Inventory Management Strategy for the Supply Chain of a Medical Device Company

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Abstract

In the medical device industry, many companies rely on a high inventory strategy in order to meet their customers' urgent requirements, sometimes leading to excessive inventory. This problem is compounded when it involves a long supply chain with several stages of activities and with long delivery and processing lead times. It is further exacerbated when high inventory leads to the frequent expiry of items with short shelf lives, which is typical of surgical items that have to be sterilized. Good supply chain strategies can potentially lead to a significant reduction of the supply chain cost. Through the use of relevant mathematical formulae and Strategic Inventory Placement optimization method, this paper examines the extent of the usefulness of a few possible strategies, such as kitting architecture change and continuous review system, for a family of medical emergency surgical kits across the whole supply chain for a medical device company. The result shows that reducing production lead time and review period, as well as adopting certain kitting architecture changes can reduce inventory value by more than 60% and operating cost by more than 20%. In addition, the paper shows that the Strategic Inventory Placement method can further reduce the total inventory value and operating cost by increasing the inventory of finished products and reducing the inventory of components in the supply chain.

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1 Introduction

1.1 Overview of Medical Device Industry

The medical device industry in the US has faced challenges and harsh realities in recent years, forcing companies in the industry to rethink their business strategy. First, there is an ever increasing trend of healthcare cost. In addition, the hospitals, which are the key customers of the medical device industry, will be reimbursed on value added, rather than the volume of work done or the material used to perform surgery (Global Healthcare Exchange, 2011). The increase in healthcare cost and the change to the way in which the hospitals are being reimbursed lead to pressure for hospitals to find areas to reduce cost so as to bring down the overall healthcare cost. This pressure will be passed on to the medical device companies that supply medical products to the hospitals. According to a research study presented to the Medical Device Supply Chain Council in 2011, 40-45% of the hospital operating expense is represented by supply chain and this portrays a clear and good target for cost reduction (Global Healthcare Exchange, 2011). The good news is that, according to the same research study, better supply chain management can potentially lead to a 5-15% reduction in the supply chain cost. It is challenging for the healthcare and medical device industries, however, to reduce the cost because the impetus for cost reduction is often superseded by the need to maintain high healthcare standards. Our thesis attempts to balance both cost and high standards for companies in the medical device industry through better supply chain management.

1.2 Background of Company

Founded in the 19th century, the medical device company (hereafter called "MedCo"), which is the subject of this research, is a subsidiary of one of the world's largest and most diverse medical device and diagnostic companies, which has various subsidiaries operating in many countries. Several of these subsidiaries provide sterilized surgical supplies to hospitals. MedCo itself is a large company that offers a broad range of neuro-related medical devices.

1.3 Current Supply Chain

In this research, we will focus on the four emergency surgical kits that pose the greatest challenge to the company because of the complex supply chain behind them. Figure 1-1 depicts the present supply chain for the production of the four emergency surgical kits, which we also refer to as the Stock-Keeping Units (SKUs).

