Chapter 10
Medical Supply Logistics

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Abstract This chapter focuses on medical supply logistics from the perspective of materials management and technology. It covers the structure of the medical supply chain and illustrates many of the issues that make the management of medical supply chains unique, complex, and challenging. Then, a review of inventory management practices and current research for medical supplies is provided. As an example, the management of blood supply is illustrated. Finally, key technological enablers such as electronic data exchange, automatic data capture technologies, and their importance within medical logistics are discussed. Future areas for research are suggested.

10.1 Introduction

Medical supply logistics encompasses purchasing, materials planning and scheduling, inventory control, material handling and physical distribution of medical supplies, and supporting services. Medical supply logistics involves both inter-facility (between locations) and intra-facility (within the facility) management of the flow of supplies and resources to enable patient care. Many different functions

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are utilized during this process, including information systems, warehousing, inventory, packaging, and transportation.

Since logistics can be conceptualized as "inventory in motion", this chapter will focus on medical supply logistics from the perspective of materials management. In fact, within many health care organizations, medical supply logistics is typically within a department of materials management. Industry-wide coverage of the professional and educational aspects of medical supply logistics can be found through the Association for Health care Resource and Materials Management (AHRMM). This association is a valuable resource for understanding materials management within the health care industry and learning about practical methods for improving its function.

Medical supply materials management is critical in ensuring the safety, availability, and affordability of supplies. A critical component of ensuring patient safety is ensuring that the right supplies are used on the right patients at the right time. The first responsibility of a health care materials manager is to ensure that the products purchased for clinical use are of good quality. This involves ensuring that the product's safety and clinical effectiveness are considered in addition to the cost. The building of a team of clinicians and logistics professionals to evaluate and select appropriate items for inclusion in the procurement functions of the provider is critical to the success of this process.

Besides ensuring that the right products are used within the system (given safety and effectiveness), materials management must ensure that the items are properly stored and controlled. This must not only control the availability of the item, but also ensure that its efficacy over time is monitored. For example, among other things, this involves ensuring the proper packaging, storage, and access control of items. Items that are controlled substances, hazardous, etc. require specialized management techniques that are not found within other industries. The rotation and usage of expiring items is just one such issue that a medical supply professional must consider. Finally, the management of recalled items and their prior use on patients must be handled through systematic processes and procedures. Many regulatory issues, management structures, and objectives (e.g. saving lives) make the materials management function within health care significantly different than that found in many other industries (e.g. retail).

As one can see, materials management is essential to the proper functioning of a health care system. However, it is beyond the scope of this chapter to cover all of the aspects of material supply logistics. To limit the scope, this chapter will focus on the controlling of inventories of medicines, medical supplies, blood, and other specialized items to ensure availability and cost. That is, we assume that the aspects of patient safety have already been adequately managed. For additional information concerning the importance of patient safety, please see Kohn et al. (2000). Therefore, this chapter concentrates on viewing the aspects, techniques, and technologies of medical supply logistics that ensure that the item will be available at the right time for the lowest cost.

Indeed, reducing the cost of supply is an increasingly important focus area for health care providers. According to Ozcan, in a typical hospital budget 25–30%

goes for medical supplies and their handling. The supply chain now represents the second largest cost center after personnel cost, and it is estimated to be approximately 15–30% of overall hospital net revenue (Williams 2004). Some industry experts are even suggesting that at current rates of growth, supply costs may eventually exceed personnel costs (Moore 2010) President and CEO resource optimization & innovation (ROi) an operating division of the Sisters of Mercy Health, personal communication). Because of the opportunities within and importance of inventory within the materials management system, this chapter will focus on aspects of inventory management within health care.

A roundtable discussion at the MIT Center for Transportation and Logistics (Meyer and Meyer 2006) highlighted some of the important issues in health care, particularly in supply chains. Some of the problems and constraints discussed included the high cost of health care, wasteful behaviors, and complex requirements and regulations. The solutions focused on making supply chains more demand driven, increasing collaboration between the various parties involved, increasing visibility of practices and inventories, and implementing more and better standards. In a survey released by HFMA (Anonymous 2002), executives and supply chain leaders of health care organizations identified ways to improve care and reduce cost. These included standardizing supplies, central purchasing, reducing inventory, improving demand forecasts, reducing labor costs through automation, improved collaboration with vendors, online purchasing, and more. These important issues motivate the importance of looking at the health care supply chain from an integrated perspective.

The next section reviews the medical supply chain and some of the complexities that make the management of inventories more challenging within a health care system. Then, Sect. 10.3 describes the management science aspects of inventory management required within a health care setting. Some of the current industry practices will be reviewed. In addition, a review of relevant literature and its application (or potential application) is discussed. Specialized models for blood supply management will be used as an illustration of some of the unique challenges faced by health care providers in Sect. 10.4. Finally, Sect. 10.5 discusses enabling information systems and technologies that are critical to ensuring the proper functioning of the materials management system.

The final section will present some thoughts for the future of medical supply logistics.

10.2 Medical Supply Chains

A typical health care supply chain is a complex network consisting of many different parties at various stages of the value chain. According to Burns (2002), the three major types of players are: Producers (product manufacturers), Purchasers (group purchasing organizations, or GPOs, and wholesalers/distributors), and health care providers (hospital systems and integrated delivery networks, or IDNs). This chain is shown in Fig. 10.1.

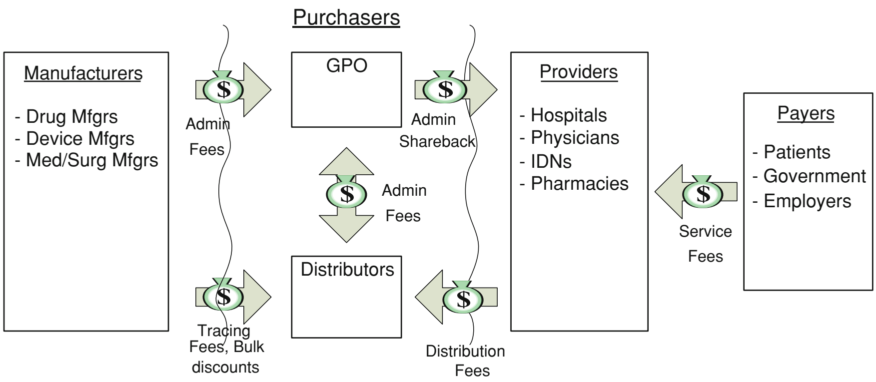

Fig. 10.1 Health care value chain [adapted from Moore (Moore V (2010)) and Burns (2002)]

Manufacturers make the products; GPOs and distributors aggregate a large number of hospitals in an attempt to leverage the economies of scale while funding their operations through administration fees and distribution fees; the provider, such as hospitals, consume the products while providing patient care; and finally the payers, such as the individual patient and his employer, pay for the services of the provider. Within the health care value chain, the products (drugs, devices, supplies, etc.) are transported, stored, and eventually transformed into health care services for the patient. A more detailed discussion of the roles and players within the health care value chain can be found in Burns (2002), Burn and Pauly (2002), Schneller and Smeltzer (2006), and Burns and Lee (2008). A summary of the product, information, and dollar flows related to the health care supply chain can be found in Schwartz (2011).

During 1990s, vertical and horizontal integration, managed care pressures, changes in federal reimbursement, the rise of e-commerce, and the passage of the Health Insurance Portability and Accountability Act (HIPAA) in 1996 all contributed to structural and operational changes within health care supply chains. Provider organizations such as hospitals and hospital systems vertically integrated into the health insurance business, such as starting up their own Health Maintenance Organizations (HMOs) and ambulatory care practices, in the process of developing Integrated Delivery Networks or IDNs. Many such attempts were unproductive and providers had to integrate upstream with the wholesalers and distributors to improve their financial position. Burns and Pauly (2002) discuss their skepticism of the trend in health care toward increasing consolidation, such as having primary care physicians or HMOs in the same organization as hospitals. They assert that the horizontal and vertical integration that health care organizations are trying to achieve are often counterproductive, and that the economies of scale of a larger organization fail to compensate for the increased bureaucracy and typically poor restructuring. Also, almost every major player along the health care value chain considered horizontally consolidation to form larger organizations.

Hospitals merged to form hospital systems or joined other systems. GPOs started catering to different systems and distributors started building warehouses where demands from various systems are consolidated.

An example of a health care system that has benefited from streamlining and integrating their inventory and distribution process is the Sisters of Mercy Health System. The St. Louis based Mercy Health System created a new supply chain division called Resource Optimization and Innovation (ROi) to establish the supply chain as an area of value for the business. ROi has simplified the health care supply chain by reducing its dependence on third-party intermediaries, such as GPOs and distributors. The ROi created its own GPO, which purchases products directly from suppliers for all products, eliminating the need for third-party GPOs. The ROi also receives products directly from suppliers to its warehouse and ships them directly to its hospitals, eliminating the need for third-party distributors. The result is a new model that has more closely linked the makers and users of health care products in a way that provides greater value for the essential trading parties. ROi converted Mercy's supply chain from a cost center to revenue center. ROi currently produces revenue in excess of $153 million. ROi also produces an annual value to the Mercy hospitals of over $16 million in net benefit.

In a traditional distribution model, suppliers ship their products to distributors. At the distributor's warehouse, the products are packed into pallets and shipped to each hospital's warehouse. The hospital warehouse then receives the pallets, breaks them down into smaller quantities, and stores the products until they are needed by the hospital. Sometimes items are also ordered directly from suppliers. Figure 10.2 shows this model. In this traditional model, there is a large amount of inventory in the system. This keeps the number of deliveries relatively low, which keeps transportation and ordering costs low. But there is a high cost in both holding inventory and the significant amount of material handling required.

