

Transportation in the Supply Chain

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Learning Objectives

After reading this chapter, you will be able to

1. Understand the role of transportation in a supply chain.
2. Evaluate the strengths and weaknesses of different modes of transportation.
3. Identify various transportation network design options and their relative strengths and weaknesses.
4. Identify trade-offs that shippers must consider when designing their transportation network.
5. Use methodologies for routing and scheduling deliveries in transportation networks.

In this chapter, we discuss the role of transportation within a supply chain and identify trade-offs that need to be considered when making transportation decisions. Our goal is to enable managers responsible for transportation decisions to make transportation strategy and design, planning, and operational decisions with an understanding of all the pros and cons of their choices.

14.1 THE ROLE OF TRANSPORTATION IN THE SUPPLY CHAIN

Transportation refers to the movement of product from one location to another as it makes its way from the beginning of a supply chain to the customer's hands. Transportation plays a key role in every supply chain because products are rarely produced and consumed in the same location. Transportation is a significant component of the cost most supply chains incur. Freight transportation costs in the United States amount to about 6 percent of the GDP.¹ With the growth in e-commerce and the associated home delivery of products, transportation costs have become even more significant in retailing. From the book industry to the grocery industry, online firms are delivering products in small packages to the customer's home instead of in full trucks to a retail outlet. As a result, transportation cost is a larger fraction of the delivered cost of products sold online. For example, shipping a truck of books to a Borders retail store costs a few cents per book. In contrast, when Borders.com sends a package to a customer's home, the transportation cost is over a dollar per book.

Any supply chain's success is closely linked to the appropriate use of transportation. Wal-Mart has effectively used a responsive transportation system to lower its overall costs. To achieve a high level of product availability at a reasonable price, Wal-Mart carries a low level of inventory (relative to demand) at its stores and replenishes frequently as product is sold. To lower the transportation cost of frequent replenishment, Wal-Mart aggregates products destined for different retail stores on trucks leaving a supplier. At DCs, Wal-Mart uses *cross-docking*, a process in which product is exchanged between trucks so that each truck going to a retail store has products from different suppliers. Wal-Mart also uses its transportation system to allow stores to exchange products based on where shortages and surpluses occur. The use of a responsive transportation system and cross-docking allows the company to lower inventories and costs and therefore increase profits. Transportation is thus a key to Wal-Mart's ability to improve the matching of supply and demand while keeping costs low.

7-Eleven Japan has a goal of carrying products in its stores to match the needs of customers as they vary by geographical location or time of day. To help achieve this goal, 7-Eleven uses a very responsive transportation system that replenishes its stores several times a day so that the products available match customers' needs. Products from different suppliers are aggregated on trucks according to the required temperature to help achieve very frequent deliveries at a reasonable cost. 7-Eleven uses a responsive transportation system along with aggregation to decrease its transportation and receiving costs while ensuring that product availability closely matches customer demand.

Supply chains also use responsive transportation to centralize inventories and operate with fewer facilities. For example, Amazon.com relies on package carriers and the postal system to deliver customer orders from centralized warehouses. Dell manufactures out of one location in the United States and uses responsive transportation provided by package carriers like Airborne to provide customers with highly customized products at a reasonable price.

¹*Distribution*, July 1997.

Transportation is a significant link between different stages in a global supply chain. Dell currently has suppliers worldwide and sells to customers all over the world from just a few plants. Transportation allows products to move from suppliers to the assembly plants to customers. Similarly, global transportation allows Wal-Mart to sell products manufactured all over the world in the United States.

In the next section, we discuss factors that affect transportation decisions for different members of a supply chain.

14.2 FACTORS AFFECTING TRANSPORTATION DECISIONS

There are two key players in any transportation that takes place within a supply chain. The *shipper* is the party that requires the movement of the product between two points in the supply chain. The *carrier* is the party that moves or transports the product. For example, when Dell uses UPS to ship its computers from the factory to the customer, Dell is the shipper and UPS is the carrier.

When making transportation-related decisions, factors to be considered vary depending on whether one takes the perspective of a carrier or shipper. A carrier makes investment decisions regarding the transportation infrastructure (rails, locomotives, trucks, airplanes, etc.) and then makes operating decisions to try to maximize the return from these assets. A shipper, in contrast, uses transportation to minimize the total cost (transportation, inventory, information, and facility) while providing an appropriate level of responsiveness to the customer.

Factors Affecting Carrier Decisions

A carrier's goal is to make investment decisions and set operating policies that maximize the return on its assets. A carrier such as an airline, railroad, or trucking company must account for the following costs when investing in assets or setting pricing and operating policies.

1. *Vehicle-related cost*: This is the cost a carrier incurs for the purchase or lease of the vehicle used to transport goods. The vehicle-related cost is incurred whether the vehicle is operating or not and is considered fixed for short-term operational decisions by the carrier. When making long-term strategic decisions or medium-term planning decisions, these costs are variable and the number of vehicles purchased or leased is one of the choices that a carrier makes. The vehicle-related cost is proportional to the number of vehicles leased or purchased.
2. *Fixed operating cost*: This includes any cost associated with terminals, airport gates, and labor that are incurred whether vehicles are in operation or not. Examples include the fixed cost of a trucking terminal facility or airport hub that is incurred independent of the number of trucks visiting the terminal or flights landing at the hub. If drivers were paid independent of their travel schedule, their salary would also be included in this category. For operational decisions, these costs are fixed. For planning and strategic decisions concerning the location and size of facilities, these costs are variable. The fixed operating cost is generally proportional to the size of operating facilities.

3. *Trip-related cost*: This cost includes the price of labor and fuel incurred for each trip independent of the quantity transported. The trip-related cost depends on the length and duration of the trip but is independent of the quantity shipped. This cost is considered variable when making strategic or planning decisions. The cost is also considered variable when making operational decisions that impact the length and duration of a trip.

4. *Quantity-related cost*: This category includes loading/unloading costs and a portion of the fuel cost that varies with the quantity being transported. These costs are generally variable in all transportation decisions unless labor used for loading and unloading is fixed.

5. *Overhead cost*: This category includes the cost of planning and scheduling a transportation network as well as any investment in information technology. When a trucking company invests in routing software that allows a manager to devise good delivery routes, the investment in the software and its operation is included in overhead. Airlines include the cost of groups that schedule and route planes and crew in overhead.

For strategic and planning decisions a carrier should consider all of the costs previously discussed to be variable. For operational decisions, most of the aforementioned costs become fixed.

A carrier's decisions are also affected by the responsiveness it seeks to provide its target segment and the prices that the market will bear. For example, FedEx designed a hub-and-spoke airline network for transporting packages to provide fast, reliable delivery times. UPS, in contrast, uses a combination of aircraft and trucks to provide cheaper transportation with somewhat longer delivery times. The difference between the two transportation networks is reflected in the pricing schedule. FedEx charges for packages based primarily on the size. UPS, in contrast, charges based on both size and destination. From a supply chain perspective, a hub-and-spoke air network is more appropriate when prices are independent of destination and rapid delivery is important, whereas a trucking network is more appropriate when prices vary with destination and a somewhat slower delivery is acceptable.

Factors Affecting Shippers Decisions

Shipper's decisions include the design of the transportation network, choice of means of transport, and the assignment of each customer shipment to a particular means of transport. A shipper's goal is to minimize the total cost of fulfilling a customer order while achieving the responsiveness promised. A shipper must account for the following costs when making transportation decisions.

1. *Transportation cost*: This is the total amount paid to various carriers for transporting products to customers. It depends on the prices offered by different carriers and the extent to which the shipper uses inexpensive and slow, or expensive and fast, means of transportation. Transportation costs are considered variable for all shipper decisions as long as the shipper does not own the carrier.

2. *Inventory cost*: This is the cost of holding inventory incurred by the shipper's supply chain network. Inventory costs are considered fixed for short-term transportation decisions that assign each customer shipment to a carrier. Inventory costs are considered

variable when a shipper is designing the transportation network or planning operating policies.

3. *Facility cost*: This is the cost of various facilities in the shipper's supply chain network. Facility costs are considered variable when supply chain managers make strategic design decisions but are considered fixed for all other transportation decisions.

4. *Processing cost*: This is the cost of loading/unloading orders as well as other processing costs associated with transportation. These are considered variable for all transportation decisions.

5. *Service level cost*: This is the cost of not being able to meet delivery commitments. In some cases it may clearly be specified as part of a contract while in other cases it may be reflected in customer satisfaction. This cost should be considered in strategic, planning, and operational decisions.

A shipper must make a trade-off between all these costs when making transportation decisions. A shipper's decisions are also impacted by the responsiveness it seeks to provide its customers and the margins generated from different products and customers. For example, a firm promising delivery within a time window specified by the customer will require more trucks than a firm whose customers are willing to accept delivery at any time.

In the next section we discuss different modes of transportation and their cost and performance characteristics.

14.3 MODES OF TRANSPORTATION AND THEIR PERFORMANCE CHARACTERISTICS

Supply chains use a combination of the following modes of transportation:

- Air
- Package carriers
- Truck
- Rail
- Water
- Pipeline
- Intermodal

We discuss the costs, pricing structure, and performance characteristics of the various modes summarized in Table 14.1.

Air

Major airlines in the United States that carry both passenger and cargo include American and Delta Airlines. Airlines have a high fixed cost in infrastructure and equipment. Labor and fuel costs are largely trip-related and independent of the number of passengers or amount of cargo carried on a flight. An airline's goal is to maximize the daily flying time of a plane and the revenue generated per trip. Given the large fixed costs and relatively low variable costs, revenue management (see Chapter 15), in which airlines vary seat prices and allocate seats to different price classes, is

TABLE 14.1 Transportation Facts

<i>Mode</i>	<i>Freight Expense (\$ Billions)</i>	<i>Intercity Ton-Miles (Billions)</i>	<i>Intercity Tonnage (Millions)</i>	<i>Revenue/Ton-Mile (cents)</i>	<i>Average Length of Haul (miles)</i>
Air	22.67	13.87	16.3	56.25	1,260
Truck/TL	401.68	1,051	3,745	9.13	289
Truck/LTL				26.12	629
Rail	35.35	1,421	1,972	2.40	722
Water	25.35	473	1,005	0.73	Rivers/canals 481 Great Lakes 509 Coastwise 1,653
Pipeline	8.74	628 (Oil)	1,142	1.37	Crude 761 Products 394

Adapted from *Transportation in America*, 1998.

a significant factor in the success of passenger airlines. At present, airlines practice revenue management for passengers but not for cargo.

Air carriers offer a very fast and fairly expensive mode of transportation. Small, high-value items or time-sensitive emergency shipments that have to travel a long distance are best suited for air transport. Normally air carriers move shipments under 500 pounds, including high-value but lightweight high-tech products. For example, Dell uses airfreight to ship many of its components from Asia. Given the growth in high technology, the weight of freight carried by air has diminished over the last two decades even as the value of the freight has increased somewhat.

Key issues air carriers face include identifying the location and number of hubs, assigning planes to routes, setting up maintenance schedules for planes, scheduling crews, and managing prices and availability at different prices.

Package Carriers

Package carriers are transportation companies like FedEx, UPS, and the U.S. postal system that carry small packages ranging from letters to shipments weighing about 150 pounds. Package carriers use air, truck, and rail to transport time-critical smaller packages. Package carriers are expensive and cannot compete with LTL carriers on price for large shipments. The major service they offer the shipper is rapid and reliable delivery. Thus, shippers use package carriers for small and time-sensitive shipments. Package carriers also provide other value-added services that allow shippers to speed inventory flow and track order status. By tracking order status, shippers can proactively inform customers about their packages. Package carriers also pick up the package from the source and deliver it to the destination site. With an increase in JIT deliveries and focus on inventory reduction, demand for package carriers has grown.

Package carriers are the preferred mode of transport for e-businesses like Amazon.com and Dell as well as companies like W. W. Grainger and McMaster Carr that send small packages to customers. With the growth in e-business, the use of package carriers has increased significantly over the last few years. Package carriers like

FedEx that primarily use airplanes are similar to air cargo carriers except that they seek out smaller and more time-sensitive shipments where tracking and other value-added services are more important. FedEx uses trucks to pick up packages at the source and deliver them to the final destination. Air cargo carriers do not provide this combined service. Companies use air cargo carriers for larger shipments and package carriers for smaller, more time-sensitive ones. For example, Dell uses air cargo to bring components from Asia but uses package carriers to deliver PCs to customers.

Given the small size of packages and several delivery points, consolidation of shipments is a key factor in increasing utilization and decreasing costs for package carriers. Package carriers have trucks that make local deliveries and pick up packages. Packages are then taken to large sort centers from which they are sent by full TL or air to the sort center closest to the delivery point. From the delivery point sort center, the package is sent to customers on small trucks making milk runs (discussed later in the chapter). Key issues in this industry include the location and capacity of transfer points as well as information capability to facilitate and track package flow. For the final delivery to a customer, an important consideration is the scheduling and routing of the delivery trucks.

Truck

Truck is the dominant mode of freight transportation in the United States and accounts for over 75 percent of the nation's freight bill.² The trucking industry consists of two major segments—TL or LTL. TL operations charge for the full truck independent of the quantity shipped. Rates vary with the distance traveled. LTL operations charge based on the quantity loaded and the distance traveled. The LTL rates exhibit economies of scale. Trucking is more expensive than rail but offers the advantage of door-to-door shipment and a shorter delivery time. It also has the advantage of requiring no transfer between pickup and delivery. Major TL carriers include Schneider National, JB Hunt, Ryder Integrated, Werner, and Swift Transportation.

TL operations have relatively low fixed costs and owning a few trucks is often sufficient to enter the business. As a result there are many TL carriers in the industry. Schneider National, the largest TL carrier, had only 17 percent of the market share among the top 40 firms in the United States in 1996. The idle time and travel distance between successive loads adds to cost in the TL industry. Carriers thus try to schedule shipments to meet service requirements while minimizing both their trucks' idle and empty travel time.

TL pricing displays economies of scale with respect to the distance traveled. Given trailers of different size, pricing also displays economies of scale with respect to the size of the trailer used. TL shipping is suited for transportation between manufacturing facilities and warehouses or between suppliers and manufacturers. For example, Proctor & Gamble offers TL shipping to customer warehouses.