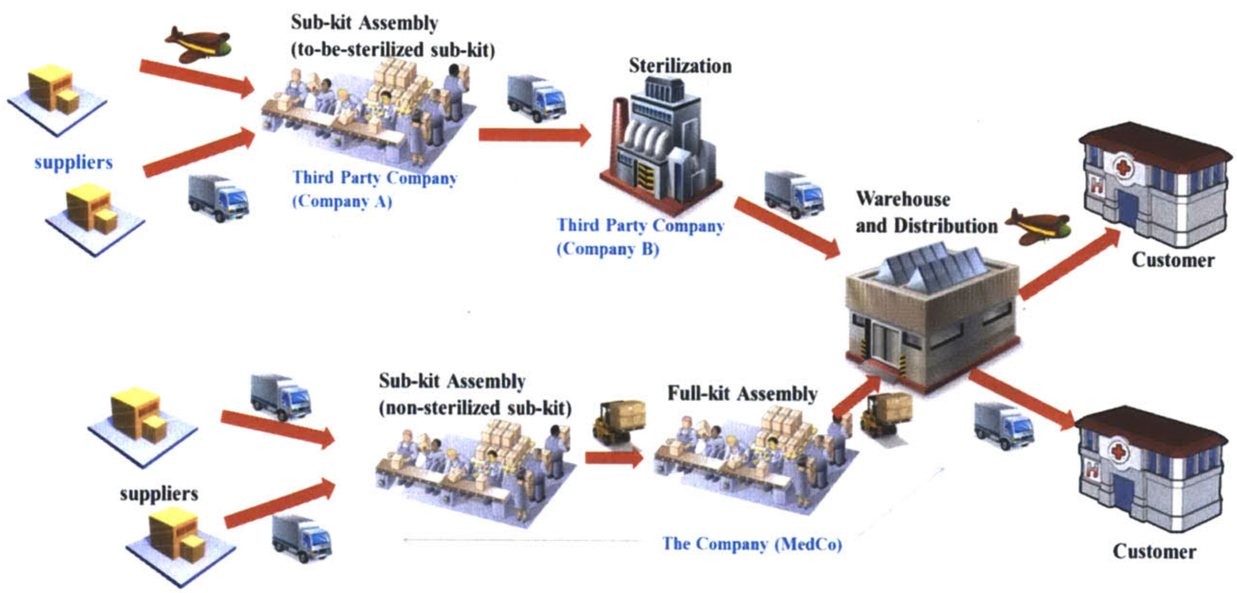


Figure 1-1: Current Supply Chain for the Emergency Surgical Kits (Source: MedCo)

It spans eleven suppliers, both local and overseas, and two other third-party companies across several stages of activity in the supply chain. Each stage of activity represents a major processing function in the process flow. The suppliers provide the components needed for the kits, while MedCo performs the inspection and quality check on the components. One of the third party companies (Company A) performs the kitting function of the sterilized portion of the kits, while the other third party company (Company B) performs the sterilization. Company A is situated some distance away from MedCo in another state of the US. The lead times involved between stages range from a day to several weeks, and vary across components and stages. MedCo is managing inventories of most of the components and all the kits in the company's distribution center cum warehouse, as well as in the third party companies' sites. To enable rapid response to requirements, MedCo adopts a Make-To-Stock (MTS) and an urgent 1-day shipping policy for the emergency surgical kits. In inventory control, the company uses a periodic review and fixed order quantity inventory management system with a review period of one month. A more detailed explanation about the current supply chain can be found in Section 3.

1.4 Challenges Faced by the Company and Motivation

The span of the network and the lack of an overall IT-enabled visibility and inventory control system underscore the complexities and challenges of managing the entire supply chain. Furthermore, the Make-To-Stock (MTS) policy and the urgent shipping policy for their products require a relatively high inventory of the full kits and components. This approach of relying on high inventory of kits poses several challenges to MedCo. Firstly, as many components have limited shelf lives, MedCo constantly faces potential expiry of its end products, and probable need for re-sterilization and repacking when the components' shelf lives expire. Secondly, in the event of any component being discontinued by a supplier, MedCo faces the possibility to invest significant amount of effort in changing over to new items. This was in fact experienced by MedCo in recent years. One of the components was discontinued and they had to repack the kits in their inventory. In hindsight, MedCo opines that the amount of inventory and the form in which it is stocked (full kits, sub-kits, individual items, pre- or post-sterilization) may not be optimal. The company has been using its current inventory control system for years, and much of the logic behind the system may no longer be valid or optimal in the current situation. It is therefore a good time now to review the system.

1.5 Key Question and Scope of Study

The issues above bag the key question of whether the current inventory value (working capital cost) of the entire supply chain can be reduced and, if so, what would be the best inventory management strategies to be employed. To the best of our knowledge through literature review, there is no previous published research done on inventory management and the study of medical kitting architecture for medical device industry. The purpose of our study is to examine the company's current supply chain and its inventory management policy, and to propose better inventory management strategies to reduce the inventory value and the operating costs across a multi-echelon supply chain, while maintaining the highest healthcare standards.