In the newer model used by Mercy, a centralized warehouse system replaces the distributor and the need for a hospital warehouse is greatly reduced. In this model, the suppliers ship directly to the central warehouse called the central service center (CSC). The CSC breaks down the shipments into smaller units and repackages them for use in the hospitals. The materials are then shipped directly to the hospitals, called strategic service units (SSU). The Mercy network consists of approximately ten hospitals across four states. If the hospitals are not close enough to the CSC, the materials are cross-docked in an intermediate location. Figure 10.3 illustrates this model.

In this newer model, the CSC takes full responsibility of material handling and inventory management. The CSC receives shipments from the suppliers, which are then broken down, repackaged, bar coded, and stored. The CSC receives the orders for the next day's demand through the central server every evening. These orders show up on the pick list and are picked, sorted, packed based on their destination, and shipped early in the morning. The trucks return back to the CSC at the end of the day.

The Mercy model offers many improvements over the traditional model. No third parties between the suppliers and hospitals are used, increasing efficiency and

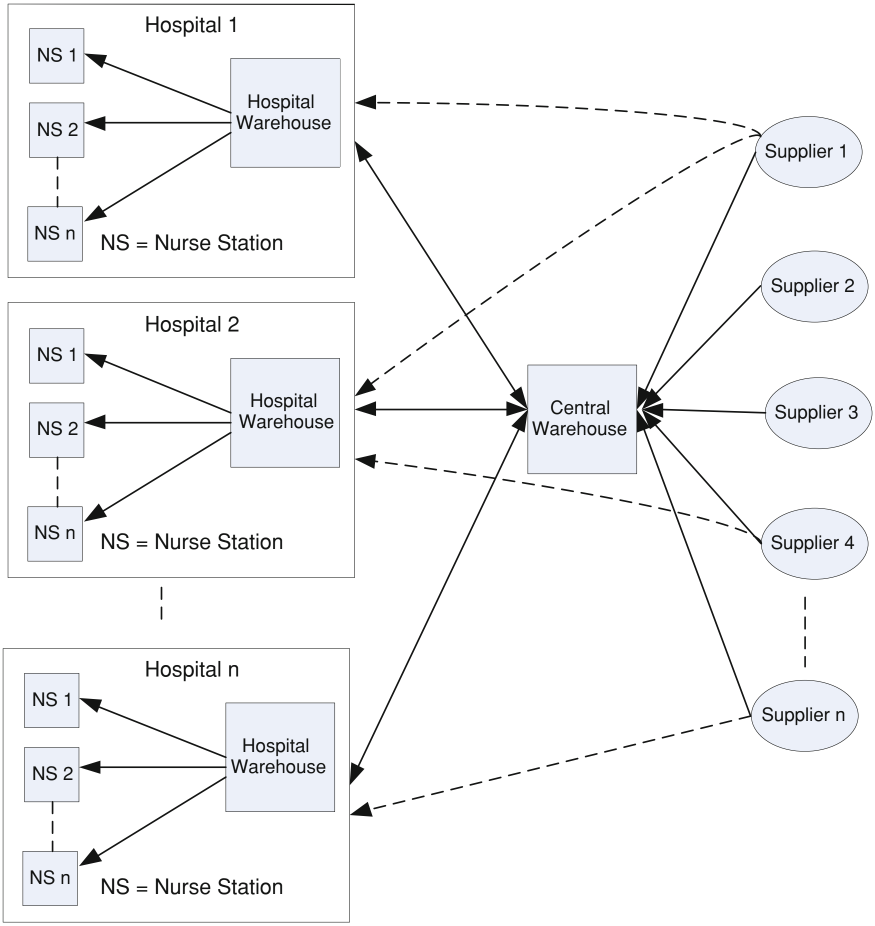

Fig. 10.2 Traditional supply chain

eliminating third-party mark-up fees. Mercy even owns its own trucking fleet, in order to further reduce cost. Inventory holding costs and material handling costs, which make up a large portion of total costs, are greatly reduced over a traditional system. The CSCs large warehouse, which stores products for all its hospitals, allows for bulk purchasing discounts to further reduce costs. In this new system, 3,000 nursing level stock-outs per week were eliminated over Mercy's old system and next day, first time, fill rates improved from 85–90% to 99% (Moore 2010). Since the CSC uses automatic repackaging equipment to repackage products into smaller, bar coded containers, the inventory management system is also greatly improved. The improved inventory management system included medicine cabinets, which automatically pick the medicines for the nurses, and a bed-side scanning system which verifies the medication by scanning the nurse's badge,

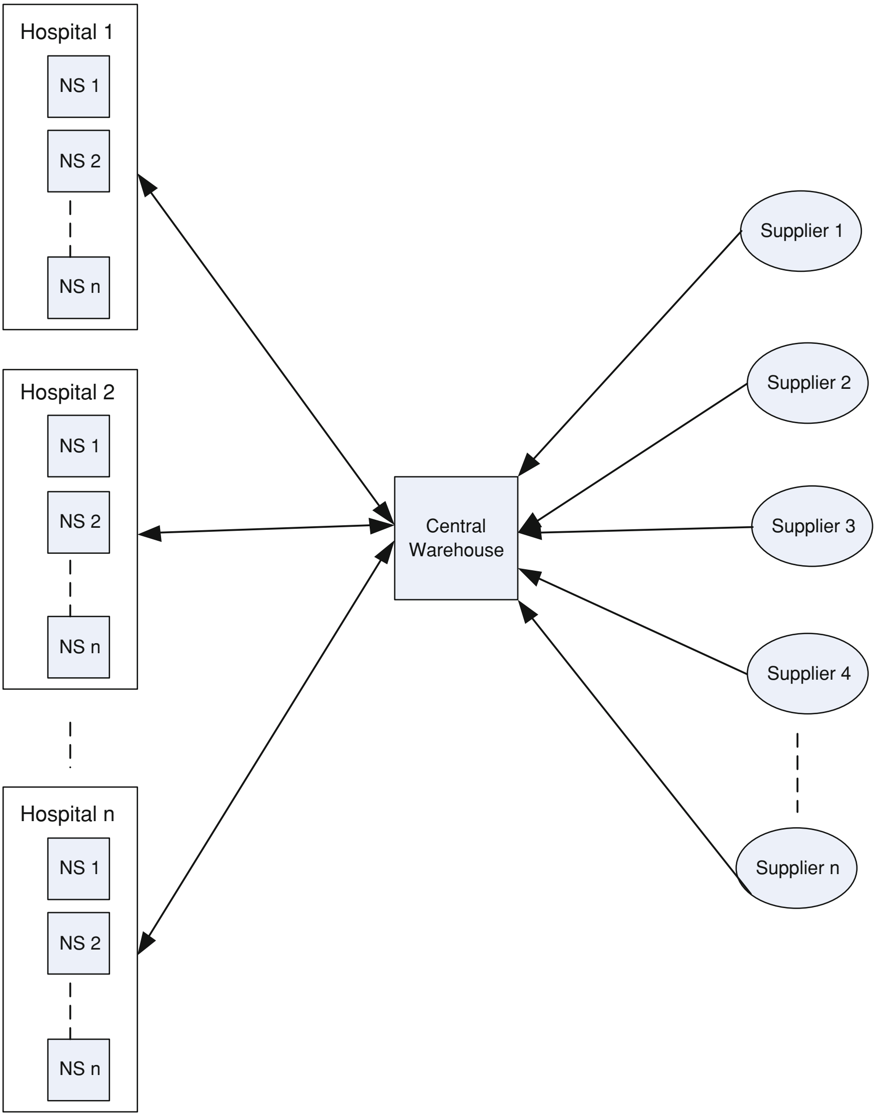

Fig. 10.3 Newer model used by Mercy

the patient's arm band, and the medication. This annually eliminated more than 178,000 medication errors such as giving medication to the wrong patient or giving the patient the wrong dosage. In addition, the CSC polls all the medicine cabinets each night and automatically downloads replenishment orders for needed medicines.

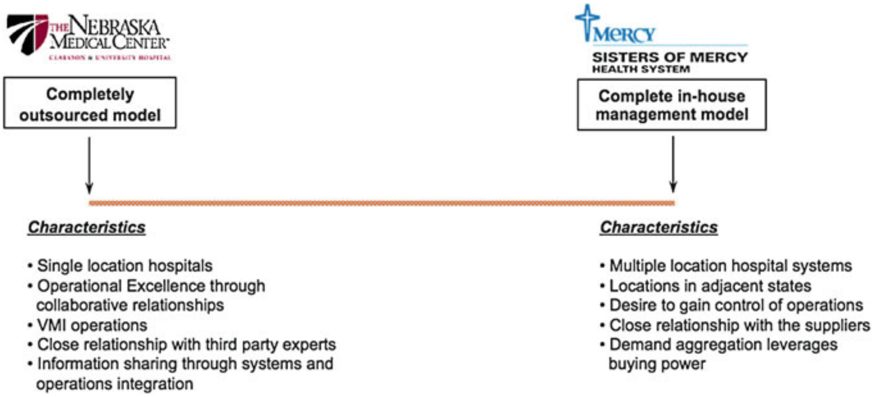

Fig. 10.4 Health care value chain spectrum

Another place that does not make use of the traditional system of GPOs and distributors is the Nebraska Medical Center (NMC). In the Nebraska model, the entire supply chain of the NMC is outsourced to a single company, Cardinal Health Inc. Cardinal has a warehouse in the same city, Omaha NE, and sends shipments to the hospital four times per week. The NMC pays Cardinal a single flat fee to manage the hospital's inventory. Unlike Mercy, the NMC is a single location hospital, which cannot easily leverage economies of scale to create a more efficient supply chain system. Also, by outsourcing its inventory management system, the NMC is able to use the comparatively small amount of capital it has to focus on patient care. Not only does the NMC not need to worry about transportation costs, material handling costs, etc., but since Cardinal owns all of the NMC inventory, the NMC does not need to tie up its capital on holding inventory.