LTL operations are priced to encourage shipments in small lots, usually less than half a TL as TL tends to be cheaper for larger shipments. Prices display some economies of scale with the quantity shipped as well as the distance traveled. LTL shipments take longer than TL shipments because of other loads that need to be picked up

²Transportation in America, 1998.

and dropped off. LTL shipping is suited for shipments that are too large to be mailed as small packages but constitute less than half a TL.

A key to reducing LTL costs is the degree of consolidation that carriers can achieve for the loads carried. LTL carriers use consolidation centers where trucks bring in many small loads originating from a geographical area and leave with many small loads destined for the same geographical area. This allows LTL carriers to improve their truck use although it increases delivery time somewhat. Larger firms enjoy an advantage in the LTL industry given the importance of consolidation and the fixed cost of setting up consolidation centers. Strong regional players have developed in the LTL industry because of the advantage offered by a high density of pickup and delivery points in a geographical area.

Key issues for the LTL industry include location of consolidation centers, assigning of loads to trucks, and scheduling and routing of pickup and delivery. The goal is to minimize costs through consolidation without hurting delivery time and reliability.

Rail

Major rail carriers in North America include Burlington Northern Santa Fe, Canadian National, CSX Transportation, and Norfolk Southern. Rail carriers incur a high fixed cost in terms of rails, locomotives, cars, and yards. There is also a significant trip-related labor and fuel cost that is independent of the number of cars (fuel costs do vary somewhat with the number of cars) but does vary with the distance traveled and the time taken. Any idle time, once a train is powered, is very expensive because labor and fuel costs are incurred even though trains are not moving. Idle time occurs when trains exchange cars for different destinations. It also occurs because of track congestion. Labor and fuel together account for over 60 percent of railroad expense. From an operational perspective, it is thus important for railroads to keep locomotives and crew well utilized.

Rail is priced to encourage large shipments over a long distance. Prices display economies of scale in the quantity shipped as well as the distance traveled. The price structure and the heavy load capability makes rail an ideal mode for carrying large, heavy, or high-density products over long distances. Transportation time by rail, however, can be large. Rail is thus ideal for very heavy, low-value shipments that are not very time sensitive. The resulting transportation cost tends to be low. Coal, for example, is a major part of each railroad's shipments. Small, time-sensitive, short distance, or short lead time shipments rarely use rail.

Railroad revenues have not grown significantly over the past two decades and hover in the mid \$30 billion range. Most of the improvement in financial performance over that period has come from abandoning unprofitable lines and making better use of existing assets. The growth in the intermodal sector (discussed later in the chapter) has also helped railroad performance during this period.

A major goal in railroads is to keep locomotives and crew well utilized. Major operational issues at railroads include vehicle and staff scheduling, track and terminal delays, and poor on-time performance. Railroad performance is hurt by the large amount of time taken at each transition. The travel time is usually a small fraction of the total time for a rail shipment. Delays get exaggerated because trains today are typically not scheduled but "built." In other words, a train leaves once there are enough

cars to constitute the train. Cars wait for the train to build, adding to the uncertainty of the delivery time for a shipper. A railroad can improve on-time performance by scheduling some of the trains instead of building all of them. In such a setting, a more sophisticated pricing strategy that includes revenue management (see Chapter 15) will need to be instituted for scheduled trains.

Water

Major ocean carriers include Maersk Sealand, Evergreen Group, American President Lines, and Hanjin Shipping Co. Water transport, by its nature, is limited to certain areas. Within the United States, water transport takes place via the inland waterway system (Great Lakes and rivers) or coastal waters. Water transport is ideally suited for carrying very large loads at low cost. Within the United States, water transport is used primarily for the movement of large bulk commodity shipments and is the cheapest mode for carrying such loads. It is, however, the slowest of all the modes and significant delays occur at ports and terminals. This makes water transport difficult to operate for short-haul trips though it is used effectively in Japan and parts of Europe for daily short-haul trips of a few miles.

Within the United States, the passage of the Ocean Shipping Reform Act of 1998 has been a significant event for water transport. This bill allows carriers and shippers to enter into confidential contracts, effectively deregulating the industry. The bill is similar to the deregulation that occurred in the trucking and airline industries over two decades ago and is likely to have a similar impact on the shipping industry.

In global trade, water transport is the dominant mode for shipping all kinds of products. Cars, grain, apparel, and other products are shipped by sea. For the quantities shipped and the distances involved, water transport is by far the cheapest mode of transport for global shipping. Delays at ports, customs, and the management of containers used are major issues in global shipping.

Pipeline

Pipeline is used primarily for the transport of crude petroleum, refined petroleum products, and natural gas. A significant initial fixed cost is incurred in setting up the pipeline and related infrastructure that does not vary significantly with the diameter of the pipeline. Pipeline operations are typically optimized at about 80 to 90 percent of pipeline capacity. Given the nature of the costs, pipelines are best suited when relatively stable and large flows are required. Pipeline may be an effective way of getting crude oil to a port or a refinery. Sending gasoline to a gas station does not justify investment in a pipeline and is done better with a truck. Pipeline pricing usually consists of two components—a fixed component related to the shipper's peak usage and a second charge relating to the actual quantity transported. This pricing structure encourages the shipper to use the pipeline for the predictable component of demand with other modes often being used to cover fluctuations.

Intermodal

Intermodal transportation is the use of more than one mode of transport to move a shipment to its destination. A variety of intermodal combinations are possible, with the most common being truck/rail. Major intermodal providers with rail include CSX

Intermodal, Pacer Stacktrain, and Triple Crown. Intermodal traffic has grown considerably with the increased use of containers for shipping and the rise of global trade. Containers are easy to transfer from one mode to another and their use facilitates intermodal transportation. Containerized freight often uses truck/water/rail combinations, particularly for global freight. For global trade, intermodal is often the only option because factories and markets may not be next to ports. As the quantity shipped using containers has grown, the truck/water/rail intermodal combination has also grown. In 1996, intermodal activity contributed 16 percent of rail revenues.³ On land, the rail/truck intermodal system offers the benefit of lower cost than TL and delivery times that are better than rail, thereby bringing together different modes of transport to create a price/service offering that cannot be matched by any single mode. It also creates convenience for shippers who now deal with only one entity representing all carriers who together provide the intermodal service.

Key issues in the intermodal industry involve the exchange of information to facilitate shipment transfers between different modes because these transfers often involve considerable delays, hurting delivery time performance.

14.4 DESIGN OPTIONS FOR A TRANSPORTATION NETWORK

The design of a transportation network impacts the performance of a supply chain by establishing the infrastructure within which operational transportation decisions regarding scheduling and routing are made. A well-designed transportation network allows a supply chain to achieve the desired degree of responsiveness at a low cost. We discuss a variety of design options for transportation networks and the strengths and weaknesses for each option in the context of a retail chain with many stores and several suppliers.

Direct Shipping Network

With this option, the retail chain structures its transportation network to have all shipments come directly from suppliers to retail stores as shown in Figure 14.1. With a direct shipment network, the routing of each shipment is specified and the supply chain manager only needs to decide on the quantity to ship and the mode of transportation to use. This decision involves a trade-off between transportation and inventory costs as discussed later in the chapter.

The major advantage of a direct shipment transportation network is the elimination of intermediate warehouses and its simplicity of operation and coordination. The shipment decision is completely local and the decision made for one shipment does not influence others. The transportation time from supplier to retail store will be short because each shipment goes direct.

A direct shipment network is justified if retail stores are large enough such that optimal replenishment lot sizes are close to a TL from each supplier to each retailer. With small retail stores, however, a direct shipment network tends to have high costs. If a TL carrier is used for transportation, the high fixed cost of each truck results in large

³*Distribution*, July 1997.

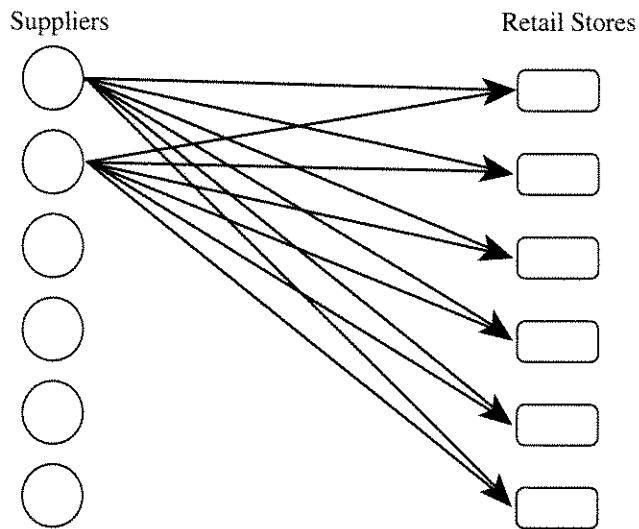


FIGURE 14.1 Direct Shipment Network

lots moving from suppliers to each retail store, resulting in high supply chain inventories. If an LTL carrier is used, the transportation cost and the delivery time increase though inventories are lower. If package carriers are used, transportation cost will be very high. With direct deliveries from each supplier, receiving costs will be high because each supplier must make a separate delivery.

Direct Shipping with Milk Runs

A *milk run* is a route in which a truck either delivers product from a single supplier to multiple retailers or goes from multiple suppliers to a single retailer as shown in Figure 14.2. In direct shipping with milk runs, a supplier delivers directly to multiple retail stores on a truck or a truck picks up deliveries from many suppliers destined for the same retail store. When using this option, a supply chain manager has to decide on the routing of each milk run.

Direct shipping provides the benefit of eliminating intermediate warehouses, whereas milk runs lower transportation cost by consolidating shipments to multiple stores on a single truck. For example, the replenishment lot size for each retail store may be small and require LTL shipping if sent directly. The use of milk runs allows deliveries to multiple stores to be consolidated on a single truck, resulting in a better utilization of the truck and somewhat lower costs. Companies like Frito-Lay that make direct store deliveries use milk runs to lower their transportation cost. If very frequent, small deliveries are needed on a regular basis and either a set of suppliers or a set of retailers is in geographical proximity, the use of milk runs can significantly reduce transportation costs. For example, Toyota uses milk runs from suppliers to support its JIT manufacturing system in both Japan and the United States. In Japan, Toyota has many assembly plants located close together and thus uses milk runs from a single

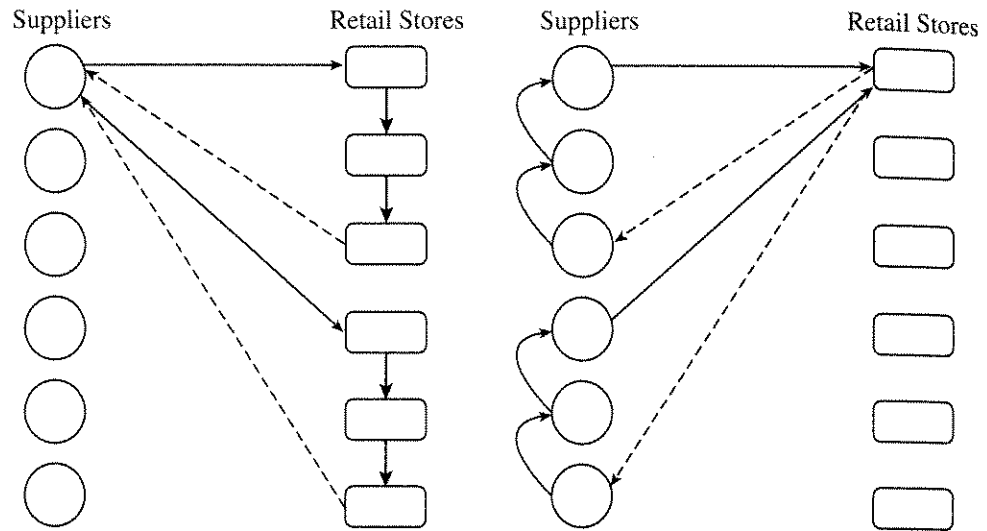


FIGURE 14.2 Milk Runs from Multiple Suppliers or to Multiple Retailers

supplier to many plants. In the United States, however, Toyota uses milk runs from many suppliers to its assembly plants.

All Shipments via Central DC

With this option, suppliers do not send shipments directly to retail stores. The retail chain divides stores by geographical region and a DC is built for each region. Suppliers send their shipments to the DC and the DC then forwards appropriate shipments to each retail store as shown in Figure 14.3.

The DC is an extra layer between suppliers and retailers and can play two different roles. One is to store inventory and the other is to serve as a transfer location. In either case, the presence of DCs can help reduce supply chain costs when suppliers are located far from the retail stores and transportation costs are high. The presence of a DC allows a supply chain to achieve economies of scale for inbound transportation to a point close to the final destination because each supplier sends a large shipment to the DC containing product for all stores the DC serves. Because DCs serve stores located nearby, the outbound transportation cost is not very large.

If transportation economies require very large shipments on the inbound side, DCs hold inventory and send product to retail stores in smaller replenishment lots. For example, when Wal-Mart sources from an overseas supplier, the product is held in inventory at the DC because the lot size on the inbound side is much larger than the sum of the lot sizes for the stores served by the DC. If replenishment lots for the stores served by the DC are large enough to achieve economies of scale on inbound transportation, the DC does not need to hold inventory. In this case the DC can cross-dock product arriving from many suppliers on inbound trucks by breaking each inbound shipment into smaller shipments that are then loaded onto trucks going to each retail store. When a DC cross-docks product, each inbound truck contains product from a

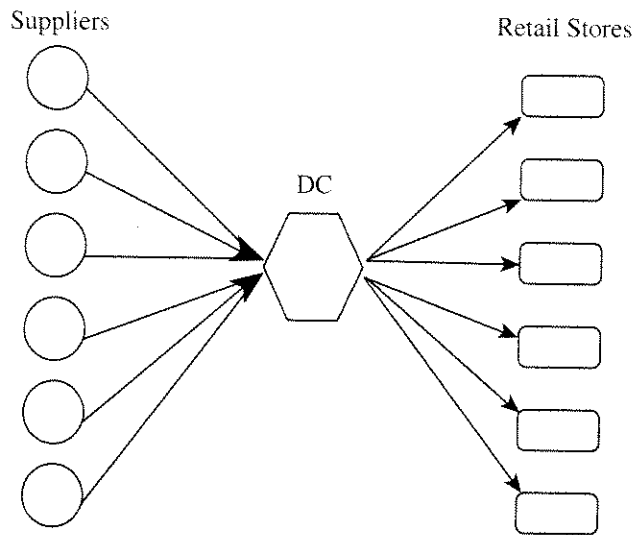


FIGURE 14.3 All Shipments via DC

supplier for several retail stores while each outbound truck contains product for a retail store from several suppliers. A major benefit of cross-docking is that little inventory needs to be held and product flows faster in the supply chain. Cross-docking also saves on handling cost because product does not have to be moved into and out of storage. Successful cross-docking, however, does require a significant degree of coordination and synchronization between the incoming and outgoing shipments.