To begin, we first present related literature in this area. This is covered in Section 2. We then apply the relevant methods to our system. Specifically, we employ a scenario-based approach to examine the various strategies and use mathematical formulae to quantify the benefits in each case. We also employ an optimization model to further improve the strategies for the supply chain. The methodology can be found in Section 3. Based on the understanding of the results and the practicality of the implementation of the changes, we then suggest a revised strategy that combines several of the results. The assumptions, data analysis results, the insights from the results, and the recommended strategy are presented in Section 4. We then present our conclusion and recommendations of the strategy to be adopted by the company and the future research work to be done in Section 5.

2 Literature Review

Due to the relative infancy of research related to supply chain management in the medical device industry, limited amount of published literature is available. What is available generally indicates that recent developments focus more on information sharing through the use of Information Technology (IT) and application of Radio Frequency Identification (RFID) rather than on inventory management and kitting architecture techniques in the medical device industry. Through this section, we attempt to document significant sources of information relevant to developing inventory management strategies for a medical supply chain, although they are not directly related to the inventory management in the medical device industry. We first present the recent development of the medical device supply chain. We then examine the traditional inventory management models used by most industries, followed by the concept of postponement, a technique used by many companies to improve their supply chain. The last sub-section describes an optimization method that can be used to minimize the inventory value.

2.1 Development of the Medical Device Supply Chain

Emphasis on the supply chain management excellence across many industries started around two decades ago, particularly in the manufacturing and retailer markets. However, the medical device industry gave prominence to improving its supply chain network only 8-10 years ago. One of key trend indicators was the establishment of the Medical Device Supply Chain Council in 2004 by supply chain and operations executives from leading medical device manufacturers.

However, even with the 8-10 years of growth in emphasis, the supply chain in the medical industry still has huge potential for optimization. A healthcare technology company, Global Healthcare Exchange (GHX), in its presentation to the Medical Device Supply Chain Council in

2011, assessed that 40-45% of the total hospital operating expenses is represented by supply chain and potential savings of 5-15% of supply chain cost can be realized with better supply chain management strategies (Global Healthcare Exchange, 2011).

Against this backdrop, the purpose of this study is to identify areas of improvement in inventory management for a medical device company by applying knowledge gained from information pertaining to the successful applications of the theories in other industries.

2.2 An Examination of Traditional Inventory Management System

This section provides an overview of the traditional inventory management systems that are used in many industries.

According to Silver, Pyke and Peterson, there are two broad categories of inventory management systems for managing products with stochastic demands – continuous review and periodic review (Silver, 1998). Within the two categories, there are four types of inventory management systems. Under continuous review category, we have Re-Order Point, Fixed Order Quantity (Q, s) (aka "two-bin") System, and Re-Order Point, Order-Up-to (s, S) System. Under the periodic review category, we have the Periodic Review, Order-Up-To-Level (R, S) (aka Base Stock) System, and the Periodic Review, Re-Order Point, Order-Up-To-Level (R, s, S) System.

In choosing the type of control system to use, we need to consider the product and the specific business context. In general, the continuous review system is able to achieve the same level of service standards as the periodic review system at a lower safety stock, but it requires a higher set-up cost, including IT infrastructure and labor, in order to perform the continuous review function. In lieu of the effort required, the continuous system is more suitable for small amounts of items that have high profit margin value and/or high sales volumes (Category A item), whereas the periodic review system is more suitable for large numbers of items with lower values and/or lower sales volume (Category B and C).

Specifically, we will use the (Q, s) continuous review and (R,S) periodic review systems, as they can be implemented easily and are suitable for Category B items, the type of items that we are investigating as identified by MedCo.

2.2.1 Re-Order Point, Fixed Order Quantity (Q, s) (aka "Two Bins") System

In (Q, s) System, the policy is to re-order Q amount of inventory whenever the inventory position drops below the re-order point (s). The controlling factor is the inventory position level. Mathematically, the (Q, s) continuous review system can be represented by the following formulae:

$$\boldsymbol{s = \mu_L + Z \times \sigma_L} \qquad (2\text{-}1)$$

where s is the Re – order point; Z is the Safety Factor; μ_L is the demand over the lead time; σ_L is the standard deviation (SD) of the demand over the lead time or the Root Mean Square Error (RMSE) of the forecast error over the replenishment lead time.