Like Mercy, the NMC does not directly rely on the complicated network of GPOs and distributors to meet its inventory needs. Neither system relies on the use of a large warehouse at the hospital, and both minimize material handling at the hospital. Also, like Mercy, the NMC has frequent shipments to minimize the inventory needed at the hospital while keeping stock-outs low and fill rates high. Both the Mercy system and the NMC system represent two ends of the outsourcing spectrum for the health care value chain as illustrated in Fig. 10.4.

10.2.1 Healthcare Provider Supply Chains

Each health care supply chain player performs specific processes with the essential goal of assuring product availability for health care services for the patient (i.e. consumption of products at the provider while providing patient care). From the provider perspective, the supply chain processes can be classified in three main groups: external, internal, and bedside administration.

The external supply chain processes include transactions with other players upstream in the supply chain: distributors, manufacturers, and GPOs. These transactions are typically related to contract management, ordering, shipping and payment, administration fee, rebates, and sales tracing among others.

The role of a GPO in the supply chain has already been discussed; however, it is beneficial to understand information, money, and product flow in greater detail. GPOs in general negotiate contracts with manufacturers on behalf of hospitals making products available at lower prices. The contracts consist of different pricing tiers and the baseline tier is available to all GPO members (health care providers). However, based on the amount of used products, the manufacturer decides the pricing tier for GPO members. In some cases, the pricing tiers are documented via Letter of Commitment/Participation (LOC/LOP) from the provider. The contract information is shared across the supply chain to ensure accurate pricing for each provider. The distributor performs sales tracing for each provider. The sales tracing is passed to the manufacturer who estimates the administration fee based on the sales. The administration fee is sent to the GPO and the GPO sends a portion to the provider.

A typical health care provider has numerous internal clinical locations (units/floors/PAR locations) replenished by direct shipment from the supplier or replenished internally from a centralized distribution center. The direct shipments to these internal locations as well as shipments to the centralized distribution center of the provider and other models of external replenishment are achieved through three modes of purchasing. The purchase order (PO) is generated and sent to the supplier (manufacturer or distributor), the supplier processes the order and the product is delivered to the hospital receiving dock. The PO can be sent to: (1) the manufacturer; both products and invoice are received from the manufacturer (this scenario is also known as direct shipment) (2) the distributors; both products and invoice are received from the distributor (this scenario is known as indirect shipment), or (3) the distributor and in the event of stock out at distributor POs are sent to the manufacturer; products are received from the manufacturer and invoice is received from distributor (this scenario is known as drop shipment).

Internal supply chain processes are performed within the health care provider and include product and information flow from receiving the product at the dock to replenishing the internal clinical locations. The main internal supply chain processes for stocked items are warehouse/storeroom receiving, put away, storage, cart count, picking, and floor replenishment. Meanwhile, non-stocked items are received and sent directly to replenish the clinical location. The level of automation of the processes and their integration with the Materials Management Information System (MMIS) can vary. However, the handling of patient billable items is usually automated via Automatic Dispensing Cabinets (ADC) whereas non-billable items are typically stored on the open shelves in utility rooms. In the case of the use of ADCs, replenishment requisitioning and generating pick tickets are typically automated. On the other hand, open shelf items require cart count processes where the inventory is counted. In this case requisitioning is generally a

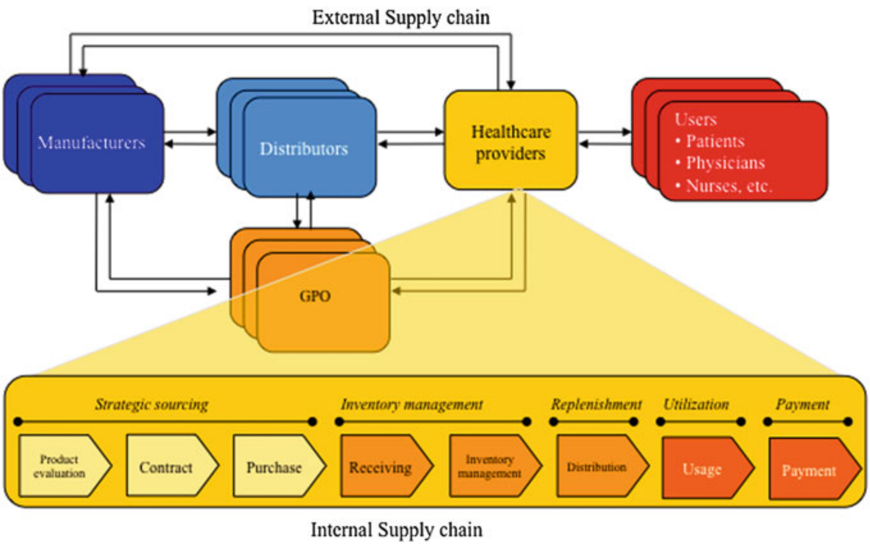

Fig. 10.5 External and internal supply chain processes (adapted from Smoker 2005)

manual process and generating pick tickets may be automated. Both the external and internal processes are depicted in Fig. 10.5.

Bedside administration processes are related to the final stage of product delivery in which the product is administered to the patient. The processes at the bedside may include verification and validation of the products to be administered, recall and outdates management, notification to patient billing, and clinical records systems. The automatic identification of product via technologies such as barcode or RFID, improves the efficiency of bedside processes.

Even with strategic reorganizations of the health care value chain and processes, supply costs have continued to increase. This has motivated the need for focused research and best practice applications for managing and reducing inventory and supply costs within the health care value chain through better inventory management.

10.3 Inventory Management in Healthcare

Inventory management encompasses all materials related activities including purchasing, transportation, logistics, production control, and inventory control. When managing inventory, there is a trade-off between the availability of the items and the cost of providing the items. The main goal of inventory management activities within health care organizations is to reduce the cost associated with the materials and supply costs of health care delivery without sacrificing service and

Table 10.1 Forms of inventory policies

Continuous Review	Periodic Review
(s, S)	(R, s, S)
(r, Q)	(R, r, Q)
	(R, S)

quality of care. This comes down to answering two fundamental questions: When to order and how much to order? No matter how complex the inventory control situation, the answers of these fundamental questions based on the state of the inventory system, as well as demand and cost factors associated with keeping and ordering inventory must be determined. These questions are addressed with the use of inventory models.

10.3.1 Overview of Inventory Modeling

Inventory modeling is predicated on describing the state of inventory over time. The state of the inventory system can be best summarized in the key state variable, *inventory position*. Inventory position reflects the inventory on hand, pending orders, and backorders. If it is shown as a formula,

Inventory position = stock on hand + pending orders minus; backorders.

Inventory can be managed by periodic or continuous review processes. In a continuous review system, a decision is made to order (or not order) a replenishment quantity whenever the value of inventory position changes. Typically, an order is placed whenever the inventory position reaches a target level (or reorders point). In a periodic-review system, the state of the inventory system (either in the form of the inventory position or inventory level) is checked at regularly scheduled times (e.g. every week). The review period is the time interval between reviews. Periodic review generally is used with slow-moving items. On the other hand, continuous review is typically utilized for fast moving items or when very inexpensive processes exist for checking the state of the inventory.

There are two common inventory ordering policies, and these policies are (r, Q) and (s, S) policies. When they are combined with periodic and continuous review, a number of fundamental inventory policies are available. These inventory policies are shown in Table 10.1.

The reorder point, order quantity (r, Q) system is a continuous review policy and the order quantity is constant. When the inventory position is on or under the reorder point (r), the order is placed for order quantity (Q). The advantage of this inventory policy is that it is quite simple and easy to understand due to its easy implementation using a two-bin system. In a two-bin system, the inventory on hand is divided into two-bins. The second bin holds r items. The first bin holds the rest of the items. Whenever a demand occurs, the required items are taken from the first bin. When there are no items left in the first bin, r has been reached, and it is time to reorder Q items. Thus, the second bin holds the safety stock, designed to hold enough inventory to last until the replenishment arrives. After the replenishment order is placed, the bins are swapped, i.e. the second bin becomes the 1st bin (where items are taken), and the original first bin becomes the second bin waiting for the replenishment of Q items. When the reorder for Q arrives, the second bin is filled with r items, and any extra are placed in the first bin. Then the process repeats. In the case of lumpy demand, an (r, NQ) policy can be used. In this case, orders for size Q are repeated until the inventory position gets above the reorder point. In addition, it can be shown theoretically that the (r, Q) policy will not have the lowest policy cost, when compared under the same assumptions as the (s, S) policy.

The reorder point, order-up-to (s, S) system uses continuous review like a (r, Q) policy. The reorder point is indicated by s, and if the inventory position decreases to or below s, the order is placed up to maximum stock level of S. Because of this, the amount ordered will be $(S - I(t))$, where $I(t)$ is the current inventory on hand at time t. Thus, the amount ordered will not be constant. A disadvantage of this system is the variable order quantity. In addition, it is more difficult to synchronize shipment quantities when the size of the order varies. However, this policy can be shown to be a theoretically optimal policy under certain conditions.