Cross-docking is appropriate for products with large, predictable demands and requires that DCs be set up such that economies of scale in transportation can be achieved on both the inbound and outbound side. Wal-Mart has successfully used cross-docking to decrease inventories in the supply chain without incurring excessive transportation costs. Wal-Mart builds many large stores in a geographical area supported by a DC. As a result, the total lot size to all stores from each supplier fills trucks on the inbound side to achieve economies of scale. On the outbound side, the sum of the lot sizes from all suppliers to each retail store fills up the truck to achieve economies of scale.

Shipping via DC Using Milk Runs

As shown in Figure 14.4, milk runs can be used from a DC if lot sizes to be delivered to each retail store are small. Milk runs reduce outbound transportation costs by consolidating small shipments. For example, 7-Eleven Japan cross-docks deliveries from its fresh food suppliers at its DCs and sends out milk runs to the retail outlets because the total shipment to a store from all suppliers does not fill a truck. The use of cross-docking and milk runs allows 7-Eleven to lower its transportation cost while sending small replenishment lots to each store. The use of cross-docking with milk runs requires a significant degree of coordination and suitable routing and scheduling of milk runs.

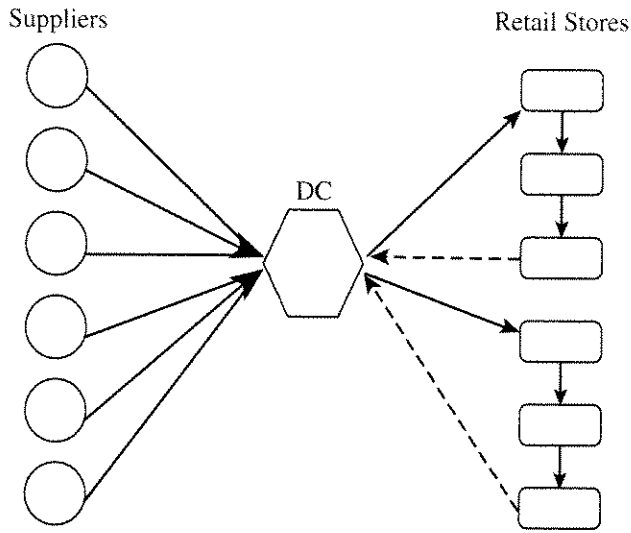


FIGURE 14.4 Milk Runs from DC

The online grocer Peapod uses milk runs from DCs when making customer deliveries to help reduce transportation costs for small shipments to be delivered to homes. OshKosh B’Gosh, a manufacturer of children’s wear, has used this idea to virtually eliminate LTL shipments from its DC in Tennessee to retail stores.

Tailored Network

This option is a suitable combination of previous options that reduces the cost and improves responsiveness of the supply chain. Here transportation uses a combination of cross-docking, milk runs, and TL and LTL carriers, along with package carriers in

TABLE 14.2 Pros and Cons of Different Transportation Networks

<i>Network Structure</i>	<i>Pros</i>	<i>Cons</i>
Direct shipping	No intermediate warehouse Simple to coordinate	High inventories (due to large lot size) Significant receiving expense
Direct shipping with milk runs	Lower transportation costs for small lots Lower inventories	Increased coordination complexity
All shipments via central DC with inventory storage	Lower inbound transportation cost through consolidation	Increased inventory cost Increased handling at DC
All shipments via central DC with cross-dock	Very low inventory requirement Lower transportation cost through consolidation	Increased coordination complexity
Shipping via DC using milk runs	Lower outbound transportation cost for small lots	Further increase in coordination complexity
Tailored network	Transportation choice best matches needs of individual product and store	Highest coordination complexity

some cases. The goal is to use the appropriate option in each situation. High-demand products to high-demand retail outlets may be shipped directly while low-demand products or shipments to low-demand retail outlets are consolidated to and from the DC. The complexity of managing this transportation network is high because different shipping procedures are used for each product and retail outlet. Operating a tailored network requires significant investment in information infrastructure to facilitate the coordination. Such a network, however, allows for the selective use of the shipment method to minimize the transportation as well as inventory costs.

Table 14.2 summarizes the pros and cons of the various transportation network options discussed.

In the next section we discuss a variety of trade-offs that supply chain managers need to consider when designing and operating a transportation network.

14.5 TRADE-OFFS IN TRANSPORTATION DESIGN

All transportation decisions in a supply chain network must be made taking into account their impact on inventory costs, facility and processing costs, the cost of coordinating operations, as well as the level of responsiveness provided to customers. For example, Dell's use of package carriers for delivering PCs to customers increases transportation cost but allows Dell to centralize its facilities and reduce inventory costs. If Dell wants to reduce its transportation costs, the company must either sacrifice responsiveness to customers or increase the number of facilities and resulting inventories to move closer to customers.

The cost of coordinating operations is generally hard to quantify. Companies should evaluate different transportation options in terms of various costs as well as revenues and then rank them according to coordination complexity. A manager can then make the appropriate transportation decision. Managers must consider the following trade-offs when making transportation decisions:

- Transportation and inventory cost trade-off
- Transportation cost and customer responsiveness trade-off

Transportation and Inventory Cost Trade-off

The trade-off between transportation and inventory costs is significant when designing a supply chain network. Two fundamental supply chain decisions involving this trade-off are

- Choice of transportation mode
- Inventory aggregation

Choice of Transportation Mode

Selecting a transportation mode is both a planning and an operational decision in a supply chain. The decision regarding carriers with which a company contracts is a planning decision, whereas the choice of transportation mode for a particular shipment is an operational decision. For both decisions, a shipper must balance transportation and inventory costs. The mode of transportation that results in the lowest transportation cost does not necessarily lower total costs for a supply chain. Cheaper modes of transport typically have longer lead times and larger minimum shipment quantities,

both of which result in higher levels of inventory in the supply chain. Modes that allow for shipping in small quantities lower inventory levels but tend to be more expensive. Dell, for example, airfreights several of its components from Asia. This choice cannot be justified on the basis of transportation cost alone. It can only be justified because the use of a faster mode of transportation for shipping valuable components allows Dell to carry low levels of inventory.

The impact of using different modes of transportation on inventories, response time, and costs in the supply chain is shown in Table 14.3. Each transportation mode is ranked along various dimensions with 1 being the lowest and 6 being the highest.

Faster modes of transportation are preferred for products with a high value to weight ratio where reducing inventories is important, whereas slower modes are preferred for products with a small value to weight ratio where reducing transportation costs is important.

Ignoring inventory costs when making transportation decisions can result in choices that worsen the performance of a supply chain. To illustrate the importance of evaluating the trade-off between transportation and inventory costs, consider the example of Eastern Electric (EE), a major appliance manufacturer with a large plant in the Chicago area.⁴ EE purchases all the motors for its appliances from Westview Motors located near Dallas. EE currently purchases 120,000 motors each year from Westview at a price of \$120 per motor. Demand has been relatively constant for several years and is expected to stay that way. Each motor averages about 10 lbs. in weight and EE has traditionally purchased in lots of 3,000 motors. Westview ships each EE order within a day of receiving it. At its assembly plant, EE carries a safety inventory equal to 50 percent of the average demand for motors during the delivery lead time.

The plant manager at EE has received several proposals for transportation and must decide on the one to accept. The details of various proposals are provided in Table 14.4, where one cwt. is equal to a hundred pounds.

Golden's pricing represents a marginal unit quantity discount (see Chapter 10). Golden's representative has proposed lowering the marginal rate for the quantity over 2500 cwt. in a shipment from \$4/cwt. to \$3/cwt. Golden's new proposal will result in very low transportation costs for EE if the plant manager orders in lots of 400 motors.

The plant manager, however, decides to include inventory costs in the transportation decision. Eastern Electric's annual cost of holding inventory is 25 percent, which

TABLE 14.3 Impact of Transportation Modes on Supply Chain Performance

	<i>Rail</i>	<i>TL</i>	<i>LTL</i>	<i>Package</i>	<i>Air</i>	<i>Water</i>
Lot size	5	4	3	1	2	6
Safety inventory	5	4	3	1	2	6
In-transit inventory	5	4	3	1	2	6
Transportation cost	2	3	4	6	5	1
Transportation time	5	3	4	1	2	6

⁴This example is inspired by the Honfleur Corporation case in *Logistics Strategy: Cases and Concepts* by R. D. Shapiro and J. L. Heskett, 1985.

TABLE 14.4 Transportation Proposals for EE Electric

<i>Carrier</i>	<i>Range of Quantity Shipped (cwt.)</i>	<i>Shipping Cost (\$/cwt.)</i>
AM Railroad	200 +	6.50
Northeast Trucking	100 +	7.50
Golden Freightways	50–150	8.00
Golden Freightways	150–250	6.00
Golden Freightways	250–400	4.00

implies an annual holding cost of $H = \$120 \times 0.25 = \30 per motor. Shipments by rail require a five-day transit time, whereas shipments by truck have a transit time of three days. The transportation decision affects the cycle inventory, safety inventory, and in-transit inventory for EE. Therefore, the plant manager decides to evaluate the total transportation and inventory cost for each transportation option.

The AM Rail proposal requires a minimum shipment of 20,000 lb. or 2,000 motors. The replenishment lead time in this case is $L = 5 + 1 = 6$ days. For a lot size of $Q = 2,000$ motors, the plant manager obtains the following:

$$\text{Cycle inventory} = Q/2 = 2,000/2 = 1,000 \text{ motors,}$$

$$\begin{aligned} \text{Safety inventory} &= L/2 \text{ days of demand} = (6/2)(120,000/365) \\ &= 986 \text{ motors,} \end{aligned}$$

$$\text{In-transit inventory} = 120,000(5/365) = 1,644 \text{ motors,}$$

$$\text{Total average inventory} = 1,000 + 986 + 1,644 = 3,630 \text{ motors.}$$

$$\text{Annual holding cost using AM Rail} = 3,630 \times 30 = \$108,900.$$

AM Rail charges \$6.50 per cwt, resulting in a transportation cost of \$0.65 per motor because each motor weighs 10 lbs. Thus,

$$\text{Annual transportation cost using AM Rail} = 120,000 \times .65 = \$78,000.$$

The total annual cost for inventory and transportation using AM Rail is thus \$186,900.

The plant manager then evaluates the cost associated with each transportation option as shown in Table 14.5.

Based on the analysis in Table 14.5, the plant manager decides to sign a contract with Golden Freightways and order motors in lots of 500. This option has the highest transportation cost but the lowest overall cost. If the selection of the transportation option was made using only the transportation cost incurred, Golden's new proposal lowering the price for large shipments would look attractive. In reality, Eastern pays a high overall cost for this proposal. Thus, considering the trade-off between inventory and transportation costs allows the plant manager to make a transportation decision that minimizes Eastern's total cost.

Key Point When selecting a mode of transportation, managers must account for inventory costs. Modes with high transportation cost can be justified if they result in significantly lower inventories.

TABLE 14.5 Analysis of Transportation Options for Eastern Electric

<i>Alternative</i>	<i>Lot Size (Motors)</i>	<i>Transportation Cost</i>	<i>Cycle Inventory</i>	<i>Safety Inventory</i>	<i>In-Transit Inventory</i>	<i>Inventory Cost</i>	<i>Total Cost</i>
AM Rail	2,000	\$78,000	1,000	986	1,644	\$108,900	\$186,900
Northeast Trucking	1,000	\$90,000	500	658	986	\$64,320	\$154,320
Golden	500	\$96,000	250	658	986	\$56,820	\$152,820
Golden	1,500	\$96,000	750	658	986	\$71,820	\$167,820
Golden	2,500	\$86,400	1,250	658	986	\$86,820	\$173,220
Golden	3,000	\$78,000	1,500	658	986	\$94,320	\$172,320
Golden (old proposal)	4,000	\$72,000	2,000	658	986	\$109,320	\$181,320
Golden (new proposal)	4,000	\$67,500	2,000	658	986	\$109,320	\$176,820

Inventory Aggregation

Firms can significantly reduce the safety inventory they require by physically aggregating inventories in one location (see Chapter 11). Most e-businesses have used this technique to gain advantage over firms with facilities in many locations. For example, Amazon.com has focused on decreasing its facility and inventory costs by holding inventory in a few warehouses, whereas booksellers like Borders and Barnes and Noble have to hold inventory in many retail stores.

Transportation cost, however, increases when inventory is aggregated. Consider a bookstore chain such as Borders. The inbound transportation cost to Borders is due to the replenishment of bookstores with new books. There is no outbound cost because customers transport their own books home. If Borders decides to close all its bookstores and only sell online, it will have to incur both inbound and outbound transportation costs. The inbound transportation cost to warehouses will be lower than to all bookstores. On the outbound side, however, transportation cost will increase significantly because the outbound shipment to each customer will be small and will require an expensive mode such as a package carrier. The total transportation cost will increase on aggregation because each book will travel the same distance as when it was sold through a bookstore, except that a large fraction of the distance will be on the outbound side using an expensive mode of transportation. As the degree of inventory aggregation increases, total transportation cost goes up. Thus, all firms planning inventory aggregation must consider the trade-off between transportation, inventory, and facility costs when making this decision.

Inventory aggregation is a good idea when inventory and facility costs form a large fraction of a supply chain's total costs. Inventory aggregation is useful for products with a large value to weight ratio and for products with high demand uncertainty. For example, inventory aggregation is very valuable in the PC industry for new products because PCs have a large value to weight ratio and demand is uncertain. Inventory aggregation is also a good idea if customer orders are large enough to ensure sufficient economies of scale on outbound transportation. When products have a low value to weight ratio and customer orders are small, however, inventory aggregation may hurt a

supply chain's performance because of high transportation costs. Compared to PCs, the value of inventory aggregation is smaller for best-selling books that have a lower value to weight ratio and more predictable demand.