For the re-order quantity, Q, it can be calculated using the Economic Order Quantity (EOQ) formula:

$$\boldsymbol{Q = \sqrt{\frac{2A\mu}{vr}}} \qquad (2\text{-}2)$$

where A is the fixed cost per order; μ is the demand per year; v is the variable cost per unit; r is the holding cost rate per year ($/$/year) (Silver et al., 1998).

2.2.2 Periodic Review, Order-Up-To-Level (R, S) (aka Base Stock) System

In (R,S) System, the policy is to re-order an amount of inventory that increases the current inventory position to the order-up-to level (S) every R period of time. The controlling factor is the review period, R, instead of the inventory position level.

Mathematically, the (R, S) periodic review system can be represented by the following formula:

$$S = \mu_{L+R} + Z \times \sigma_{L+R} \tag{2-3}$$

where S is the Order-up-to level; Z is the safety factor; μ_{L+R} is the demand over the lead time and review period; $\sigma_{L+R}$is the SD of demand or the Root Mean Square Error of the demand forecast over the replenishment lead time and review period (Silver et al., 1998).

2.2.3 Insight

The medical device company we are working is currently adopting the periodic review system for the end-products that we are studying with a review period of one month. In view of the relative importance of the end products to the company, it is worth considering reducing the review period or adopting the continuous review system. With the company's current IT system, the application of the continuous review system could be achieved with minimal increase in overhead labor cost, which is usually the cost driver. The suggested inventory control systems given above can serve as the basis for us to perform our review and comparison.

2.3 Postponement

Companies today offer increased variety of products with shortened life cycles. This demands greater responsiveness from them to compete in the market (Bhattacharya et al., 1996). Significant research has been done on delaying the product configuration to custom specifications in order to manage the increasingly complex supply chains of these products. This approach of delaying activities further downstream with the intention of customizing products, as opposed to performing those activities in anticipation of future orders, is termed "postponement" (Van Hoek, 2001) and (Lee & Tang, 1997).

Effective applications of postponement have been discussed by Swaminathan and Tayur for IBM (Swaminathan & Tayur, 1998). Feitzinger and Lee presented the role of postponed manufacturing in making mass customization a reality at Hewlett-Packard. For example, Hewlett Packard delayed the point of differentiation to make its PCs country-specific from the factory to the distribution center (Feitzinger & Lee, 1997). Brown et al. shared that another company, Xilinx, redesigned its integrated circuits so that a ''generic'' device could be customized within a certain range of parameters, rather than determining all product characteristics during fabrication (Brown et al., 2000).

Lee and Billington categorized postponement into two types: form postponement and time postponement (Lee & Billington, 1994). Form postponement refers to standardizing the upstream stages as much as possible; time postponement aims to delay product differentiation tasks as late as possible. In this paper, we explore the special case of make-to-stock with form postponement. Specifically, we exploit the commonalities in components to combine similar finished products.

Yang et al. investigated the role of postponement in the management of uncertainty. In their research, Yang et al. developed the model to choose the right strategy between high uncertainty and high modularity. They noted that in cases of high product modularity and low demand uncertainty, production postponement gives the best results (Yang et al., 2004). In our research, the company works with stable demand and high modularity. Hence, we use the concept of production postponement as proposed by the Yang et al. model. Specifically, we look at the commonality in finished products, combine finished products that are similar, and allow the customers to select the configuration they require. This is akin to pushing differentiation downstream, after the demand is known, as suggested in the time postponement concept discussed above.

We utilize the knowledge that if demand for n individual products is independent and identically distributed, aggregation reduces safety stock by a factor of $\sqrt{n}$, known as the Square Root law (Maister, 1976).