The periodic review, order-up-to-level (R, S) system is also known as a replenishment cycle policy. The control procedure is that the inventory level is checked every R units of time and an order will be placed to make the inventory level up to S. The order quantity is not constant. Due to the periodic-review feature, it is widely used in practice since it allows combining different orders in R units of time for shipment consolidation. The biggest disadvantage of this system is that it causes more stock on hand than the systems using continuous review. Within the health care industry, this system is referred to as a “par-level” system. The value of S is the par level. The idea is to bring the inventory up to par. It is by far the dominant inventory control method used to manage stock within hospitals.

The (R, s, S) system is the combination of (s, S) and (R, S) systems. The control procedure is to check inventory position every R units of time. If the inventory position is under the reorder point, the order is placed to complete the inventory level up to S. The (s, S) is the special case where $R = 0$, and (R, S) is a special case where $s = S - 1$. The disadvantage of this system is that the calculation of three parameters of the system at optimal levels is more difficult.

The (R, r, Q) system is the application of the (r, Q) system at periodic intervals. The control procedure is to check the inventory position every R time units. If the inventory position is equal to or under the reorder point, then an order for Q items is placed. This policy is often confused with the (r, Q) policy in practice. In many cases, even if the inventory position is checked continuously, the company will only place an order at the “end of the day”. Thus, their review period is in fact one day. Unfortunately, the analysis often ignores this period and assumes a continuous review policy, which can make a difference in policy setting procedures.

In these models, the reorder point answers when to order and the reorder quantity, Q, provides how much to order. The calculation of the optimal order quantity has been investigated under a number of different approaches for constant, time-varying and stochastic demand. The classic economic order quantity (EOQ) developed by F.W. Harris in 1913 can be used to calculate the order quantity, under some assumptions, such as (1) demand is constant and deterministic, (2) lead time is zero, (3) no shortage is allowed, and (4) constant unit cost and it does not depend on the replenishment quantity. The EOQ is the optimal order quantity that minimizes the total inventory cost including holding and ordering cost. Even when the assumptions for the EOQ are not readily met it is used as an approximation for the optimal amount to order. The reorder point represents the safety stock necessary to cover the demand that might occur during a lead time. If the inventory policy with periodic review is used, the lead time and review period are considered together to set up the reorder point. If continuous review is used, only the lead needs to be considered. Different techniques are considered to determine the reorder point when demand is stochastic. First, the reorder point can be calculated by modeling demand using a stochastic model. Customer demand can be characterized by two components: (1) the time between demands, and (2) the amount of the demand. The amount of demand can be modeled with a discrete random variable. The time between demand occurrences is often modeled with a renewal process governed by a continuous random variable. This can be used to approximate the demand during lead-time distribution. After deciding the lead-time demand distribution, the distribution function will be used to define a reorder point that achieves a desired level of service or minimizes total cost.

Inventory management is a challenging topic in supply chains with thousands of items even though all items are located in the same echelon. The challenges of managing inventory are much bigger when items are stored in distinct echelons, such as the CSC and hospitals within the Mercy network. The typical multi-echelon network includes suppliers, regional distribution centers, distribution centers, and hospitals, etc. When an item is moving through more than one echelon before reaching the end users, a "multi-echelon" inventory system can be conceptualized. It is difficult to determine the reorder point including safety stock within a multi-echelon structure because of the interactions between the levels. Two additional questions need to be answered: how much total safety stock is needed and how to keep the stock in the different echelons.

The Clark–Scarf model is one of the best-known techniques for determining the safety stock within the multi-echelon inventory system (Clark and Scarf 1960). The technique is based on decomposition. First, the most downstream echelons meet customer demand. Shortage at the next echelon leads to stochastic delay having an additional cost. This additional cost affects the process of determining the optimal policy for the next upstream installation. For stochastic multi-echelon inventory systems, the seminal paper by Sherbrooke (1968) presents a model for determining the optimal stock levels at the bases (warehouse) and the depots (hospitals) in order to minimize the total number of outstanding backorders at the hospital level for a given amount of investment. Deuermeyer and Schwarz developed analytical models to approximate the service level of multi-echelon supply chain network by assuming (r, Q) policies with stationary Poisson demand. The model was applied to a system consisting of one warehouse that supplies *N* retailers to obtain the expected service level including fill rate and backorders.

While it is beyond the scope of this chapter to fully describe the methods of multi-echelon inventory systems, a key insight for health care supply chains is the impact of the pooling effect. The pooling effect shows up in multi-echelon inventory systems as more units of inventory are moved up to a supporting echelon, allowing less units of inventory to be held locally. This can reduce the total amount of inventory within the system while still maintaining the necessary service levels. The pooling effect is a key factor that enables the reorganized supply chain used by Mercy to be able to reduce supply chain costs.

The following section overviews some of the latest research trends in the application of advanced inventory modeling methods within medical supply contexts.

10.3.2 A Review of Inventory Modeling in Medical Supply Contexts

Enormous pressure has been brought on the health care industry to reduce inventory investment and labor costs. Many studies have been conducted to start to improve health care costs as well as external and internal customer satisfaction. Even with the awareness to improve the health care supply chain and the studies addressing inventory management, inventory management in health care is still an active and extremely large topic. In its traditional form, health care supply chains have not paid adequate attention to inventory management. See also Kelle et al. (2009).

The purpose of this section is to provide an overview of recent research into inventory modeling within health care supply chains in order to raise the awareness of this important topic. Many of the papers discussed in this section provide general techniques for reducing cost, while others go into more depth by discussing one or two specific techniques. The review proceeds more or less within a chronological framework within each section. The main ideas discussed in this section will focus on reducing inventories, better inventory management practices, and making health care supply chains more demand driven.

Multi-Item Single Location Inventory Applications

Although there are many studies of single-echelon applications for industrial companies, the research in this area within health care area is limited. VanderLinde provides a discussion of the implementation of a computerized ABC/EOQ inventory model in a 146 bed nonprofit community hospital with the goal of maximizing inventory performance involving turnover, month-end inventory cost, and inventory cost per patient, as well as a number of other measures. The results from ABC/EOQ inventory model were compared to the current situation within the hospital, and the improvements noted, such as turnover increasing from 3–4 annual turns to 9–27 annual turns. In addition, inventory cost was reduced by 28.4%.

The theme of applying inventory models to items within hospitals occurs in a variety of papers. For example, Satir and Cengiz provide a discussion of inventory control within a university health center for 47 different medicines by a stochastic, periodic-review model with a stock-out objective and budgetary constraints. Also, Prashant presents a systematic approach for optimization of inventory functions. This study provides solutions for some issues in the inventory management, which include the amount of excess and slow movement inventory, stock-out rate, and par level to manage inventory. For excess and no movement inventory, the inventory can be classified based on the age of inventory as a report to monitor the inventory level continuously and to take action proactively. For eliminating and reducing stock-outs, the author concludes that communication is the key practice. Strong communication between material management and the hospital staff enable better on-time delivery. In this application, the safety stock level and the number of stock-out situations decreased. PAR-level evaluation caused inventory reduction at the nursing units. The primary methods of this approach were based on a data driven analysis and decision making as a group.

Dellaert and van de Poel extended a new and simple inventory rule from EOQ to support a purchasing department at a university hospital in the Netherlands. This new inventory rule is called (R, s, c, S) model, where R is the periodic-review period, S is the maximum stock level, s is the minimum stock level, and c is the can-order level. After the (R, s, c, S) model is defined, some theoretical and more sophisticated alternatives are presented to compare the total cost of each model. The (R, s, c, S) model provided many beneficial results, such as reduced holding cost and total cost, increased service level, and decreased total number of orders to suppliers.

Woosley and Wiley-Patton examined a local hospital's policies, applied two quantitative inventory models for the inventory control process, and offered a decision support tool for hospital managers to make the inventory process easy-manageable. Three quantitative models were developed, but Model 1 was not used due to its complexity. Model 1 was a general multi-product (s, S) model with space constraints. The purpose of the model was to minimize the total cost including holding, ordering, and shortage costs with space constraint. Model 2 was designed to determine an optimal allocation of supplies based on ordering and holding costs by minimizing total cost with fill rate and space constraints. The last model was based on determining the optimal allocation based on ordering cost with the objective of minimizing the total number of expected orders with fill rate and space constraints. This research showed a 70–80 % cost reduction when models 2 and 3 are implemented. Even though the research results are outstanding, this does not include the reaction of the health care stakeholders for this new decision support system. Therefore, the health care stakeholder's reaction toward this decision support system is an unanswered question, and it can be a future research topic. This study is a good illustration of single-echelon inventory management by using quantitative models.

Just-In-Time and Stockless Applications

Kim et al. (1993) compare the conventional, just-in-time (JIT), and stockless material management systems in the health care industry. The authors sent survey questionnaires to randomly selected health care institutions from the database of the Health Care Material Management Society and collected data from the 66 responses. The authors then used statistical methods to compare conventional, JIT, and stockless systems based on 32 problem variables given in the questionnaire. The results of a stockless system compared to a conventional system included both psychological benefits, such as reduced employee resistance to major changes and management more willing to delegate tasks, and inventory related benefits such as fewer problems managing large inventories and better responsiveness to demand fluctuations. The study also found that there was not a significant difference between JIT and stockless systems, and that implementing either a JIT or a stockless system in a hospital that currently operates a conventional material management system would significantly improve the effectiveness of the operation.