We illustrate the trade-off involved in making aggregation decisions in the context of HighMed Inc., a manufacturer of medical equipment used in heart procedures. HighMed is located in Wisconsin and cardiologists all over North America use its equipment. The medical equipment is not sold through purchasing agents but directly to doctors. HighMed has currently divided the United States into 24 territories, each with its own sales force. All product inventories are maintained locally and replenished from Madison every four weeks using UPS. The average replenishment lead time using UPS is one week. UPS charges at a rate of $\$0.66 + 0.26x$, where x is the quantity shipped in pounds. The products sold fall into two categories—Highval and Lowval. Highval products weigh 0.1 lbs. and cost \$200 each. Lowval products weigh 0.04 lbs. and cost \$30 each.

Weekly demand for Highval products in each territory is normally distributed with a mean of $\mu_H = 2$ and a standard deviation of $\sigma_H = 5$. Weekly demand for Lowval products in each territory is normally distributed with a mean of $\mu_L = 20$ and a standard deviation of $\sigma_L = 5$. HighMed maintains sufficient safety inventories in each territory to provide a CSL of 0.997 for each product. Holding cost at HighMed is 25 percent.

The management team at HighMed wants to evaluate the operating cost of the current operating procedure and compare it with two other options they have been considering.

1. *Option A:* Keep the current structure but start replenishing inventory once a week rather than once every four weeks.
2. *Option B:* Eliminate inventories in the territories, aggregate all inventories in a finished goods warehouse at Madison, and replenish the warehouse once a week.

If inventories are aggregated at Madison, orders will be shipped using FedEx, which charges $\$5.53 + 0.53x$ per shipment, where x is the quantity shipped in pounds. The factory requires a one-week lead time to replenish finished goods inventories at the Madison warehouse. An average customer order is for 1 unit of HighVal and 10 units of LowVal.

HighMed can reduce transportation cost by aggregating the quantity shipped at a time because prices for both UPS and FedEx display economies of scale. When comparing Option A with the current system, the management team must trade off the savings in transportation cost through less frequent replenishment with the savings in inventory cost with more frequent replenishment. When considering Option B, the management team must trade off the increase in transportation cost upon aggregation of inventories and the use of a faster but more expensive carrier (FedEx) with the decrease in inventory cost.

The management team first analyzes the current situation. For each territory,

Replenishment lead time $L = 1$ week,
 Reorder interval $T = 4$ weeks,
 $CSL = 0.997$.

1. *HighMed inventory costs (current scenario):* For HighVal in each territory, the management team obtains the following:

Average lot size $Q_H =$ Expected demand during T weeks $= T\mu_H = 4 \times 2 = 8$ units,

Safety inventory $ss_H = F^{-1}(CSL) \times \sigma_{T+L} = F^{-1}(CSL) \times \sqrt{T+L} \times \sigma_H =$

$$F^{-1}(0.997) \times \sqrt{4+1} \times 5 = 30.7 \text{ units (see Equation 11.16),}$$

Total HighVal inventory $= Q_H/2 + ss_H = (8/2) + 30.7 = 34.7$ units.

Across all 24 territories, HighMed thus carries HighVal inventory of $24 \times 34.7 = 832.8$ units. For LowVal in each territory, the management team obtains the following:

Average lot size $Q_L =$ Expected demand during T weeks $= T\mu_L = 4 \times 20 = 80$ units,

Safety inventory $ss_H = F^{-1}(CSL) \times \sigma_{T+L} = F^{-1}(CSL) \times \sqrt{T+L} \times \sigma_L$

$$= F^{-1}(0.997) \times \sqrt{4+1} \times 5 = 30.7 \text{ units,}$$

Total LowVal inventory $= Q_L/2 + ss_H = (80/2) + 30.7 = 70.7$ units.

Across all 24 territories HighMed thus carries LowVal inventory $= 24 \times 70.7 = 1696.8$ units.

The management team thus obtains the following:

$$\begin{aligned} \text{Annual inventory holding cost for HighMed} &= (\text{Average HighVal inventory} \\ &\times \$200 + \text{Average LowVal inventory} \times \$30) \times 0.25 \\ &= (832.8 \times \$200 + 1696.8 \times \$30) \times 0.25 = \$54,366. \end{aligned}$$

2. *HighMed transportation cost (current scenario)*: The average replenishment order from each territory consists of Q_H units of HighVal and Q_L units of LowVal. Thus

$$\begin{aligned} \text{Average weight of each replenishment order} &= 0.1Q_H + 0.04Q_L = 0.1 \times 8 + 0.04 \\ &\times 80 = 4 \text{ lbs,} \end{aligned}$$

$$\text{Shipping cost per replenishment order} = \$0.66 + 0.26 \times 4 = \$1.7.$$

Each territory has 13 replenishment orders per year and there are 24 territories. Thus

$$\text{Annual transportation cost} = \$1.7 \times 13 \times 24 = \$530.$$

3. *HighMed total cost (current scenario)*: Annual inventory and transportation cost at HighMed = Inventory cost + Transportation cost = $\$54,366 + \$530.4 = \$54,896$. The HighMed management team evaluates the costs for Option A and Option B similarly and the results are summarized in Table 14.6.

From Table 14.6 observe that increasing the replenishment frequency under Option A decreases total cost at HighMed. The increase in transportation costs is much smaller than the decrease in inventory costs resulting from smaller lots. HighMed is able to reduce total cost the most by aggregating all inventories and using FedEx for transportation because the decrease in inventories on aggregation is larger than the increase in transportation costs.

If customer order sizes are small, the increase in transportation cost on aggregation can be significant and inventory aggregation may increase total costs. Consider the case of HighMed where each customer order averages 0.5 *HighVal* and 5 *LowVal* (half the size considered earlier). The costs for the current option as well as option A remain unchanged because HighMed does not pay for outbound transportation and only

TABLE 14.6 HighMed Costs Under Different Network Options

	<i>Current Scenario</i>	<i>Option A</i>	<i>Option B</i>
Number of stocking locations	24	24	1
Reorder interval	4 weeks	1 week	1 week
HighVal cycle inventory	96 units	24 units	24 units
HighVal safety inventory	736.8 units	466 units	95.2 units
HighVal inventory	832.8 units	490 units	119.2 units
LowVal cycle inventory	960 units	240 units	240 units
LowVal safety inventory	736.8 units	466 units	95.2 units
LowVal inventory	1,696.8 units	706 units	335.2 units
Annual inventory cost	\$54,366	\$29,795	\$8,474
Shipment type	Replenishment	Replenishment	Customer order
Shipment size	8 HighVal + 80 LowVal	2 HighVal + 20 LowVal	1 HighVal + 10 LowVal
Shipment weight	4 lbs.	1 lb.	0.5 lb.
Annual transport cost	\$530	\$1,148	\$14,464
Total annual cost	\$54,896	\$30,943	\$22,938

incurs the cost of transporting replenishment orders under both options. Option B, however, becomes more expensive because outbound transportation costs increase with a decrease in customer order size. The costs under Option B are as follows:

$$\begin{aligned} \text{Average weight of each customer order} &= 0.1 \times 0.5 + 0.04 \times 5 = 0.25 \text{ lbs,} \\ \text{Shipping cost per customer order} &= \$5.53 + 0.53 \times 0.25 = \$5.66 \\ \text{Number of customer orders per territory per week} &= 4, \\ \text{Total customer orders per year} &= 4 \times 24 \times 52 = 4,992, \\ \text{Annual transportation cost} &= 4,992 \times 5.66 = \$28,255, \\ \text{Total annual cost} &= \text{inventory cost} \\ &\quad + \text{transportation cost} = \$8,474 + \$28,255 = \$36,729. \end{aligned}$$

Thus, with small customer orders, inventory aggregation is no longer the lowest cost option for HighMed because of the large increase in transportation costs. The company is better off maintaining inventory in each territory and using Option A, which gives a lower total cost.

Key Point Inventory aggregation decisions must account for inventory and transportation costs. Inventory aggregation decreases supply chain costs if the product has a high value to weight ratio, high demand uncertainty, and customer orders are large. If a product has a low value to weight ratio, low demand uncertainty, or customer orders are small, inventory aggregation may increase supply chain costs.

Trade-Off between Transportation Cost and Customer Responsiveness

The transportation cost a supply chain incurs is closely linked to the degree of responsiveness the supply chain aims to provide. If a firm has high responsiveness and ships all orders within a day of their receipt from the customer, it will have small outbound shipments resulting in a high transportation cost. If it decreases its responsiveness and aggregates orders over a longer time horizon before shipping them out, it will be able to exploit economies of scale and incur a lower transportation cost because of larger shipments. *Temporal aggregation* is the process of combining orders across time. Temporal aggregation decreases a firm’s responsiveness because of shipping delay but also decreases transportation costs because of economies of scale that result from larger shipments. Thus, a firm must consider the trade-off between responsiveness and transportation cost when designing its transportation network.

Consider Alloy Steel, a steel service center in the Cleveland area. Alloy ships all orders to customers using an LTL carrier that charges $\$100 + 0.01x$, where x is the number of pounds of steel shipped on the truck. The LTL carrier also charges \$10 for each customer delivery. Currently, Alloy Steel ships orders on the day they are received. Allowing for two days in transit, this policy allows Alloy to achieve a response time of two days. Daily demand at Alloy Steel over a two-week period is shown in Table 14.7.

The general manager at Alloy Steel feels that customers do not really value the 2-day response time and would be satisfied with a four-day response. As the response time increases, Alloy Steel has the opportunity to aggregate demand over multiple days for shipping. For a response time of three days, Alloy Steel can aggregate demand over two successive days before shipping. For a response time of four days, Alloy Steel can aggregate demand over three days before shipping. The manager evaluates the quantity shipped and transportation costs for different response times over the two-week period as shown in Table 14.8.

From Table 14.8 observe that the transportation cost for Alloy Steel decreases as the response time increases. The benefit of temporal consolidation, however, diminishes rapidly on increasing the response time. As the response time increases from two to three days, transportation cost over the two-week window decreases by \$700. Increasing the response time from three to four days reduces the transportation cost by only \$200. Thus a limited amount of temporal aggregation can be very effective at reducing transportation cost in a supply chain. Firms, however, must trade off the decrease in transportation cost on temporal aggregation with the loss of revenue because of poorer responsiveness when choosing the appropriate response time.

Temporal consolidation also improves transportation performance because it results in more stable shipments. For example, in Table 14.7, when Alloy Steel sends daily shipments, the coefficient of variation is 0.44, whereas temporal aggregation across three days (achieved with a four-day response time) has a coefficient of

TABLE 14.7 Daily Demand at Alloy Steel Over Two-Week Period

Week 1	19,970	17,470	11,316	26,192	20,263	8,381	25,377
Week 2	39,171	2,158	20,633	23,370	24,100	19,603	18,442

TABLE 14.8 Quantity Shipped and Transportation Cost as a Function of Response Time

Day	Demand	2-Day Response		3-Day Response		4-Day Response	
		Quantity Shipped	Cost	Quantity Shipped	Cost	Quantity Shipped	Cost
1	19,970	19,970	\$ 299.7	0	\$ —	0	\$ —
2	17,470	17,470	\$ 274.70	37,440	\$ 474.40	0	\$ —
3	11,316	11,316	\$ 213.16	0	\$ —	48,756	\$ 587.56
4	26,192	26,192	\$ 361.92	37,508	\$ 475.08	0	\$ —
5	20,263	20,263	\$ 302.63	0	\$ —	0	\$ —
6	8,381	8,381	\$ 183.81	28,644	\$ 386.44	54,836	\$ 648.36
7	25,377	25,377	\$ 353.77	0	\$ —	0	\$ —
8	39,171	39,171	\$ 491.71	64,548	\$ 745.48	0	\$ —
9	2,158	2,158	\$ 121.58	0	\$ —	66,706	\$ 767.06
10	20,633	20,633	\$ 306.33	22,791	\$ 327.91	0	\$ —
11	23,370	23,370	\$ 333.70	0	\$ —	0	\$ —
12	24,100	24,100	\$ 341.00	47,470	\$ 574.70	68,103	\$ 781.03
13	19,603	19,603	\$ 296.03	0	\$ —	0	\$ —
14	18,442	18,442	\$ 284.42	38,045	\$ 480.45	38,045	\$ 480.45
			\$4,164.46		\$3,464.46		\$3,264.46

variation of only 0.16. More stable shipments allow both Alloy Steel and the carrier to better plan operations and improve utilization of their assets.

Key Point Temporal aggregation of demand results in a reduction of transportation costs because it entails larger shipments and also reduces the variation in shipment sizes from one shipment to the next. It does, however, hurt customer response time. The marginal benefit of temporal aggregation declines as the time window over which aggregation takes place increases.

In the next section we discuss how transportation networks can be appropriately structured to supply customers with differing needs.

14.6 TAILORED TRANSPORTATION

Tailored transportation is the use of different transportation networks and modes based on customer and product characteristics. Most firms sell a variety of products and serve many different customer segments. For example, W. W. Grainger sells over 200,000 MRO supply products to both small contractors and very large firms. Products vary in size and value and customers vary in the quantity purchased, responsiveness required, uncertainty of the orders, and distance from W. W. Grainger branches and DCs. Given these differences, a firm like W. W. Grainger should not design a common

transportation network to meet all needs. A firm can meet customer needs at a lower cost by using tailored transportation to provide the appropriate transportation choice based on customer and product characteristics. In the following sections we describe various forms of tailored transportation in supply chains.

Tailored Transportation by Customer Density and Distance

Firms must consider customer density and distance from warehouse when designing transportation networks. The ideal transportation options based on density and distance are shown in Table 14.9.

When a firm serves a very high density of customers close to the DC, it is often best for the firm to own a fleet of trucks that are used with milk runs originating at the DC to supply customers because this scenario makes very good use of the vehicles. If customer density is high but distance from the warehouse is large, it does not pay to send milk runs from the warehouse because trucks will travel a long distance empty on the return trip. In such a situation it is better to use a public carrier with large trucks to haul the shipments to a cross-dock center close to the customer area, where the shipments are loaded onto smaller trucks that deliver product to customers using milk runs. In this situation, it may not be ideal for a firm to own its own fleet. As customer density decreases, use of an LTL carrier or a third party doing milk runs is more economical because the third-party carrier can aggregate shipments across many firms. If a firm wants to serve an area with a very low density of customers far from the warehouse, even LTL carriers may not be feasible and the use of package carriers may be the best option. Boise Cascade Office Products, an industrial distributor of office supplies, has designed a transportation network consistent with the suggestion in Table 14.9.

