2-4-P
- c. P-4-1-2-3-P
- ☒ d. P-2-4-3-1-P

18. Complete the following time-saved matrix. What are the values of the missing entries?

	2	3	4
1	-0.5	X	0.5
2		0.5	Y
3			3.5

- a. $X = 2.5, Y = 1.0$
- b. $X = 1.0, Y = 2.5$
- ☒ c. $X = 2.5, Y = 2.5$
- d. $X = 0.5, Y = 2.5$

19. Using the time-saved heuristic, what would be the lowest time tour?

- ☒ a. P-1-3-4-2-P
- b. P-1-2-3-4-P
- c. P-1-3-2-4-P
- d. P-4-1-2-3-P

20. For make-to-stock firms, the major concern is the _____ and _____ of deliveries to customers.

- a. Speed and cost
- b. Speed and consistency
- c. Consistency and cost
- d. Cost and route

21. For make-to-order firms, the main customer service consideration is

- a. Quantity
- b. Lead time
- c. Delivery speed
- d. Delivery mode

multi