Egbelu et al. (1998) proposed a cost model for different hospital material management systems and compared the costs via a case study using data from a hospital that operates currently under the conventional mode of material management with large bulk deliveries. An analysis was performed to determine if it would be profitable for the hospital to operate under JIT or Stockless systems. Three scenarios were analyzed in the study. First, the hospital operates in the JIT mode with less inventory at the central stores and frequent bulk deliveries. Second, the hospital operates in the stockless mode where the distributor delivers items in units of "eaches" to the receiving dock and the hospital does its own internal material transfer from the receiving dock to nurses' stations. Third, the distributor delivers in eaches directly to the nurses' stations under the stockless mode. The authors concluded that there are various factors that need to be taken into account before deciding on the system. Parameters such as the inventory levels at the nurses' stations and central stores, the number of full time equivalent workers, the amount of warehouse space, and the potential service charges from distributors that affect the total annual cost. This model is a good starting point for analyzing and comparing various material management systems in the health care industry based on total annual cost. A simulation study of various systems, concentrating on the inventory analysis and distribution, with the use of the cost model could give better insight into the implications of changing a hospital's material management system.

Rivard-Royer et al. (2002) discuss the adoption of a hybrid version of the stockless replenishment system, combining the stockless method with the conventional approach to patient care unit replenishment. The medical supply distributor supplied high-volume products for the patient care unit in case quantities, leaving the central stores to break down bulk purchases of low volume products into point-of-use format. The study revealed marginal benefits from the hybrid method for both the institution and the distributor. The experiment conducted at a health care institution in the province of Quebec (Canada), focused on a single patient care unit. The result indicated that the total cost of replenishment was reduced by a negligible amount. Although the results for this form of hybrid stockless system have not been conclusive, other alternatives may be examined. The study opens the door for wider discussions and experiments in the future for reducing total costs via examination of stocking policy and inventory location.

Outsourcing and Multi-Echelon Applications

Kamani (2004) talks about the issues involved in upgrading the inventory management system of a hospital in the context of outsourcing to a third party. Some of the important points the author makes include eliminating poor quality data about products and vendors, analyzing spending patterns of the hospital, using a good classification system of the medical supplies, and enhancing product entries with relevant data, such as whether or not gloves are latex or latex-free. In a similar study, Rosser (2006) describes the improvements to cost savings and patient care in hospitals in London, Ontario brought about by the 1997 creation of the Health Care Materials Management Services (HMMS). The HMMS consolidated a number of different departments of the area hospitals and standardized the supplies, procedures, and policies of those hospitals.

Nicholson et al. (2004) developed sophisticated multi-echelon optimization models to study and analyze the impact of outsourcing of inventory management decisions to third-party provider that offers inventory management in health care. They compare the inventory costs and service levels of non-critical inventory items of an in-house three-echelon distribution network to an outsourced two-echelon distribution network. They try to evaluate the cost savings associated with switching from an in-house network to the outsourced network. In addition, they compare the service levels for each department within the hospital under the two scenarios. They studied a hospital network in Florida with seven hospitals and approximately 20 patient departments within each hospital. They conclude that the outsourced network dominates the in-house network in terms of total cost. The service levels of both the systems were comparable.

Logistics Coordination and Scheduling

Lapierre and Ruiz (2007) present an approach for improving hospital logistics by focusing on scheduling decisions and a supply chain approach rather than the more common multi-echelon inventory management. In an inventory management model, products for a care unit are ordered from central storage based on a certain minimum stock level known as the reorder point. The central storage also makes orders from suppliers based on reorder points. However, this model does not take into account the reality that orders for items are placed together at set times. Secondly, this model may not take into account the time-expensive "hot-picks," or unscheduled picks from stock-outs at care units, which may occur as a result of this model. And thirdly, this model may not take into account the limited amount of storage capacity in both the care units and the central storage.

In a supply chain approach, all the operations involving a significant amount of labor associated with ordering are taken into account, such as the replenishment decisions, order picking, delivery of products, purchasing activities, and handling of supplies at the reception docks. Additionally, in this approach some items may be delivered directly to care units instead of the central storage. The authors use the supply chain approach in their two models, both of which focus on making decisions for the optimal time to buy and deliver products to each care unit and also decisions for employee management such as work shift and task assignments. The first model seeks primarily to minimize inventory costs, and the second model seeks primarily to balance workload among the days of the week. Since both models were complex, heuristic methods were used to solve the models. Eventually, a version of the second model was used and applied to the satisfaction of a hospital in Montreal, Canada.

The drawbacks of this approach concern the fact that models used in this paper are much more complex than traditional inventory models. Furthermore, optimal solutions could not be found due to the use of heuristics. However, given the improvements in cost, labor, organization, and stock control, this type of research, which focuses on scheduling, may warrant further study.

Vries (2010) focused on the reshaping a hospital inventory system of medicines by conducting a case study that had three phases. In the first phase, the inventory system was analyzed to address the main strengths and weakness of inventory systems. In the second phase of the project, further discussion was made to redesign the inventory system. In the third phase, the new inventory system was partly implemented. The objective of the project was to analyze and improve inventory systems containing pharmaceuticals at the provider level. In the study, a qualitative exploratory case study was conducted since the case study approach allowed an in depth analysis and allowed detailed data to be gathered for the analysis process. Even though all problems were not solved, many improvements were seen in the hospital. These improvements included: partially fixing software problems, better management of rush-orders, reorganizing the communication channel, and changing the organizational structure.

Demand Management and Forecasting

O'Neill et al. (2001) examines the effect of implementing a Materials Requirement Planning (MRP) system in a health care setting. A two-part study was conducted at The University of Iowa Hospitals and Clinics (UIHC) concerning the inventory of green linens. Green linens are linens used for surgery, which for each use require laundering, material processing, and, for many items, sterilization. In the old system, more than ten thousand pounds of laundry were processed during five and a half days per week. A number of factors made managing this system difficult. Very high service levels were required, and shortages caused delays, extra cost, and unnecessary stress. Surgical schedules for the next day were not posted until 6 pm, meaning short lead times. Most green linens had to be sterilized using a 12-h process, and sterilized items had a shelf life of only 14 days. Some items were issued both separately in pre-made packs of several items. Demand was cyclical, i.e. different for each day, and small variations for each day caused large variations for laundry, material processing, and sterilization. Finally, the system was overly complicated and resulted in some days of overflowing inventory and other days of no inventory at all.

In the first part of the study, the hospital's green linen use was monitored over an 8 week period, which was then used to estimate demand. As expected, average demand for each day was different. The study proposed two alternatives to fix the system. The first alternative proposed processing only the amount of green linens needed for the day, resulting in a variable amount of labor for each day. The second alternative proposed processing a constant amount of green linens, holding stock for the days when demand was less than that amount, and using up stock when demand was greater than that amount. Both alternatives included safety stock. Ultimately, the second alternative was chosen due to lower cost of holding stock compared to paying workers overtime in every department along the supply chain.

For the new production schedule to work, the hospital needed the cycle time and total inventory of green linens. Total inventory was especially difficult to find due to losses from pilferage and the discarding of worn out linens. In the second part of the study, 49 green linen pillowcases were dyed blue and affixed with a bar code. The pillowcases were tracked as they left laundry and material processing. Average cycle time was found, and total inventory and seepage levels were estimated using statistical methods. As a result of this study, many improvements were made. An analysis of the system revealed redundant folding and inspections across several departments. A streamlined system resulted in 5 h per day of saved labor. Safety stock was reduced by 20%, inventory within packs were reduced by 40%, and five different pack types were eliminated. Additionally, an improved system resulted in fewer incidents of stock-outs and better communication among the departments.

In Apras (Applying inventory control practices within the Sisters of Mercy Health Care supply chain, unpublished MS Thesis, University of Arkansas, 2011) a systematic application of inventory management practices within the Sisters of Mercy Health System was performed. The methods take into account the practical realities of applying inventory management practices within health care settings and are demonstrated through a case study. The case study consists of three focus areas: (1) understanding and depicting the demand and inventory control system for bulk and unit dose items, (2) examining a second location, for a comparative

Table 10.2 Number of items and percentage of items in each ABC category based on usage value, demand, and unit cost

	Usage Value		Demand		Unit Cost	
	No. of items	percentage of items	No. of items	percentage of items	No. of items	percentage of items
A	160	7	267	12	238	11
B	918	42	833	38	1036	48
C	1091	50	1069	49	895	41
Total	2,169		2,169		2,169	

analysis, and (3) understanding the multi-echelon nature of the problem and the effect of inventory pooling within the supply chain.

An ABC inventory analysis was performed to select the items that would most likely have an impact in reducing costs. ABC inventory analysis is a grouping technique by the demand, average unit cost and usage value. Typically, 20 % of the items can cover approximately 80 % of the usage value (dollar value). There are three priority rankings to show importance of the category. Category A is very important, category B is important, and category C is less important Silver et al. (1998). A Pareto ABC inventory analysis was chosen based on annual usage value because the usage value gives the same importance for both demand and unit cost.

Table 10.2 tabulates the results for a selected sample of the inventory items. The majority of items are in the B and C categories for demand and unit cost. This is typical of most inventory systems but causes challenges in hospital environment because of the need to carry a wide variety of item types. This is the so-called stock keeping unit (SKU) proliferation problem. Rossetti and Liu (2009) examine this issue within the context of a health care supply chain via simulation. The SKU proliferation problem is often caused by physician preference items (PPI), in which the physician can decide which items to stock simply by choice. Not many industries allow their customers (i.e. physicians) to decide what to have on the shelves! This often creates items that have very low usage levels because they are tied to a single physician. This creates very difficult issues in forecasting demand for these items.