Customer density and distance should also be considered when firms decide on the degree of temporal aggregation to use when supplying customers. Firms should serve areas with high customer density more frequently because these areas are likely to provide sufficient economies of scale in transportation, making temporal aggregation less valuable. To lower transportation costs, firms should use a higher degree of temporal aggregation when serving areas with a low customer density.

Tailored Transportation by Size of Customer

Firms must consider customer size and location when designing transportation networks. Very large customers can be supplied using a TL carrier, whereas smaller customers will require an LTL carrier or milk runs. When using milk runs, a shipper incurs two types of costs:

- Transportation cost based on total route distance
- Delivery cost based on number of deliveries

TABLE 14.9 Transportation Options Based on Customer Density and Distance

	<i>Short Distance</i>	<i>Medium Distance</i>	<i>Long Distance</i>
High density	Private Fleet with milk runs	Cross-dock with milk runs	Cross-dock with milk runs
Medium density	Third-party milk runs	LTL carrier	LTL or package carrier
Low density	Third-party milk runs or LTL carrier	LTL or package carrier	Package carrier

TAB
Pro.
High

Low

The transportation cost is the same whether going to a large or small customer. If a delivery is to be made to a large customer, including other small customers on the same truck can save on transportation cost. For each small customer, however, the delivery cost per unit is higher than for large customers. Thus, it is not optimal to deliver to small and large customers with the same frequency at the same price. One option firms have is to charge a higher delivery cost for smaller customers. Another option is to tailor milk runs so that they visit larger customers with a higher frequency than smaller customers. Firms can partition customers into large (L), medium (M), and small (S) based on the demand at each. The optimal frequency of visits can be evaluated based on the transportation and delivery costs (see Section 10.2). If large customers are to be visited every milk run, medium customers every other milk run, and low-demand customers every three milk runs, suitable milk runs can be designed by combining large, medium, and small customers on each run. Medium customers would be partitioned into two subsets (M_1, M_2) and small customers would be partitioned into three subsets (S_1, S_2, S_3). The firm can sequence the following six milk runs to ensure that each customer is visited with the appropriate frequency: (L, M_1, S_1), (L, M_2, S_2), (L, M_1, S_3), (L, M_2, S_1), (L, M_1, S_2), (L, M_2, S_3). This tailored sequence has the advantage that each truck carries about the same load and larger customers are provided more frequent delivery than smaller customers, consistent with their relative costs of delivery.

Tailored Transportation by Product Demand and Value

The degree of inventory aggregation and the modes of transportation used in a supply chain network should vary with the demand and value of a product as shown in Table 14.10.

The cycle inventory for high-value products with high demand is disaggregated to save on transportation costs because this allows replenishment orders to be transported less expensively. Safety inventory for such products can be aggregated to reduce inventories (see Chapter 11) and a fast mode of transportation can be used if the safety inventory is required to meet customer demand. For high-demand products with low value, all inventories should be disaggregated and held close to the customer to reduce transportation costs. For low-demand, high-value products, all inventories should be aggregated to save on inventory costs. For low-demand, low-value products, cycle inventories can be held close to the customer and safety inventories aggregated

TABLE 14.10 Impact of Value and Demand of Product on Aggregation

<i>Product Type</i>	<i>High Value</i>	<i>Low Value</i>
High Demand	Disaggregate cycle inventory. Aggregate safety inventory. Inexpensive mode of transportation for replenishing cycle inventory and fast mode when using safety inventory.	Disaggregate all inventories and use inexpensive mode of transportation for replenishment
Low Demand	Aggregate all inventories. If needed, use fast mode of transportation for filling customer orders.	Aggregate only safety inventory. Use inexpensive mode of transportation for replenishing cycle inventory.

to reduce transportation costs while taking some advantage of aggregation. Cycle inventories are replenished using an inexpensive mode of transportation to save costs.

Key Point Tailoring transportation based on customer density and distance, customer size, or product demand and value allows a supply chain to achieve appropriate responsiveness and cost.

14.7 ROUTING AND SCHEDULING IN TRANSPORTATION

The most important operational decision related to transportation in a supply chain is the routing and scheduling of deliveries. Managers must decide on the customers to be visited by a particular vehicle and the sequence in which they will be visited. For example, an online grocer like Peapod is built on delivering customer orders to their homes. The success of its operations turns on its ability to decrease transportation and delivery costs while providing the promised level of responsiveness to the customer. Given a set of customer orders, the goal is to route and schedule delivery vehicles such that the costs incurred to meet delivery promises are as low as possible. Typical objectives when routing and scheduling vehicles are a combination of minimizing cost by decreasing the number of vehicles needed, the total distance traveled by vehicles, and the total travel time of vehicles, as well as eliminating service failures such as a delay in shipments.

We discuss routing and scheduling problems in the context of the manager of a Peapod DC. After customers place orders for groceries online, staff at the DC has to pick the items needed and load them on trucks for delivery. The manager must decide which trucks will deliver to which customers and the route that each truck will take when making deliveries. The manager must also ensure that no truck is overloaded and that promised delivery times are met.

One morning, the DC manager at Peapod has orders from 13 different customers that are to be delivered. The location of the DC, each customer on a grid, and the order size from each customer are shown in Table 14.11. The manager has four trucks, each capable of carrying up to 200 units. The manager feels that the delivery costs are strongly linked to the total distance the trucks travel and that the distance between two points on the grid is correlated with the actual distance that a vehicle will travel between those two points. The manager thus decides to assign customers to trucks and identify a route for each truck with a goal of minimizing the total distance traveled.

The DC manager must first assign customers to be served by each vehicle and then decide on each vehicle's route. After the initial assignment, route sequencing and route improvement procedures are used to decide on the route for each vehicle. The DC manager decides to use the following computational procedures to support his decision:

- The savings matrix method
- The generalized assignment method

We discuss how each method can be used to solve the routing and scheduling decision at Peapod.

TABLE 14.11 Customer Location and Demand for Peapod

	<i>X-Coordinate</i>	<i>Y-Coordinate</i>	<i>Order Size a_i</i>
Warehouse	0	0	
Customer 1	0	12	48
Customer 2	6	5	36
Customer 3	7	15	43
Customer 4	9	12	92
Customer 5	15	3	57
Customer 6	20	0	16
Customer 7	17	-2	56
Customer 8	7	-4	30
Customer 9	1	-6	57
Customer 10	15	-6	47
Customer 11	20	-7	91
Customer 12	7	-9	55
Customer 13	2	-15	38

Savings Matrix Method

This method is simple to implement and can be used to assign customers to vehicles even when delivery time windows or other constraints exist. The major steps in the savings matrix method are

1. Identify the distance matrix
2. Identify the savings matrix
3. Assign customers to vehicles or routes
4. Sequence customers within routes

The first three steps are used to assign customers to vehicles and the fourth step is used to route each vehicle to minimize the distance traveled.

Identify the Distance Matrix

The *distance matrix* identifies the distance between every pair of locations to be visited. The distance is used as a surrogate for the cost of traveling between the pair of locations. If the transportation costs between every pair of locations are known, the costs can be used in place of distances. The distance $Dist(A, B)$ on a grid between a point A with coordinates (x_A, y_A) and a point B with coordinates (x_B, y_B) is evaluated as

$$Dist(A, B) = \sqrt{(x_A - x_B)^2 + (y_A - y_B)^2} \quad (14.1)$$

The distance between every pair of locations for Peapod is shown in Table 14.12.

The distances between every pair of locations are next used to evaluate the savings matrix.

TABLE 14.12 Distance Matrix for Peapod Deliveries

DC	Cust 1	Cust 2	Cust 3	Cust 4	Cust 5	Cust 6	Cust 7	Cust 8	Cust 9	Cust 10	Cust 11	Cust 12	Cust 13	
DC	0													
Cust 1	12	0												
Cust 2	8	9	0											
Cust 3	17	8	10	0										
Cust 4	15	9	8	4	0									
Cust 5	15	17	9	14	11	0								
Cust 6	20	23	15	20	16	6	0							
Cust 7	17	22	13	20	16	5	4	0						
Cust 8	8	17	9	19	16	11	14	10	0					
Cust 9	6	18	12	22	20	17	20	16	6	0				
Cust 10	16	23	14	22	19	9	8	4	8	14	0			
Cust 11	21	28	18	26	22	11	7	6	13	19	5	0		
Cust 12	11	22	14	24	21	14	16	12	5	7	9	13	0	
Cust 13	15	27	20	30	28	22	23	20	12	9	16	20	8	0

Identify the Savings Matrix

The *savings matrix* represents the savings that accrue on consolidating two customers on a single truck. Savings may be evaluated in terms of distance, time, or money. The manager at Peapod constructs the savings matrix in terms of distance. A *trip* is identified as the sequence of locations a vehicle visits. The trip DC → Cust *x* → DC

TABLE 14.13 Savings Matrix for Peapod Deliveries

	Cust 1	Cust 2	Cust 3	Cust 4	Cust 5	Cust 6	Cust 7	Cust 8	Cust 9	Cust 10	Cust 11	Cust 12	Cust 13
Cust 1	0												
Cust 2	11	0											
Cust 3	21	15	0										
Cust 4	18	15	28	0									
Cust 5	10	14	18	19	0								
Cust 6	9	13	17	19	29	0							
Cust 7	7	12	14	16	27	33	0						
Cust 8	3	7	6	7	12	14	15	0					
Cust 9	0	2	1	1	4	6	7	8	0				
Cust 10	5	10	11	12	22	28	29	16	8	0			
Cust 11	5	11	12	14	25	34	32	16	8	32	0		
Cust 12	1	5	4	5	12	15	16	14	10	18	19	0	
Cust 13	0	3	2	2	8	12	12	11	12	15	16	18	0

starts at the DC, visits customer x , and returns to the DC. The savings $S(x,y)$ is the distance saved if the trips $DC \rightarrow Cust\ x \rightarrow DC$ and $DC \rightarrow Cust\ y \rightarrow DC$ are combined to a single trip $DC \rightarrow Cust\ x \rightarrow Cust\ y \rightarrow DC$. This saving can be calculated by the following formula:

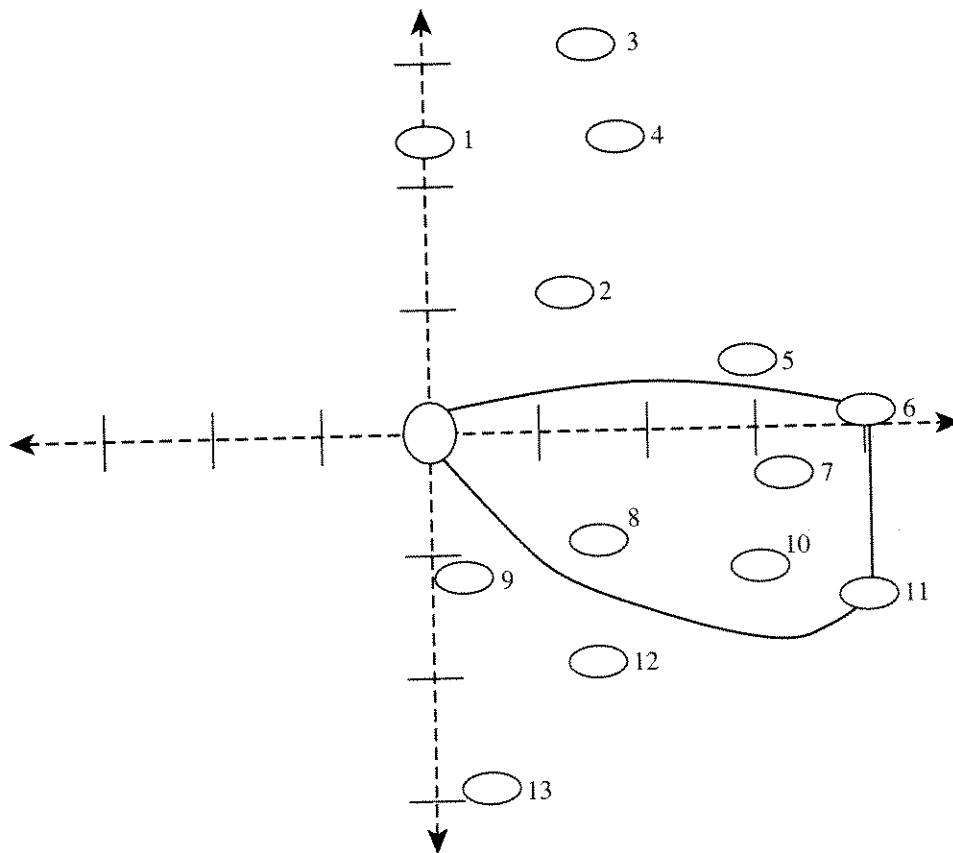
$$S(x,y) = Dist(DC, x) + Dist(DC, y) - Dist(x, y). \quad (14.2)$$

For example, using Table 14.12 the manager evaluates $S(1,2) = 12 + 8 - 9 = 11$. The savings matrix for the Peapod deliveries is shown in Table 14.13. The savings matrix is then used to assign customers to vehicles or routes.