Hence, for each product i = 1, 2…n, we assume that demand at end of period t is denoted by the independently and identically distributed random variable $D_i(t)$, which is normally distributed with $E(D_i(t)) = \mu_i$; $Var((D_i(t)) = (\sigma)^2$. The aggregated safety stock is influenced by the correlation of demands (ρ) and it can be calculated using the following equation:

$$\boldsymbol{\sigma_0} = \sqrt{\sum_{i=1}^{n} \sigma_i^2 + 2\sum_{i=1}^{n-1}\sum_{j=i+1}^{n} \sigma_i \sigma_j \rho_{ij}} \qquad (2\text{-}4)$$

where σ_i is the SD of product i, σ_0 is the SD of aggregate demand,

ρ_{ij} is the correlation coefficient of demands between products i and j ($-1 \leq \rho \leq 1$). Σ_0 decreases as ρ decreases.

Wong, Potter and Naim evaluated the benefits of postponement by identifying differentiation and decoupling points in a soluble coffee supply chain (Wong et al., 2011). We apply this framework to develop our kitting strategy study and analyze savings in safety stock and cycle stock using the equations from Silver et al. (Silver et al., 1998).

2.4 Supply Chain Network Optimization

In our research, we are dealing with a network of different stages of activities to produce the final products. The underlying principle of network optimization is that there are greater savings to be reaped from a globally optimized system than a sub-optimized system and that it is attainable through better co-ordination and communication. As such, we aim to work on optimizing the whole supply chain and reducing the total inventory value at the entire network level.

Building on the model given by Simpson (1958), Graves et al. considered a multi-stage production/distribution supply chain subject to stochastic demands and derived an optimization method to determine the best locations in the supply chain for placing de-coupling inventories, or so-called strategic inventories, to minimize the inventory cost (Graves et al., 2000).

The assumptions are that the demands are bounded, the lead times between various stages are deterministic, and there is no capacity constraint at each stage of activity. They also assumed that there is an associated service time and activity lead time at each stage of activity, on which the amount of safety stock at that stage is dependent. The service time is the lead time promised by someone in a stage preceding someone in a downstream stage that the upstream stage is supplying or providing a service to. The service times for the different stages form the decision variables for the optimization problem. The objective is to determine the service times at each stage that minimize the holding cost of all the safety stocks at the different stages. This is a form of Strategic Inventory Placement (SIP) method; more specifically, it is termed as Guaranteed-Service model (Graves et al., 2000).

Graves et al. first applied the concept to a serial line model and showed that it can be expressed mathematically as follows:

$$\min \sum_{i=1}^{i=N} h_i I_i \tag{2-5}$$

Subject to:

$$I_i = k\,\sigma\sqrt{S_{i-1} + T_i - S_i} \qquad i = 1, \dots, N$$

$$0 \le S_i \le S_{i-1} + T_i \qquad i = 1, \dots, N,$$

where I_i denotes the expected safety stock at stage I and S_0 is assumed to be 0.

Simpson (1958) showed that there is an optimal solution such that $S_i^* = 0$ or $S_i^* = S_{i-1}^* + T_i$ for all i = 1, 2 … N-1. $S_i^* = 0$ implies that there is sufficient safety stock to decouple Stage i from its downstream stage while $S_i^* = S_{i-1}^* + T_i$ implies that Stage i has no safety stock (Graves et al., 2000).

Graves et al. later built on the serial line model, extending it to assembly networks, distribution networks and more general networks.

We could use the concept, specifically the one for the assembly network, for our thesis analysis to find the lowest inventory value. However, there is a limitation in directly applying it to our context. It assumes a single end product with a single average demand and SD of demand (i.e. demand variation), which means all the safety stock of components at the upstream stages will be subjected to the same average demand and variation. In our case, we have multiple end products with different average demands and standard deviations. That means different components at upstream stages will have different demands and standard deviations, depending on which end products they will be assembled into. We could not find any other formulation that could have been applied to our context directly. Therefore, in our thesis research, we aim to adapt the optimization formulation described above into new formulations that serve our purpose and allow us to optimize multiple end products across the supply chain.