The literature refers to the "hard to forecast" demand scenarios as intermittent demand, lumpy demand, erratic demand, sporadic demand, and slow-moving demand. Silver et al. (1998) proposed a definition for intermittent demand as "*infrequent in the sense that the average time between consecutive transactions is considerably larger than the unit time period, the latter being the interval of forecast updating*." Syntetos et al. (2005) in their research on intermittent demand forecasting techniques, proposed a demand categorization scheme with recommendations for an appropriate cut-off value for squared coefficient of variation and mean interval between non-zero demands. Based on the mean inter-demand interval ($p = 1.32$) and the squared coefficient of the variation of the demand size ($CV^2 = 0.49$) Table 10.3 tabulates the classification for the items analyzed in

Table 10.3 Number of items in each demand class from Apras (Applying inventory control practices within the Sisters of Mercy Health Care supply chain, unpublished MS Thesis, University of Arkansas, 2011)

Demand Class	No of Items	Percentage of Items
Erratic	108	4.97
Intermittent	1,197	55.19
Lumpy	657	30.29
Smooth	207	9.54
Total	2169	

Apras (Applying inventory control practices within the Sisters of Mercy Health Care supply chain, unpublished MS Thesis, University of Arkansas, 2011). It is clear that within this health care setting the vast majority of items are "hard to forecast".

In Apras (Applying inventory control practices within the Sisters of Mercy Health Care supply chain, unpublished MS Thesis, University of Arkansas, 2011) a subset of the items were subjected to individual forecasting techniques including autoregressive moving average (ARMA), autoregressive (AR), moving average (MA), cumulative average (CA), simple exponential smoothing (SES), damped trend linear exponential smoothing (DTLES), average demand (AD), linear Holt exponential smoothing (LHES), and naïve forecasting. In naïve forecasting, the forecasted value is simply the previously observed value. The following steps were used to determine the most appropriate forecasting model: (1) plot the data, (2) interpret the results based on the information from the data plotted, (3) define demand patterns, such as trend, seasonality, and (4) fit the forecasting model while comparing some measures of accuracy, such as the measures of forecasting errors (MAE, MAPE), AIC, BIC, and R-Square, etc. MAE is the average mean absolute errors between actual and predicted demand. MAPE is mean absolute percentage errors between actual and predicted demand. AIC and BIC are measures of the goodness of fit of forecasting models. Smaller values of these criteria indicate better fit. Table 10.4 illustrates the result of this process for 70 items analyzed within Apras (Applying inventory control practices within the Sisters of Mercy Health Care supply chain, unpublished MS Thesis, University of Arkansas, 2011). Unfortunately, this sort of analysis is hardly ever done within a health care setting because of the lack of data, the lack of analysis tools, and the lack of expertise within materials management departments.

Callahan et al. (2004) discusses the importance of demand forecasting within a health care setting, including the issues involved in making good demand forecasts and the benefits of good demand forecasts for health care. The ideal health care supply chain, according to the authors, is one that automatically performs a number of operations after a medical procedure has been scheduled. These include choosing standardized products for the patient, assessing the need for backup supplies, picking necessary supplies, grouping supplies that need to be together, verifying the latest price of items based on the latest contract price, determining if

Table 10.4 Summary of selected forecasting models from Apras (Applying inventory control practices within the Sisters of Mercy Health Care supply chain, unpublished MS Thesis, University of Arkansas, 2011)

Model	Frequency	Percentage
ARMA	28	40.0
AR	16	22.9
MA	9	12.9
CA	8	11.4
SES	4	5.7
DTLES	2	2.9
AD	1	1.4
LHES	1	1.4
Naïve	1	1.4
Grand Total	70	

any products need replenishment, placing orders for those products, and recording data for predicting future demand.

An effective demand forecast, according to the authors, first requires accurate means of tracking items, such point-of-entry data entry and RFID tags. This chapter examines the use of technology in point-of-use capture in Sect. 10.5. Next, demand can be forecasted based on hospital scheduling, seasonal variation, and the preferences of the physicians. The demand forecast can then be further refined with data about the patients, such as age, weight, gender, medical conditions, and allergies. Any effective demand forecast should include all the phases of patient care, including pre-op, procedural, and recovery phases.

There are many benefits of an improved demand forecasts and a supply chain, which is responsive to these forecasts. These include lower costs for case preparation, improved fill rates and service levels, and reduced inventory. Since many products have a high risk of obsolescence, expiration, damage, or recall, keeping low inventory levels can greatly reduce cost. Additionally, good demand forecasts also help the manufacturers and distributors of the hospital or clinic in supplying the necessary products.

The health care supply chain has a number of unique aspects because of the types of structures and how they interact with patient care. The following section highlights one such component: the blood supply.

10.4 Blood Supply Management

A critical component of any health care system is its supply of blood. Having the correct type of blood, when and where it is needed is necessary to the success of a health care system. The 2007 National Blood Collection and Utilization Survey (Whitaker et al.2007) reported that 15,688,000 Whole Blood (WB) and Red Blood Cell (RBC) units were collected in the United States in 2006. This exceeded the number of transfusions by 7.8%. Despite this excess of over 1.2 Million units of blood, 6.89% of the hospitals surveyed reported cancellations of elective surgeries for one of more days because of blood shortages. The median number of days delayed for the 412 patients affected was 3.0 days. One of the contributors to this shortage is the number of units that become outdated due to their lack of use before their expiration date. For 2006, Whitaker et al. (2007) reported that 1,276,000 (4.6%) units of whole blood and all components were disposed of by blood centers and hospitals due to expiration (35 days). This perishable life saving commodity has also increased in unit cost during this period. Whitaker et al. (2007) reported that the average cost of a unit of platelets from whole blood ($84.25) increased by 32% from 2004 to 2006. Similarly the cost of red blood cells ($213.94) increased by 6.4% during the same period. Thus, as evidenced above, the efficient design and operation of the blood supply chain is a necessary component to reducing costs and delivering timely health care services.

The blood supply chain problem has attracted the attention of many operations researchers. Nahmias (1982) and Prastacos (1984) provide comprehensive reviews of perishable inventory and blood inventory management respectively, Pierskalla (2005) states that research on the management of the blood supply chain started in the 1960s, peaked in early 1980s and dropped of significantly since then. He hypothesizes that the large drop off was due to a reduction in federal funding in the area, the difficulty of the remaining problems in the area, and the shift in emphasis to blood supply safety largely due to the advent of human immunodeficiency virus (HIV) and a suspected cancer causing agent, the human T-cell lymphotropic virus (HTVL) (Jagannathan and Sen 1991).

What makes this problem interesting and challenging from an operations research perspective? Pierskalla (2005) identifies several factors that make this an interesting and challenging problem. First, whole blood can be processed into many different components (for example, plasma, platelets, cryoprecipitate, and granulocytes), each of which is perishable but at differing rates. Second, the supply of whole blood is a random variable. This is largely a function of the effort put forth by regional and community blood centers to recruit donors. In 2006, Whitaker et al. (2007) noted that community donations accounted for 87.5% of collections, while directed donations only accounted for 0.4%. Blood centers accounted for 95.3% of the donations while hospitals accounted for only 4.7% of all donations. Once collected, the blood needs to be screened for a variety of diseases and bad units eliminated which introduces more variability into the supply. Third, just as the supply of whole blood is a random variable, so is the demand for whole blood and its components. Pierskalla (2005) states that both the frequency and size of the demand for whole blood and its components need to be modeled as random variables. Finally, Pierskalla (2005) points out that the entire blood supply system can be modeled as a complex system, and as such it needs analysis at the tactical, operational and strategic level. Policies and decisions at each of these levels need to be designed such that shortages are minimized while at the same time efforts are made to reduce costs and waste of this valuable perishable resource.

The next couple of sections briefly summarize some of the key work in this area that has recently appeared in the literature. The goal is to familiarize readers with the type of work currently being performed in this area. Readers are encouraged to refer to the specific articles for modeling and analysis details.

10.4.1 The Blood Supply Chain Management Problem

Pierskalla (2005) provides an excellent strategic overview of the blood supply chain and of all of its components. The basic supply chain begins with the collection of the unit of blood from a donor at a collection center; from there the blood is sent to a regional blood center (RBC) or community blood center (CBC) for processing. Once at the centers, the blood gets processed into different blood products such as red blood cells, platelets, fresh frozen plasma, and other possible products. This is an important step because each different product has a different shelf life. The blood then gets tested for diseases, and gets thrown out if it fails any of the tests. After passing the tests, it gets stored and is ready for delivery. The blood often gets delivered in the first in, first out sequence for either routine deliveries, or emergency deliveries. The centers send the appropriate components of the original donated unit to the local hospitals based upon their demand. Once in the hospital, the blood goes into another type of storage. In the hospital, the blood is cross-matched before transfusion to determine the compatibility between the donor and recipient's blood. Another part of the transfusion process is mismatching. Mismatching refers to the fact that one type of blood is compatible with another type of blood. This is normally discouraged because it increases the risk to the patient.

In his book chapter, Pierskalla (2005) develops a number of operational procedures for blood bank management. These procedures are designed to help answer some strategic issues such as what blood bank functions should be performed, how many community blood banks one should have in a region, and how does one coordinate the supply and demand of whole blood and its products. Pierskalla (2005) provides models and analysis that shows that economies of scale exist for many of the blood bank functions. He develops algorithms that assist in allocating donor sites (including hospitals) to community blood banks and in turn to regional blood banks. Pierskalla (2005) uses simulation and time series models to help forecast average daily demand and determine appropriate inventory decisions at all levels (hospital blood banks, community blood banks, and regional blood banks). He provides a broad set of tools and techniques capable of assisting blood bank managers with many of their key strategic and operational management decisions. For details on the specific models and results see Pierskalla (2005).