Assign Customers to Vehicles or Routes

When assigning customers to vehicles, the manager attempts to maximize savings. An iterative procedure is used to make this assignment. Initially each customer is assigned to a separate route. Two routes can be combined into a *feasible* route if the total deliveries across both routes do not exceed the vehicle's capacity. At each iterative step, the Peapod manager attempts to combine routes with the highest savings into

FIGURE 14.5 Delivery Route by Assigning 6 and 11 to a Common Route



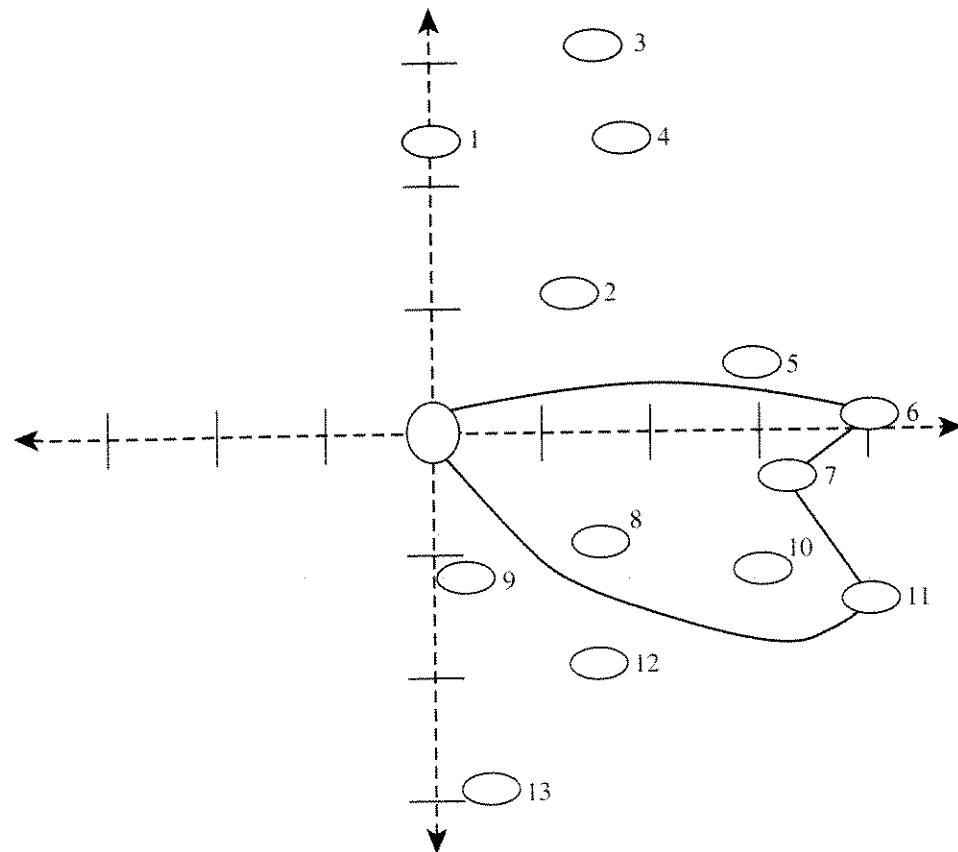
a new feasible route. The procedure is continued until no more combinations are feasible.

At the first step, the highest savings of 34 results on combining truck Routes 6 and 11. The combined route is feasible because the total load is $16 + 91 = 107$, which is below 200. The two customers are thus combined on a single route as shown in Figure 14.5 and the saving 34 is eliminated from further consideration.

The next highest saving is 33 on adding Customer 7 to the route for Customer 6. This is feasible because the resulting load is $107 + 56 = 163$, which is under 200. Thus, Customer 7 is also added to Route 6 as shown in Figure 14.6.

The next highest saving now is 32 on adding Customer 10 to Route 6 (we need not consider the saving of 32 on combining Customer 7 with Customer 11 because both are already in Route 6). This, however, cannot be done because the addition of Customer 10 results in a delivery of 47 units and adding this amount to the deliveries already on Route 6 would exceed the vehicle capacity of 200. The next highest saving is 29 on adding either Customer 5 or 10 to Route 6. Each of these is also infeasible

FIGURE 14.6 Delivery Route by Assigning 6, 7, and 11 to a Common Route



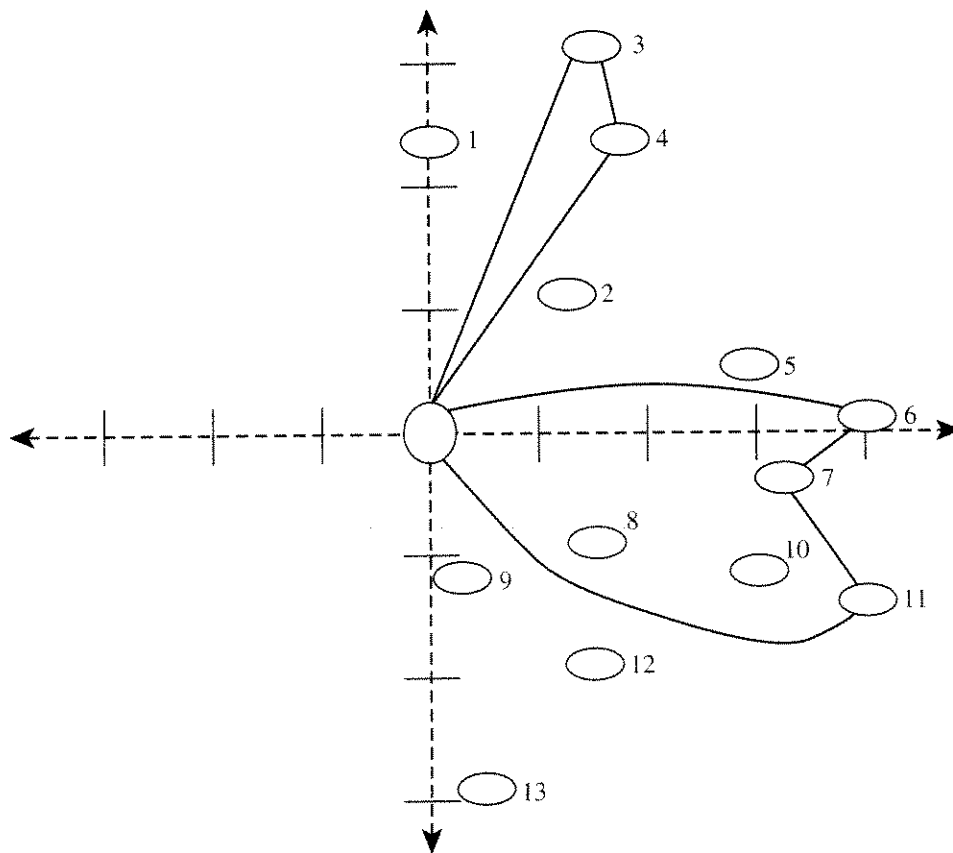
because of the capacity constraint. The next highest saving is 28 on combining Routes 3 and 4, which is feasible. The two routes are combined into a single route as shown in Figure 14.7.

Continuing the iterative procedure, the manager partitions customers into four groups {1, 3, 4}, {2, 9}, {6, 7, 8, 11}, {5, 10, 12, 13} with each group assigned to a single vehicle. The next step is to identify the sequence in which each vehicle will visit customers.

Sequence Customers within Routes

At this stage the manager's goal is to sequence customer visits so as to minimize the distance each vehicle must travel. Changing the sequence in which deliveries are made can have a significant impact on the distance traveled by vehicles. Consider the truck that has been assigned deliveries to Customers 5, 10, 12, and 13. If the deliveries are in the sequence 5, 10, 12, 13, the total distance traveled by the truck is $15 + 9 + 9 + 8 + 15 = 56$ (distances are obtained from Table 14.12). In contrast, if deliveries are in the sequence 12, 5, 13, 10, the truck covers a larger distance of $11 + 14 + 22 + 16 + 16 = 79$. Delivery sequences are determined by obtaining a initial route sequence and then

FIGURE 14.7 Delivery Route by Assigning 3 and 4 to a Common Route



using route improvement procedures to obtain delivery sequences with a lower transportation distance or cost.

Route Sequencing Procedures The manager at Peapod can use route sequencing procedures to obtain an initial trip for each vehicle. The initial trip is then improved using the route improvement procedure discussed later in the chapter. All route sequencing procedures are illustrated for the vehicle assigned to Customers 5, 10, 12, and 13.

1. *Farthest insert.* Given a vehicle trip (including a trip consisting of only the DC) for each remaining customer, find the minimum increase in length for this customer to be inserted from all the potential points in the trip that they could be inserted. Then choose to actually insert the customer with the largest minimum increase to obtain a new trip. This step is referred to as a farthest insert because the customer farthest from the current trip is inserted. The process is continued until all remaining customers to be visited by the vehicle are included in a trip.

For the Peapod example, the manager is seeking a trip starting at the DC and visiting Customers 5, 10, 12, 13. The initial trip consists of just the DC with a length of 0. Including Customer 5 in the trip adds 30 to its length, including Customer 10 adds 32, including Customer 12 adds 22, and including Customer 13 adds 30 (see Table 14.12). Using farthest insert, the manager adds Customer 10 to obtain a new trip (DC, 10, DC) of length 32.

At the next step, inserting Customer 5 in the trip raises the length of the trip to a minimum of 40, inserting Customer 12 raises it to 36, inserting Customer 13 raises it to 46. The manager thus inserts the farthest Customer 13 to obtain the new trip (DC, 10, 13, DC) of length 46. This still leaves Customers 5 and 12 to be inserted. The minimum cost insertion for Customer 5 is (DC, 5, 10, 13, DC) for a length of 55 and the minimum cost insertion for Customer 12 is (DC, 10, 12, 13, DC) for a length of 48. The manager thus inserts Customer 5 to obtain the trip (DC, 5, 10, 13, DC) of length 55. Customer 12 is then inserted between Customers 10 and 13 to obtain the trip (DC, 5, 10, 12, 13, DC) of length 56.

2. *Nearest insert.* Given a vehicle trip (including a trip consisting of only the DC), for each remaining customer, find the minimum increase in length for this customer to be inserted from all the potential points in the trip that they could be inserted. Insert the customer with the smallest minimum increase to obtain a new trip. This step is referred to as a nearest insert because the customer closest to the current trip is inserted. The process is continued until all remaining customers the vehicle will visit are included in a trip.

For the Peapod example, the manager applies the nearest insert to the vehicle serving Customers 5, 10, 12, and 13. Starting at the DC, the nearest customer is 12. Inserting Customer 12 results in the trip (DC, 12, DC) of length 22. At the next step, inserting Customer 5 results in a trip of length 40, inserting Customer 10 in a trip of length 36, and inserting Customer 13 in a trip of length 34. Customer 13 results in the smallest increase and is inserted to obtain the trip (DC, 12, 13, DC) of length 34. The next nearest insertion is Customer 10 resulting in the trip (DC, 10, 12, 13, DC) of length 48 and the final insertion of Customer 5 results in the trip (DC, 5, 10, 12, 13, DC) of length 56.

3. *Nearest neighbor.* Starting at the DC, this procedure adds the closest customer to extend the trip. At each step, the trip is built by adding the customer closest to the point last visited by the vehicle until all customers have been visited.

For the Peapod example, the customer closest to the DC is 12 (see Table 14.12). This results in the path (DC, 12). The customer closest to Customer 12 is 10, extending the path to (DC, 12, 10). The nearest neighbor of Customer 10 is 5 and the nearest neighbor of Customer 5 is 13. The Peapod manager thus obtains the trip (DC, 12, 10, 5, 13, DC) of length 66.

4. *Sweep.* In the sweep procedure, any point on the grid is selected (generally the DC itself) and a line is swept either clockwise or counterclockwise from that point. The trip is constructed by sequencing customers in the order they are encountered during the sweep.

The Peapod manager uses the sweep procedure with the line centered at the DC. Customers are encountered in the sequence 5, 10, 12, 13 to obtain the trip (DC, 5, 10, 12, 13, DC) for a length of 56.

The initial trips resulting from each route sequencing procedure and their lengths are summarized in Table 14.14.

Route Improvement Procedures Route improvement procedures start with a trip obtained using a route sequencing procedure and improve the trip to shorten its length. The Peapod manager next applies route improvement procedures to alter the sequence of customers visited by a vehicle and shorten the distance a vehicle must travel. The two route improvement procedures discussed are illustrated on the trip obtained as a result of the nearest neighbor procedure.

1. *2-OPT.* The 2-OPT procedure starts with a trip and breaks it at two places. This results in the trip breaking into two paths, which can be reconnected in two possible ways. The length for each reconnection is evaluated and the smaller of the two is used to define a new trip. The procedure is continued on the new trip until no further improvement results.

For example, the trip (DC, 12, 10, 5, 13, DC) resulting from the nearest neighbor procedure can be broken into two paths (13, DC) and (12, 10, 5) and reconnected into the trip (DC, 5, 10, 12, 13, DC) as shown in Figure 14.8. The new trip has length 56, which is an improvement over the existing trip.

2. *3-OPT.* The 3-OPT procedure breaks a trip at three points to obtain three paths that can be reconnected to form up to eight different trips. The length of each of the eight

TABLE 14.14 Initial Trips Using Different Route Sequencing Procedures at Peapod

<i>Route Sequencing Procedure</i>	<i>Resulting Trip</i>	<i>Trip Length</i>
Farthest insert	DC, 5, 10, 12, 13, DC	56
Nearest insert	DC, 5, 10, 12, 13, DC	56
Nearest neighbor	DC, 12, 10, 5, 13, DC	66
Sweep	DC, 5, 10, 12, 13, DC	56

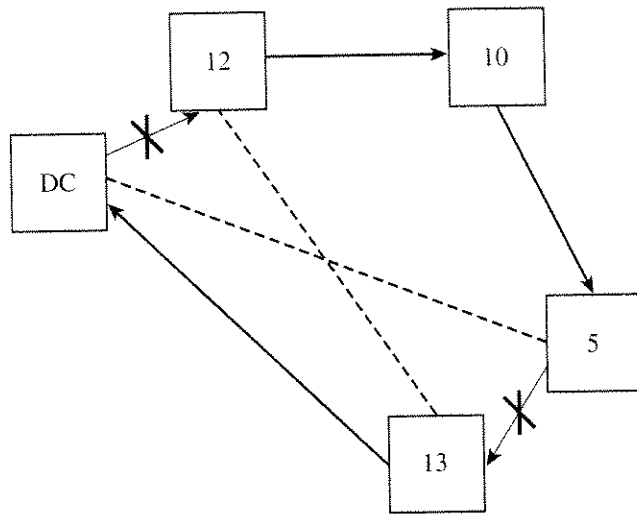


FIGURE 14.8 Improving Route Sequencing Using 2-OPT

possible trips is evaluated and the shortest trip is retained. The procedure is continued on the new trip until no further improvement results.

The trip (DC, 5, 10, 12, 13, DC) resulting from the 2-OPT procedure is broken up into three paths (DC), (5, 10), (12, 13). The various resulting trips on reconnecting the three paths are (DC, 12, 13, 5, 10, DC) of length 65, (DC, 12, 13, 10, 5, DC) of length 81, and (DC, 13, 12, 5, 10, DC) of length 61. All other trips correspond to one of these four trips reversed. This application of the 3-OPT procedure does not improve the trip because the current trip is the shortest. At this stage the Peapod manager can form three new paths from the trip and repeat the procedure.