3 Methodology and Scenarios

3.1 Introduction

The total amount of inventory required and the placement of the inventory within a supply chain depend on many factors: demand, demand uncertainty, lead time (delivery, receipt, and production), lead time uncertainty, cost and other characteristics of the product, performance requirement to meet customer expectation, number of stages, and the amount of economic contribution to the value chain by each stage. Given such as a wide range of factors, it is not easy to have a single model that examines all the factors at one go and devise a good strategy. In addition to this complexity, it is also important to optimize the entire supply chain, rather than to optimize every stage by itself as it leads to an overall sub-optimal solution.

Keeping this in mind, we began by analyzing the influence of each key factor on various cost components by using a scenario-based approach, with each scenario capturing a specific strategy. For our analysis, we quantified the changes in the cost components using appropriate mathematical formulae given by the inventory models that we adapt. We then drew insights from the results of each scenario, synthesizing them and using the overall insights to devise a best case scenario. We also employed the Strategic Inventory Placement (SIP) – Guaranteed Service Model as mentioned in our Literature Review to determine the most optimal solution and strategy.

3.2 Overview of the Current Supply Chain

This sub-section presents an overview of the current supply chain relevant to our study, the inventory management policy currently adopted by the company, and an examination of the various factors affecting the supply chain.

3.2.1 Existing Supply Chain

Figure 3-1 illustrates the current supply chain of the four types of emergency medical kits that we focused on in this thesis research.

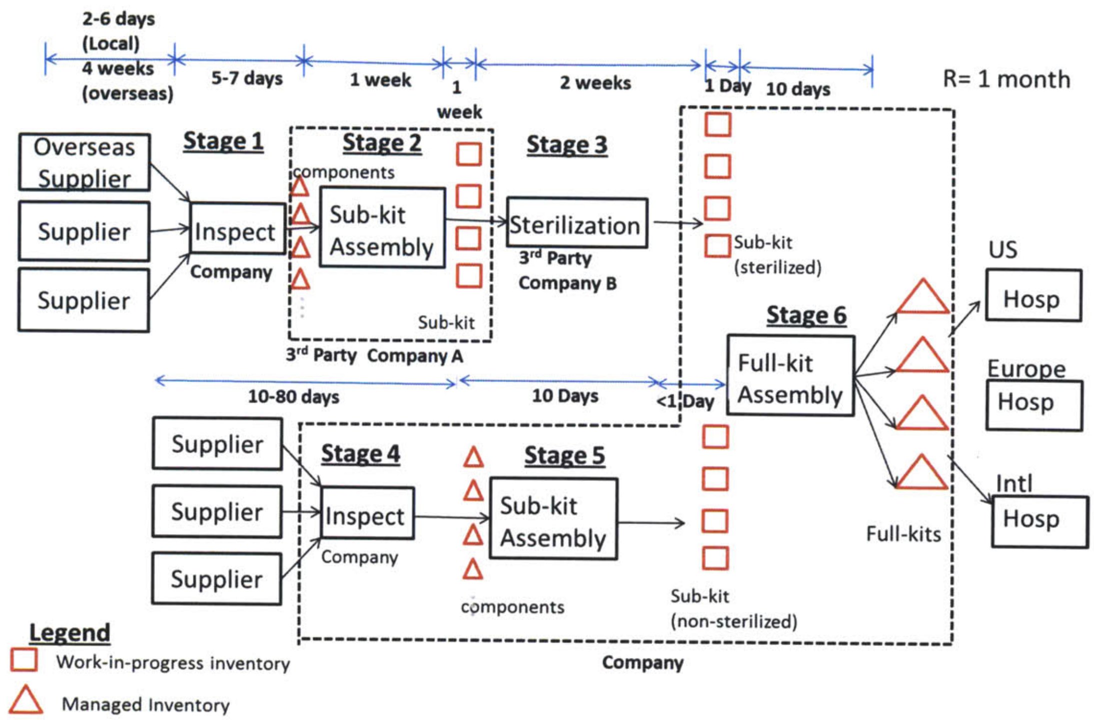


Figure 3-1: Current Supply Chain (MedCo)