10.4.2 Two-Stage Perishable Inventory Model for the Blood Supply Chain

Goh et al. (1993) present a two-stage perishable inventory system model of the blood supply chain. In their model, fresh items will be kept in the first stage and after a certain amount of days, will be transferred to the second stage. With blood, fresh blood is needed for certain types of surgeries, so blood for these surgeries would be taken from the first stage of inventory. Blood that's ten days or older will be stored in the second stage until it is used or becomes outdated. Goh et al. (1993) explore two different first in, first out policies. The first one is a restricted policy. This means that when there are requests for old blood, it can only be fulfilled from the second stage. For the second policy, they use an unrestricted policy. This means that requests for old blood can be filled from the first stage, but only when the second stage is empty. Goh et al. (1993) measure the number of shortages and the amount of outdated blood under each policy.

Three different approximations were used to analyze both of the policies. First, Goh et al. (1993) used a one-moment approximation where all of the processes were assumed to be Poisson. The restricted policy used the moment equations from the model to evaluate performance, and approximate the performance in the second stage. The unrestricted policy had to have the second stage approximated also as Poisson, along with the first stage's rate of requests. Goh et al. (1993) assumed that unsatisfied demand from the second stage was also an independent Poisson process. Next, a two-moment approximation was used. This method takes into account the different attempts, and the information associated with the number of outdates and shortages for the processes. The last approximation used by Goh et al. (1993) was the two-configuration approximation method. The first configuration assumes that there's no inventory in the second stage. This is a single-stage system and a Poisson process is used to approximate this stage. The second configuration gets used when a blood unit exceeds its expiration date in the first stage. When the second configuration get's used it is assumed that the second stage has inventory, and no shortages occur. A simulation model was used to analyze the various models. After looking at the results, it was determined that the two-moment model should be used for the restricted policy. To approximate the performance of the unrestricted policy, the two-configuration method was shown to produce the best results.

10.4.3 Delivery Strategies for the Blood Product Supplies

Hemmelmayr et al. (2009) explore cost effective ways for delivering blood for the Australian Red Cross. In this chapter, they move from the current vendee-managed inventory, first come first serve fixed route approach, to a more flexible vendor-managed inventory approach. Hemmelmayr et al. (2009) developed two different strategies for the proposed vendor-managed inventory system. The first one retains the concept of regions and the use of fixed routes while the second one combines more flexible routing decisions with a focus on delivery regularity. To figure out which one was better, they took three different solution approaches.

The first approach taken by Hemmelmayr et al. (2009) was a basic heuristic approach. Delivery routes were constructed each day based on a hospitals current inventory levels. When a hospital received a delivery, the inventory level is filled to capacity. This policy does not specifically take into account inventory holding costs or vehicle capacities. To reduce spoiling, the inventory capacity is adjusted based on previous experience with waste of blood products at the specific hospital. The second approach used integer programing. With this method, Hemmelmayr et al. (2009) still used the fixed route, but they included short cutting by skipping the hospitals that did not require a delivery. This allowed for a reduction in delivery cost, but had to be executed carefully to make sure all hospitals have a sufficient blood supply. The integer programing model was constructed based on the demand patterns to determine the actual routes over a 14-day period. The third approach used by Hemmelmayr et al. (2009) was a variable neighborhood search approach. They selected the variable neighborhood search approach by viewing the problem as a periodic vehicle routing problem with tour length constraints. In this approach, Hemmelmayr et al. (2009) select a visit combination for each hospital and solve the implied daily vehicle routing problems. The algorithm was developed to improve the flexibility in routing decisions while still achieving delivery regularity. They did this by exploring multiple neighborhoods when delivering, instead of just one when they were routing. Although these approaches resulted in a more sophisticated delivery system, they did significantly reduced delivery costs. Hemmelmayr et al. (2009) found that their approaches achieved a cost savings of about 30%.

10.4.4 Using Simulation to Improve the Blood Supply Chain

In this study, Katsaliaka and Brailsford (2007) analyze the blood supply chain for the UK National Health Service and use a simulation model to help improve it. Katsaliaka and Brailsford (2007) attempt to address some issues that have been overlooked or oversimplified in previous models of the blood supply chain. They model the entire supply chain from donor to patient including mismatching, the various types of blood products, and the shelf life for each of the unique products (for example, 35 days for adult red blood cells, 14 days for irradiated red blood cells, 5 days for platelets). The model is based on discrete event simulation. The authors use a Poisson distribution to model the arrival process for donated blood and a time dependent Poisson process to model the different types of blood requests from physicians. The size of the request is modeled using a LogNormal distribution. The quality of the system's performance was measured using the number of outdates for blood products by group in the hospital only, the number of shortages, the number of mismatches, and the number and percentage of routine/emergency deliveries to the hospital. Using the simulation model, Katsaliaka and Brailsford (2007) show that system performance can be improved by making minor adjustments to the supply chain. Examples of minor adjustments include decreasing the holding stock to four days, managing the routine deliveries better and allowing two deliveries rather than one each week, reducing the crossmatch release period, getting more accurate orders from doctors, applying multiple-crossmatching techniques, and adhering to the rules of first in, first out so less units go bad because they exceeded their expiration period.

10.4.5 Ongoing Research Opportunities

Despite all of the previous work, there still remain many open problems in this area and plenty of opportunities exist for researchers in this interesting area. Recently, Nagurney et al. (2011) presented a generalized network optimization model of the blood supply chain. Their multi-criteria model captures discarding costs associated with waste and disposal of blood products as well as costs associated with shortages. Their model accounts for the uncertainty of demand and quantifies the supply-side risk associated with procurement of blood products. Pierskalla (2005) points out that Prastacos (1984) identified several research problems that still remain open today. These open research opportunities include optimal component processing policies, distribution scheduling for multiple products, pricing of blood products and inter-regional cooperation, and finally an analysis of donor scheduling algorithms. These are but a few examples of research opportunities in this area. Pierskalla (2005) points out that since the use of blood products account for about 1% of total hospital costs in the United States, any efficiency derived from the blood supply chain may yield significant cost savings.

A critical issue in blood supply management (as well as for other classes of inventory) is the appropriate tracking of usage and coordinating the purchase/billing cycle. The use of advance information systems is becoming a key enabler for this area and is discussed in the following section.

10.5 Important Technology Advances for Medical Supply Management

The health care industry has been slower than other industries in leveraging the immense opportunities for using technologies, especially in the medical supply chain. However, there has been progress such that health care delivery is moving in the direction of becoming a series of technology-assisted activities driven by the improved productivity, cost savings and improved patient safety associated with technological innovations. The majority of health care providers transact with their main distributor or manufacturers using an Electronic Data Interchange (EDI) platform. The use of fax or e-mail is also common. The MMIS supports inventory management and is usually integrated with financial applications such as patient billing. Automatic identification and data capture technologies like barcode and RFID is in slow and growing use. Once these technologies are integrated with the MMIS there will be significant enhancement of supply chain process automation. Once the product reaches the hospital floor, it is available for patient use; the integration of product related information with patient billing and clinical applications such as Electronic Health Records (EHR) is also common. The following sections briefly discuss these technologies.

10.5.1 Electronic Data Interchange

Electronic Data Interchange (EDI) is a technology that has been used for more than twenty years in the automotive and retail industries. The EDI transactions minimize human interventions in external supply chain processes and thus ensure accuracy in product flow, especially in ordering and receiving. It is based on the concept of electronic transmission of specific information in the form of transaction sets. A typical order cycle that starts with a purchase order and ends with the payment of invoice may involve the following transaction sets: purchase order EDI 850, purchase order acknowledgment EDI 855, advanced ship notice EDI 856 and invoice EDI 810. According to a report published by HIMSS (HIMSS2010), 70% of the purchase orders generated by hospitals are sent via EDI.

10.5.2 Materials Management Information Systems and Ancillary Systems

Materials Management Information Systems (MMIS) are computer-based systems used to manage external and internal supply chain processes, which drive the product and information flows. The MMIS manages inventory related information including inventory on hand and on order, order period and quantity, corresponding PO number, product storage locations, as well as product vendor related information, which are essential to support internal supply chain processes. MMIS functionalities are integrated with financial applications, usually provided by the same vendor. Meanwhile, ancillary systems empower MMIS for complementary functionalities and include such technologies as barcode automation and Automatic Dispensing Cabinets (ADC). A current study conducted by HIGPA, CHES, GS1 US and AHRMM in 2009 (Burks 2009) reports that the MMIS market is saturated and mainly controlled by four main vendors: Lawson, McKesson, PeopleSoft, and MediTech.

10.5.3 Automatic Identification and Data Capture

Automatic identification is the broad name given to a host of technologies that are used to help systems identify assets and products and is often coupled with automatic data capture. The objective is to identify the item, capture the information related to it, and store the information electronically without manual processing and hence increasing efficiency, reducing data entry errors and freeing staff time to perform more value added functions. Some examples of automatic identification and data capture technologies are Barcode, Radio Frequency Identification (RFID), character and voice recognition systems, machine vision systems, and magnetic stripes. Prominent among them are barcode and RFID in the context of health care system. However, the level of adoption of Automatic Identification and Data Capture technologies is low at the health care provider level, as reported by a recent American Hospital Association survey. Only 16% of hospitals fully use barcode technology and 3% RFID for supply chain related activities (AHA, 2007).