The Peapod manager uses route sequencing and improvement procedures to obtain delivery trips for each of the four trucks as shown in Table 14.15 and Figure 14.9. The total travel distance for the delivery schedule is 185.

Generalized Assignment Method

The generalized assignment method is more sophisticated than the savings matrix method and usually results in better solutions when there are few delivery constraints to be satisfied. The procedure for routing and sequencing of vehicles consists of the following steps:

TABLE 14.15 Peapod Delivery Schedule Using Saving Matrix Method

<i>Truck</i>	<i>Trip</i>	<i>Length of Trip</i>	<i>Load on Truck</i>
1	DC, 2, 9, DC	32	93
2	DC, 1, 3, 4, DC	39	183
3	DC, 8, 11, 6, 7, DC	58	193
4	DC, 5, 10, 12, 13, DC	56	197

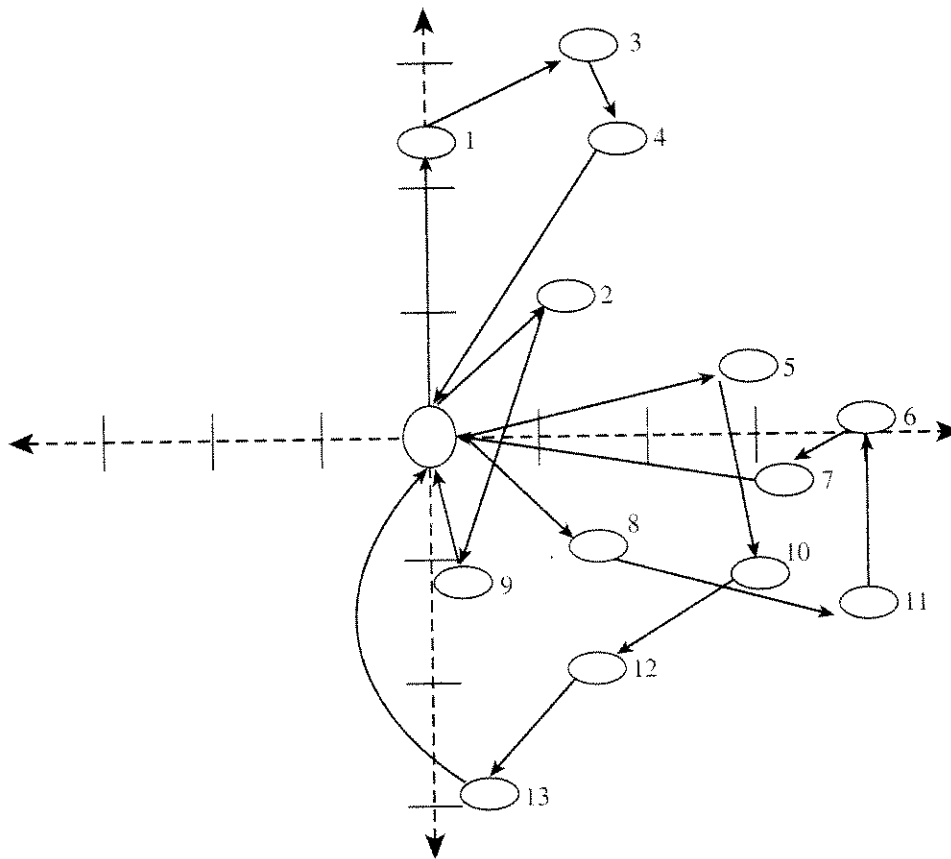


FIGURE 14.9 Delivery Routes at Peapod Using Savings Matrix Method

1. Assign seed points for each route
2. Evaluate insertion cost for each customer
3. Assign customers to routes
4. Sequence customers within routes

The first three steps assign customers to vehicles and the fourth step identifies a route for each vehicle to minimize the distance traveled. We discuss each step in greater detail in the context of the delivery decision at Peapod.

Assign Seed Points for Each Route

The goal of this step is to determine a seed point corresponding to the center of the trip taken by each vehicle using the following procedure:

1. Divide the total load to be shipped to all customers by the number of trucks to obtain L_{seed} , the average load allocated to each seed point.
2. Starting at any customer, use a ray starting at the DC to sweep clockwise to obtain cones assigned to each seed point. Each cone is assigned a load of L_{seed} .

3. Within each cone, the seed point is located in the middle (in terms of angle) at a distance equal to that of the customer (with a partial or complete load allocated to the cone) farthest from the DC.

The manager at Peapod uses the procedure described earlier to obtain seed points for the deliveries described in Table 14.11. Given four vehicles and a total delivery load across all customers of 666 units, the manager obtains an average load per vehicle of $L_{seed} = 666/4 = 166.5$ units.

The next step is to sweep clockwise with a ray emanating from the DC to obtain four cones, one for each vehicle, including all customers. The first step in defining the cones is to obtain the angular position of each customer. The angular position (θ_i) of customer i with coordinates (x_i, y_i) is the angle made relative to the x axis by the line joining the customer i to the origin (DC) as shown in Figure 14.10.

The angular position of each customer is obtained as the inverse tangent of the ratio of its y coordinate to the x coordinate.

$$\theta_i = \tan^{-1}(y_i/x_i) \tag{14.3}$$

The inverse tangent can be evaluated using the Excel function $ATAN()$ as

$$\theta_i = ATAN(y_i/x_i). \tag{14.4}$$

The angular position of each customer is obtained using Equation 14.4 as shown in Table 14.16.

The next step is to sweep clockwise and order the customers as encountered. For Peapod, a clockwise sweep encounters customers in the order 1, 3, 4, 2, 5, 6, 7, 11, 10, 8, 12, 9, and 13. Starting with Customer 1, four cones, each representing a load of $L_{seed} = 166.5$ units, are to be formed. Customers 1 and 3 combine to load 91 units on the truck. Customer 4 is encountered next in the sweep. Adding the entire load for Customer 4

FIGURE 14.10 Angular Position of Customer i

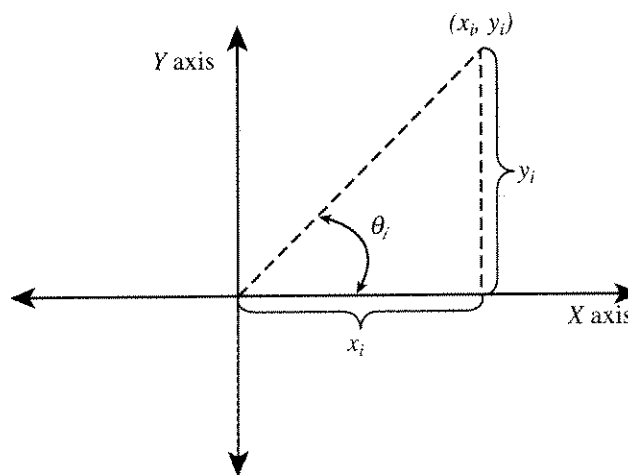


TABLE 14.16 Angular Positions of Peapod Customers

	<i>X</i> Coordinate	<i>Y</i> Coordinate	Angular Position (Radians)	Demand
DC	0	0		
Customer 1	0	12	1.57	48
Customer 2	6	5	0.69	36
Customer 3	7	15	1.13	43
Customer 4	9	12	0.93	92
Customer 5	15	3	0.20	57
Customer 6	20	0	0.00	16
Customer 7	17	-2	-0.12	56
Customer 8	7	-4	-0.52	30
Customer 9	1	-6	-1.41	57
Customer 10	15	-6	-0.38	47
Customer 11	20	-7	-0.34	91
Customer 12	7	-9	-0.91	55
Customer 13	2	-15	-1.44	38

would result in a load of 183, which is larger than $L_{seed} = 166.5$. To get a load of 166.5, only $166.5 - 91 = 75.5$ units of the load should be included. Thus, the first cone extends to a point that is $75.5 / 92$ of the angle between Customers 3 and 4. Customer 3 has an angular position of 0.93 and Customer 4 has an angular position of 0.20, resulting in an angle between them of $0.93 - 0.20 = 0.73$. The first cone thus extends to an angle $(75.5 / 92) \times 0.73$ beyond Customer 3 with a resulting angle of $0.93 - (75.5 / 92) \times 0.73 = 0.33$. The first cone thus has one end at Customer 1 (angle of 1.57) and the other at an angle of 0.33 as shown in Figure 14.11.

The seed point is then located at an angle $\alpha_1 = (0.33 + 1.57) / 2 = 0.95$ in the middle of the cone at a distance equal to that of the farthest customer included. Customer 3, at a distance $d_1 = \sqrt{(7-0)^2 + (15-0)^2} = 17$, is the farthest customer in the first cone. Given the distance d_1 , the coordinates (X_1, Y_1) of the Seed Point 1 are thus given by

$$X_1 = d_1 \cos(\alpha) = 17 \cos(1.27) = 5, \text{ and } Y_1 = d_1 \sin(\alpha) = 17 \sin(1.27) = 16$$

The second cone starts at the angle 0.33 and includes $92 - 75.5 = 16.5$ units of the Customer 4 load. On sweeping clockwise, Customers 2, 5, 6, and 7 are encountered before a load of 166.5 is exceeded. To get a load of exactly 166.5, only $41/56$ of Customer 7 load is needed. The angular position of the end of the cone is thus $41/56$ between Customers 6 and 7. Customer 6 is at angle of 0.00 and Customer 7 is at the angle of -0.12. The second cone thus ends at an angle of $0.00 - 0.12 \times (41/56) = -0.09$. The second cone has one end at an angle of 0.33 and the other at an angle of -0.09. The seed point is thus located at an angle α_2 in the middle of the cone; that is, $\alpha_2 = (0.33 - 0.09) / 2 = 0.12$. The distance d_2 of the seed point for the second cone is the same as Customer 6, the farthest customer in the cone. This corresponds to a distance of $d_2 = 20$ (see Table 14.12). The coordinates (X_2, Y_2) of the Seed Point 2 are thus given by

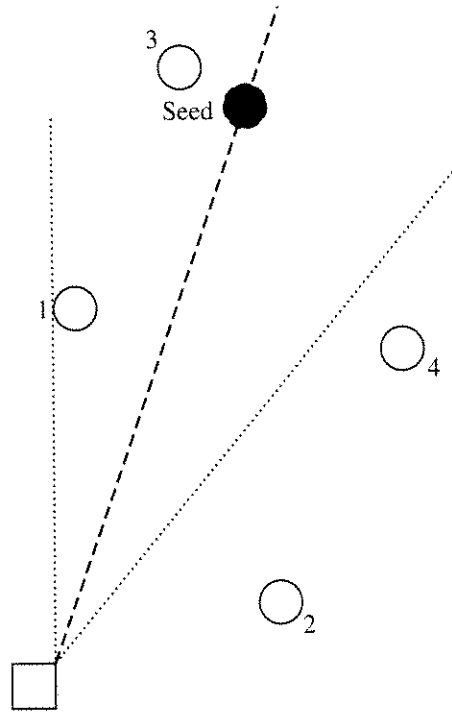


FIGURE 14.11 Sweep Method to Locate Seed 1

$$X_2 = d_2 \cos(\alpha_2) = 20 \cos(0.12) = 20, \text{ and } Y_2 = d_2 \sin(\alpha_2) = 20 \sin(0.12) = 2.$$

Proceeding in the same manner, the manager at the Peapod DC forms four cones to determine the four seed points as shown in Table 14.17.

Evaluate Insertion Cost for Each Customer

For each Seed Point S_k and Customer i , the *insertion cost* c_{ik} is the extra distance that would be traveled if the customer is inserted into a trip from the DC to the seed point and back and is given by

$$c_{ik} = \text{Dist}(\text{DC}, i) + \text{Dist}(i, S_k) - \text{Dist}(\text{DC}, S_k),$$

TABLE 14.17 Seed Point Coordinates for Peapod Deliveries

Seed Point	X Coordinate	Y Coordinate
S_1	10	14
S_2	20	2
S_3	19	-5
S_4	5	-5

where the $Dist()$ function is evaluated as in Equation 14.1. For Customer 1 and Seed Point 1, the insertion cost is given by

$$c_{11} = Dist(DC, 1) + Dist(1, S_1) - Dist(DC, S_1) = 12 + 10 - 17 = 5.$$

The manager at the Peapod DC evaluates all insertion costs c_{ik} as shown in Table 14.18.

Assign Customers to Routes

The manager next assigns customers to each of the four vehicles to minimize total insertion cost while respecting vehicle capacity constraints. The assignment problem is formulated as an integer program and requires the following input:

- c_{ik} = insertion cost of Customer i and Seed Point k ,
- a_i = order size from Customer i ,
- b_k = capacity of Vehicle k .

Define the following decision variables

$$y_{ik} = 1 \text{ if Customer } i \text{ is assigned to Vehicle } k, 0 \text{ otherwise.}$$

The integer program for assigning customers to vehicles is given by

$$\text{Min} \sum_{k=1}^K \sum_{i=1}^n c_{ik} y_{ik}$$

TABLE 14.18 Insertion Costs for Peapod Deliveries for Each Customer and Seed Point

Customer	Seed Point 1	Seed Point 2	Seed Point 3	Seed Point 4
1	5	14	18	23
2	1	2	5	11
3	3	15	21	30
4	0	10	15	25
5	10	0	4	21
6	20	2	5	29
7	17	2	1	22
8	9	2	0	3
9	11	7	4	3
10	19	5	0	19
11	27	10	4	29
12	17	8	4	8
13	28	20	15	18

subject to

$$\sum_{k=1}^K y_{ik} = 1, i = 1, \dots, n,$$

$$\sum_{i=1}^n a_i y_{ik} \leq b_k, k = 1, \dots, k,$$

$$y_{ik} = 0 \text{ or } 1 \text{ for all } i \text{ and } k$$

For Peapod, the order size for each customer is given in Table 14.11, the insertion cost c_{ik} is obtained from Table 14.20, and the capacity of each vehicle is 200 units. The manager at Peapod solves the integer program using the tool Solver in Excel to obtain the assignment of customers to vehicles as shown in Table 14.19 and Figure 14.12. The sequencing of customers within each trip is obtained using the route sequencing and route improvement procedures discussed earlier. The total distance traveled for the delivery schedule is 159.