We identified six primary stages in the network where each stage represents a major processing function in the process flow. Each SKU (full kit) comprises a sterilized sub-kit and a non-sterilized sub-kit. Components for the sterilized sub-kit are sourced partly by the company and partly by a third party provider from local and overseas suppliers (Stage 1). All parts are inspected at the company's facilities either locally or overseas and are then delivered to a third party provider (Company A)'s location. The delivery lead times vary, depending on the source of procurement. Information about actual lead time and its variability is not recorded currently. The third party provider (Company A) combines products procured from both ends into a single sub-kit ready for sterilization (Stage 2). It maintains inventory of the individual components at its own location. MedCo owns the inventory it sources directly from the suppliers, while the rest of the inventory belongs to Company A. The assembled sub-kit from Stage 2 is sent for sterilization at a third party company's (Company B) location (Stage 3).

Non-sterilized components are procured directly by MedCo. Lead times vary based on location of the external sources. MedCo inspects the individual components once they arrive at its facilities (Stage 4). Inventory is maintained for these individual components after inspection. These components are then assembled into four different sub-kits, each of which corresponds to one of the final four full kits that are being produced (Stage 5).

With reference to Stage 6, MedCo does not maintain inventory of the sterilized sub-kits that come into their centralized distribution center (DC) due to the concern of expiry of their shelf lives. The non-sterilized sub-kits are also not inventoried since the lead time to procure the non-sterilized prep-kit is much smaller than the lead times to procure the sterilized part, and therefore, there is sufficient time to activate the procurement of the non-sterilized sub-kits once the sterilized sub-kits are required. Hence, the non-sterilized kit is assembled just prior to the arrival of batches of sterilized sub-kits into the company's DC. Both sterilized and non-sterilized portions are assembled together at the DC to produce the four types of final kits (Stage 6).

To optimize inventory management for the existing supply chain, we developed a framework to consider a set of input factors that affect the inventory strategy; derived scenarios based on inventory placement, inventory models and kitting policies; and used analytical methods to determine optimal inventory levels and cost for the different scenarios. We then used the outputs to draw insights. The methodology, step-by-step, is described below.

3.2.2 Current Inventory Policy and Associated Issues

The company currently follows a Make-to-Stock (MTS) policy to meet the short response time needed by the customers. Since demand for the products is fairly stable, the company issues annual purchase orders for the components. However, it also reviews its inventory position each month and makes adjustments to the next order quantity depending on the updated monthly forecasts and inventory position. Following the current strategy, **the company generally maintains an average inventory of 8-10 weeks for the finished products and 11 weeks for components because the average sourcing and production lead time is about 8-10 weeks for the final assembly of products**. At each monthly review, it orders about one month worth of new finished products and components stock to replenish the current stock. The actual order amount is adjusted according to the amount of stock left and the desired amount.

This model, specifically the way the average inventory is calculated, leads to higher inventory values and greater risk of obsolescence of the products with limited shelf life. We examine in the following sections alternate methods to calculate optimal inventory levels and the placement of inventory at different stages to achieve lower costs while maintaining the same service level.

3.2.3 Factors that affect Inventory Strategy

The key factors that influence the amount of inventory to be held at various stages of the supply chain are discussed below:

3.2.3.1 Demand

We studied the demand for each of the four final SKUs. From the data given for past three years, we understand that demand has remained fairly stable for each product. The typical customers are the hospitals classified into three categories: (1) Domestic, (2) Europe, the Middle East and

Africa (EMEA), (3) the rest as International. A few products are shipped to distributors globally as well.

3.2.3.2 Cycle Service Level

Given the nature of the medical business, a quick response is desired by the customers to be able to ship out the products to customer site within 24 hours upon receiving the order. In addition, the company would like to maintain a Cycle Service Level (CSL) of 95% for each of the four final SKUs.

3.2.3.3 Bill of Material

We examined the Bill of Material (BOM) for each of the four SKUs and study common items that go into each of the final kits. We also examined the number of units, cost and source of supply of these individual items to identify patterns for optimizing the model. Table 3-1 illustrates the common items that are externally sourced and units required of each for the four final SKUs.