10.5.4 Data Standards in Medical Supply Chain

Data standards also known as identification standards have their origin in the retail industry with the development of the Universal Product Code (UPC) in 1974. The use of identification standards in the medical supply chain was started in 1983 by the Health Industry Business Communication Council (HIBCC) and during the same time the use of barcode technology was widely promoted among hospitals. HIBCC standards were developed as specific health care standards in contrast to the Uniform Code Council (UCC) standards developed and used by several industries. Currently, medical supply chain data standards are developed and promoted by standards organizations like GS1 (formerly UCC EAN) or HIBCC.

The basic set of GS1 identification standards include Global Trade Identification Number (GTIN) for product identification, the Global Location Number (GLN) for trading partner identification, and the Global Data Synchronization Network (GDSN) that provides a synchronization mechanism for sharing accurate product information between supply chain players. HIBCC was founded in 1983 as a standards development organization for health care related issues, including medical device identification. The basic set of HIBCC standards includes Labeler Identification Code (LIC), Health Industry Number (HIN), and Health Industry Bar Code (HIBC). Parallel to industry developments the FDA has also contributed to the development of standards by setting regulations for pharmaceutical products and efforts are underway for medical products and devices.

Data standards in the medical supply chain ensure interoperability of a number of systems across the supply chain, including external and internal processes. Effective exchange of information throughout the supply chain is vital to supply chain visibility. The implementation of data standards has impacts at the process level and affects the process related accuracy measures, exception rates and staff productivity among other performance metrics. These impacts can be due to improved item and location identification, improved item and location information synchronization across the supply chain and improved item identification efficiency via automation.

In the external supply chain processes, the use of standard product and location identifiers in contract management and GPO operations streamline membership and pricing update notification processes and increases the pricing accuracy, reimbursement rebate accuracy, and administration fee accuracy. In addition, the use of identification standards in EDI transactions reduces exceptions in ordering and shipping including missed delivery or wrong delivery.

Within internal supply chain processes, increased internal supply chain visibility can be achieved through data standards streamlining inventory management processes. The data standards bring about interoperability between the MMIS system and ancillary systems. It also decreases manual checks and eliminates product re-labeling.

In bedside administration, the use of data standards drives automated authentication bedside administration and improves patient safety. Also, product identifiers for secondary information are used with outdates and recall management. The data standards enable interoperability of systems that communicates patient's health information and also improves the accuracy in patient charge capture.

10.6 Future Directions

In the report by Meyer and Meyer (2006), a number of problems and potential solutions within the health care supply chain are articulated. Three of the future research areas for the health care supply chain suggested by the report were:

- Increasing the role of the supply chain in new product development
- Forecasting and demand management
- Inventory management practices within the walls of a hospital

The emphasis on these areas is motivated largely by the rising costs within the health care supply chain. According to Haavik (2000), in some instances supply chain costs may amount to as much as 40% of the cost of providing care and that if demand and inventory are better managed a savings of 4.5% can be achieved. Chandra and Kachhal (2004) suggest, based on a study by Pricewaterhouse Coopers that the cost savings could range from 6 to 13.5%.

Some of this cost is due to the expanded used of new products and technologies. For example, a recent study by Blue Cross Blue Shield Association (Lovern 2001) indicated that 19% of health care cost can be directly traced to the use and deployment of medical technology and that new medical technology is a key reason for double-digit health care costs. Thus, there is an increasing need to understand the role of the supply chain in new product development and adoption.

The introduction of new technology (e.g. equipment and related supplies) for patient care introduces a number of logistic management and control issues within a health care supply chain. The first decision faced by hospital systems is to evaluate whether or not a new technology and its related supplies should be adopted. This traditionally involves a cost analysis as well as an evaluation of the medical effectiveness of the technology that may or may not take into account logistic issues. After adoption, new equipment and related supplies are sometimes placed within an expense category rather than an asset category because initial treatment plans are not standardized for the use of the new technology. In addition, the potential demand for the new equipment or technology is difficult to project.

Unfortunately, as the use of the new technology matures, the items often remain an expense longer than they should rather than being moved into an inventory management category where their use can be better optimized within the health care supply chain. In addition, for many new technologies the method of marketing through personal interaction between the supplier and the doctor is well entrenched. This personal marketing can bypass the traditional controls that are in place within the managed inventory items.

To address this need, a methodology for evaluating the trade-offs between the cost and the effectiveness of the new supplies/equipment needs to be developed. Such a methodology should capture the cost of the supplies/equipment in terms of inventory asset value but also the cost of managing the inventory within the supply system. This should involve the transportation, holding, and ordering costs. A unique aspect of this inventory modeling will be in characterizing (or forecasting) the demand for new items as well as the effect of technological change on the price/value of the items over time. For example, the introduction of new technology may cause the price/value of items already in inventory to change. Planning for this change over time can be an important factor in evaluating current technology versus new technology and any discounts offered by manufacturers. In addition, "where to stock" the items will be important, because inventory pooling may be a very effective strategy for high cost, low demand items. Traditional inventory models typically assume stationary demand and static item costs over an infinite planning horizon. This will clearly provide less than ideal planning for these types of items.

An ideal methodology should also evaluate the logistical performance (e.g. fill rate) for various levels of cost. The development of such a methodology should also take into account the best practices currently being used to manage new technology as well as how to take advantage of recent advances in information technology.

As indicated in the previous discussion, even for new technology, inventory management is a critical issue. To improve inventory management, the best place to start is at the beginning of the supply chain. That is, understanding and characterizing supply chain demand is critical because so much planning depends on the form of the demand. It could not be articulated any better than in the Center for

Global Development's report on improving global health through better demand forecasts:

> "One of the weakest links—and one of the most vital for achieving both short- and long-term gains in global health—is the forecasting of demand for critical medical technologies, including vaccines, medicines and diagnostic products. Demand forecasting, which may seem at first glance to be a small piece of the very large puzzle of access to medical products, is of central importance."— CGD (2007)

Some have advocated that retail-forecasting practices be adopted within the health care supply chain; however, it is not clear how these practices should be adapted to the unique aspects of the health care supply chain. One thing that is clear is that better demand management practices are imperative for achieving the potential savings that have been suggested. Callahan et al. (2004) indicate that the time may now be right for making this adaptation:

> "Having incorporated these lessons into the lore of supply chain management, we contend that our industry is now ready to develop its own set of principles that draws upon the concepts of retail demand forecasting models, but which fully accounts for the unique nature of health care—in which a failure to meet the demands of consumers (patients and clinicians) can have dire consequences."

They indicate that projecting demand is the key. That is, utilizing all automated systems to "create realistic bill of materials for procedures from the preparation phase through recovery and follow up" (Callahan et al. 2004). See also the discussion on treatment pathway profiling in Meyer and Meyer (2006). This is a key insight to replace uncertainty with information and get closer to derived demand.

Derived demand is demand that can be computed deterministically based on the requirements from other items (e.g. end items). Typical end-item demand forecasting relies on historical records to model future demand, largely treating the demand as independent. Whenever possible, it is advisable to substitute derived demand in place of typical forecasted demand. Within manufacturing settings (e.g. make-to-assembly and make-to-order) end-item demand is forecasted and the component demand is derived via the product structure (bill of materials). Because of advances in information technology, hospitals now have large quantities of data available concerning patients and their use of supplies. These systems track diagnosis, medical events, patient satisfaction, purchasing, accounts payable, reimbursements, surgical team preferences, dispensing of pharmaceutical, etc. With this sort of information, it may now be feasible to create a probabilistic "Bill of Materials" for categories of patient types and/or disease management regiments. From such a bill of materials, it may be possible to derive demand requirements for materials according to hospital scheduling, patient demographics, admission records, and seasonal demands.

For example, consider hip-replacement surgery. These types of procedures are often scheduled weeks if not months in advance. For each procedure, there are three sets of materials (1) those that are always used, (2) those that might be used, and (3) those materials that could not have been anticipated. The analysis of information on past patients should allow some analysis of sets 1 and 2. Then, a bill of material could be determined for those materials that are always used. This could allow pre-packaged kits to be developed; however, since many procedures may have common items, it is the schedule information along with the lead time to order the item, which could allow for better just-in-time management of the items. This would allow the postponement of the kit building process to the last possible moment. Thus, given a procedure schedule, the ordering, stocking, and delivering of significant amounts of material can be pre-planned. In addition, there is the possibility of creating a probabilistic bill of materials for the items that will probably be needed. Finally, with appropriate data, those materials that are being used but could not be anticipated could be forecasted and treated as independent demand items. This process could allow for significantly reduced levels of inventory, while still meeting delivery service requirements.

In some sense, the delivery of health services (in the form of procedures) to patients can be conceptually similar to something like aircraft maintenance. In order to optimize aircraft maintenance, one looks at scheduled maintenance and unscheduled maintenance. The scheduled maintenance allows derived demand to substitute for uncertainty. Then, the supply system can handle the inventory requirements for unscheduled repairs. While the analogy is not perfect, it should be apparent that some of the techniques applied to analysis and control of spare part supply networks should be applicable to the health-care supply chain.

In order to examine these ideas within the health care supply chain, there is a need to examine and document current (best) practices in regards to demand management. Then, the information requirements for analyzing and building bill of material candidates would need to be specified. Finally, the ideas would need to be modeled and compared to current methods. This would allow for a better understanding of how much benefit could be gained before committing larger resources to demand management techniques.

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