Applicability of Routing and Scheduling Methods

The delivery schedule for Peapod resulting from the generalized assignment method in Table 14.18 is superior to the solution obtained from the savings matrix method in Table 14.14. The generalized assignment method is more sophisticated and generally gives a better solution than the savings matrix method when the delivery schedule has no constraints other than vehicle capacity. The main disadvantage of the generalized assignment method is that it has difficulty generating good delivery schedules as more constraints are included. For example, if Peapod has fixed time windows within which deliveries must be made to customers, it is difficult to use the generalized assignment method to generate a delivery schedule. The generalized assignment method is recommended if the constraints are limited to vehicle capacity or total travel time.

The main strength of the savings matrix method is its simplicity and robustness. The method is simple enough to be easily modified to include delivery time windows and other constraints and robust enough to give a reasonably good solution that can be implemented in practice. Its main weakness is the quality of the solution. It is often possible to find better delivery schedules using more sophisticated methods. The savings matrix method is recommended in case there are many constraints that need to be satisfied by the delivery schedule. Software packages for transportation planning and

TABLE 14.19 Peapod Delivery Schedule Using Generalized Assignment Method

<i>Truck</i>	<i>Trip</i>	<i>Length of Trip</i>	<i>Load on Truck</i>
1	DC, 1, 3, 4, DC	39	183
2	DC, 2, 5, 6, 7, 8, DC	45	195
3	DC, 10, 11, 12, DC	45	193
4	DC, 9, 13, DC	30	95

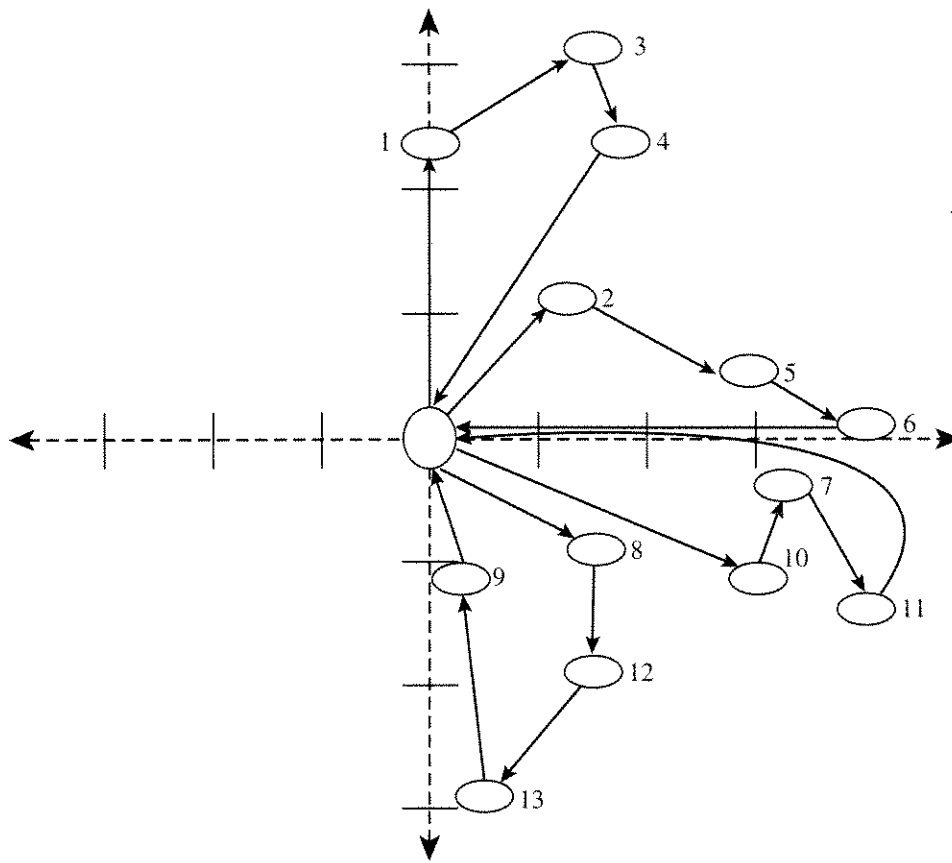


FIGURE 14.12 Delivery Routes at Peapod Using Generalized Assignment

routing and scheduling of deliveries are available from many supply chain software companies (see Chapter 17).

14.8 MAKING TRANSPORTATION DECISIONS IN PRACTICE

1. *Align transportation strategy with competitive strategy:* Managers should ensure that a firm's transportation strategy supports its competitive strategy. They should design functional incentives that help achieve this goal. Historically, the transportation function within firms has been evaluated based on the extent to which it can lower transportation costs. Such a focus leads to decisions that lower transportation costs but hurt the level of responsiveness provided to customers and may raise the firm's total cost. If the dispatcher at a DC is evaluated solely based on the extent to which trucks are loaded, he or she is likely to delay shipments and hurt customer responsiveness to achieve a larger load. Firms should evaluate the transportation function based on a

combination of transportation cost, other costs such as inventory affected by transportation decisions, and the level of responsiveness achieved with customers.

2. *Consider both in-house and outsourced transportation:* Managers should consider an appropriate combination of company-owned and outsourced transportation to meet their needs. This decision should be based on a firm's ability to handle transportation profitably as well as the strategic importance of transportation to the success of the firm. In general, outsourcing is a better option when shipment sizes are small, whereas owning the transportation fleet is better when shipment sizes are large and responsiveness is important. For example, Wal-Mart has used responsive transportation to reduce inventories in its supply chain. Given the importance of transportation to the success of their strategy, they own their transportation fleet and manage it themselves. This is made easier by the fact that they achieve good utilization from their transportation assets because most of their shipments are large. In contrast, firms like W.W. Grainger and McMaster Carr send small shipments to customers; inventory management rather than transportation is the key to their success. A third-party carrier can lower costs for them by aggregating their shipments with those of other companies. As a result, both companies use third-party carriers for their transportation.

3. *Design a transportation network that can handle e-commerce:* The growth in e-commerce for most B2C firms has resulted in a decrease in shipment sizes and a growth in home delivery. Transportation systems for the new economy need to be very responsive but must also be able to exploit every opportunity for aggregation, in some cases even with competitors, to help decrease the transportation cost of small shipments. Whereas replenishment orders are large and can use rail or TL carriers, most e-commerce shipments require more expensive package carriers or LTL carriers given their smaller size. The growth in JIT manufacturing and the focus on reduced inventories and frequent replenishment has further increased the need to handle small shipments. If managers do not take these trends into account when designing their transportation networks, firms are likely to see a significant increase in transportation cost along with a drop in responsiveness to the customer.

4. *Use technology to improve transportation performance:* Managers must use the information technology available to help decrease costs and improve responsiveness in their transportation networks. Software is crucial to helping managers do transportation planning, modal selection, and build delivery routes and schedules. Available technology allows carriers to identify the precise location of each vehicle as well as the shipments the vehicle carries. Satellite-based communication systems allow carriers to communicate with each vehicle in their fleet. These technologies can help a carrier become much more responsive and also help lower costs by better matching shipments from customers with vehicles that are best suited to carry them. These technologies also help a firm react better to unforeseen changes caused by the weather or other unpredictable factors.

5. *Design flexibility into the transportation network:* When designing transportation networks, managers should take into account uncertainty in demand as well as availability of transportation. Ignoring uncertainty encourages a greater use of inexpensive and inflexible transportation modes that perform well when everything goes as planned. Such networks, however, perform very poorly when plans change. When managers

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account for uncertainty, they are more likely to include flexible, though more expensive, modes of transportation within their network. Although these modes may be more expensive for a particular shipment, including them in the transportation options allows a firm to reduce the overall cost of providing a high level of responsiveness.

14.9 SUMMARY OF LEARNING OBJECTIVES

1. Understand the role of transportation within a supply chain.

Transportation refers to the movement of product from one location to another within a supply chain. The importance of transportation has grown with the increasing globalization in supply chains as well as the growth in e-commerce because both trends increase the distance products travel. Transportation decisions impact supply chain profitability and influence both inventory and facility decisions within a supply chain.

2. Evaluate the strengths and weaknesses of different modes of transportation.

The various modes of transportation include water, rail, intermodal, truck, air, pipeline, and package carriers. Water is typically the least expensive mode but is also the slowest whereas air and package carriers are the most expensive and the fastest. Rail and water are best suited for low-value, large shipments that do not need to be moved in a hurry. Air and package carriers are best suited for small, high-value, emergency shipments. Intermodal and TL carriers are faster than rail and water but somewhat more expensive. LTL carriers are best suited for small shipments that are too large for package carriers but much less than a TL.

3. Identify various transportation network design options and their relative strengths and weaknesses.

Networks are designed to either ship directly from origin to destination or move the product through a consolidation point. Direct shipments are most effective when large quantities are to be moved. When shipments are small, use of an intermediate warehouse or DC takes longer and is more complex but lowers transportation cost by aggregating the smaller shipments. Shipments may also be consolidated with a single vehicle either picking up from multiple locations or dropping off in multiple locations.

4. Identify trade-offs that shippers need to consider when designing their transportation network.

When designing transportation networks, shippers must consider the trade-off between transportation cost, inventory cost, operating cost, and customer responsiveness. The supply chain goal is to minimize the total cost while providing the desired level of responsiveness to customers.

5. Use methodologies for routing and scheduling deliveries in transportation networks.

The savings matrix and the generalized assignment methodology can be used to route vehicles and sequence deliveries. The methods can be used to minimize the transportation cost while meeting delivery commitments to customers. Several companies provide software that allows a manager to set delivery schedules.

DISCUSSION QUESTIONS

1. What modes of transportation are best suited for large, low-value shipments? Why?
2. Wal-Mart designs its networks to have a DC support several large retail stores. Explain how the company can use such a network to reduce transportation costs while replenishing inventories frequently.

3. Compare the transportation costs for an e-business like Amazon.com and a retailer like Home Depot when selling home improvement materials.
4. What transportation challenges does Peapod face? Compare transportation costs at online grocers and supermarket chains.
5. Do you expect aggregation of inventory at one location to be more effective when a company like Dell sells computers or when a company like Amazon.com sells books? Explain by considering transportation and inventory costs.
6. Discuss key drivers that may be used to tailor transportation. How does tailoring help?
7. What are the strengths and weaknesses of using the savings matrix method or the generalized assignment method for routing and scheduling of vehicles?

EXERCISES

1. A power plant in California uses coal at the rate of 100,000 lbs. each day. It also uses MRO material at the rate of 1,000 lbs. each day. The coal comes from Wyoming and the MRO material comes from Chicago. Coal costs \$0.01 per lb. whereas MRO material costs \$10 per lb., on average. Holding costs at the power plant are 25 percent. Transportation choices available are as follows:

TRAIN

Lead time = 15 days

Carload (100,000 lbs.) at \$400 per carload

Full train (70 cars) at \$15,000 per train

TRUCK

Lead time = 4 days

Minimum cost = \$100

Up to 10,000 lbs. at \$0.08 per lb.

Between 10,000 and 20,000 lbs. at \$0.07 per lb. for entire load

Between 25,000 and 40,000 lbs. at \$0.06 per lb. for entire load

Small TL (40,000 lbs.) for \$2,000

Large TL (60,000 lbs.) for \$2,600

Safety inventory of coal and MRO materials is kept at twice the consumption during the lead time of supply. What mode of transport do you recommend for each of the two products? Why?

2. Books-On-Line, an online bookseller, charges its customers a shipping charge of \$4 for the first book and \$1 for each additional book. The average customer order contains 4 books. Books-On-Line currently has one warehouse in Seattle and ships all orders from there. For shipping purposes, Books-On-Line divides the US into three zones—western, central, and eastern. Shipping cost incurred by Books-On-Line per customer order (average 4 books) is \$2 within the same zone, \$3 between adjacent zones, and \$4 between nonadjacent zones.

Weekly demand from each zone is independent and normally distributed with a mean of 50,000 and a standard deviation of 25,000. Each book costs on average \$10 and the holding cost incurred by Books-On-Line is 25 percent. Books-On-Line replenishes inventory every week and aims for a 99.7 percent CSL. Assume a replenishment lead time of one week.

A warehouse is designed to carry 50 percent more than the replenishment order + safety stock. The fixed cost of a warehouse is $\$200,000 + x$, where x is its capacity in books. The weekly operating cost of a warehouse is $\$0.01y$, where y is the number of books shipped. Books-On-Line is planning its network strategy. Which zones should have warehouses? Detail all costs involved.

3. A European manufacturer of industrial furniture has a factory located in Munich and four warehouses in Western Europe. The warehouses collect customer orders, which are then shipped from the factory. Upon receipt, the warehouse distributes customer orders using small trucks. Daily demand at each of the four warehouses along with distance from Munich is as shown following:

<i>Warehouse</i>	<i>Daily Demand (Kg)</i>	<i>Distance (km)</i>
Milan	25,000	800
Paris	35,000	1,000
Copenhagen	20,000	600
Madrid	20,000	1,300

All shipments are by truck. There are three truck sizes available with capacity—40,000 (small), 60,000 (medium), and 80,000 kg (large). Transportation costs for the three types of trucks are:

Small: $100 + 0.1x$ Euro,

Medium: $125 + 0.1x$ Euro,

Large: $150 + 0.1x$ Euro.

x is the distance to be traveled in km. For replenishment frequency varying between one and four days for each warehouse, identify the optimal transportation option and the associated cost. What other factors should be considered before deciding on the replenishment frequency?

4. The manager at Albertson's, a grocery chain also selling online, has 12 orders that are to be delivered to customers. The location and order size for each customer is shown in Table 14.20.

TABLE 14.20 Customer Locations and Order Sizes for Albertson's

	<i>X Coordinate</i>	<i>Y Coordinate</i>	<i>Order Size</i>
DC	0	0	
Customer 1	-12	0	74
Customer 2	-5	6	55
Customer 3	-15	7	68
Customer 4	-12	9	109
Customer 5	-3	15	81
Customer 6	0	20	41
Customer 7	2	17	74
Customer 8	4	7	52
Customer 9	6	1	80
Customer 10	6	15	69
Customer 11	7	20	103
Customer 12	9	7	75

The Alberston's fulfillment store has five trucks, each capable of carrying up to 225 units. Use the savings matrix and generalized assignment methods to devise suitable delivery schedules. What is the total distance traveled under each schedule?

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