Table 3-1: Bill of Material of the four SKUs (MedCo)

SKU 1		SKU 2		SKU 3		SKU 4	
S Kit 1	**Units**	**S Kit 2**	**Units**	**S Kit 3**	**Units**	**S Kit 4**	**Units**
S Comp 1	1	S Comp 1	1	S Comp 1	1	S Comp 1	1
S Comp 2	1	S Comp 2	1	S Comp 2	1	S Comp 2	1
S Comp 3	2	S Comp 3	2	S Comp 3	2	S Comp 3	2
S Comp 4	1	S Comp 4	1	S Comp 4	1	S Comp 4	1
S Comp 5	1	S Comp 5	1	S Comp 5	1	S Comp 5	1
S Comp 6	1	S Comp 6	1	S Comp 6	1	S Comp 6	1
S Comp 7	1	S Comp 7	1	S Comp 7	1	S Comp 7	1
S Comp 8	1	S Comp 8	1	S Comp 8	1	S Comp 8	1
S Comp 9	1	S Comp 9	1	S Comp 9	1	S Comp 9	1
3rd party supplies		3rd party supplies		3rd party supplies		3rd party supplies	
NS Sub Kit 1		**NS Sub Kit 2**		**NS Sub Kit 3**		**NS Sub Kit 4**	
NS Comp 1	1	NS Comp 1	1	NS Comp 14	1	NS Comp 14	1
NS Comp 2	1	NS Comp 2	1	NS Comp 5	1	NS Comp 3	1
NS Comp 3	1	NS Comp 3	1	NS Comp 6	1	NS Comp 4	1
NS Comp 4	1	NS Comp 4	1	NS Comp 3	1	NS Comp 16	1
NS Comp 5	1	NS Comp 5	1	NS Comp 4	1	NS Comp 17	1
NS Comp 6	1	NS Comp 6	1	NS Comp 11	1	NS Comp 18	1
NS Comp 7	1	NS Comp 7	1			NS Comp 19	1
NS Comp 8	1	NS Comp 8	1			NS Comp 11	1
NS Comp 9	1	NS Comp 9	1				
NS Comp 10	2	NS Comp 10	2				
NS Comp 11	1	NS Comp 11	1				
NS Comp 12	1	NS Comp 14	1				
NS Comp 13	1	NS Comp 13	1				
		NS Comp 15	1				
Label 1	1	Label 1	1	Label 1	1	Label 1	1
Label 2	1	Label 3	1	Label 4	1	Label 5	1

Legend	S -	Sterilized	NS -	Non Sterilized

3.2.3.4 Lead Times

In the medical devices industry, components sourcing, production and delivery lead times are generally long and stable. Table 3-2 illustrates the sourcing lead time (including administrative, inspection and transit times) from immediate predecessor stage and the production lead time of each stage in the process.

Table 3-2 : Lead Times in the Current Supply Chain (MedCo)

	Lead Times (days)		
	Sourcing	**Production**	**Total**
Stage 1	40	Up to 12	40 to 52
Stage 2	7	12	19
Stage 3	7	14	21
Stage 4	5 to 60	Up to 20	10 to 80
Stage 5	< 1	10	10
Stage 6	0	10	10

During discussions with a current employee of MedCo, we realized that there is a possibility to reduce the production lead time at Stage 6. This will be discussed subsequently in Section 3.4.4.

3.2.3.5 Review Period

The company currently reviews its inventory and places order with its suppliers monthly (Review Period I = 30 days). The length of the review period influences both cycle stock and safety stock; the shorter the review period, the lower the inventory value. However, higher number of reviews leads to higher number of orders and hence greater ordering cost. Through interviews with MedCo's staff, we found that MedCo has recently introduced an IT system for inventory management, and we saw potential benefits arising from reducing the review period due to better efficiency in monitoring inventory.

3.3 Methodology

3.3.1 Overview

In our study, we first modeled the network as one that comprises a serial and parallel connection of stages of activity; with each stage having its own stand-alone inventory management system based on one of the traditional inventory management systems mentioned in our Literature Review. Please see diagram below for a simplified graphical representation of our model.

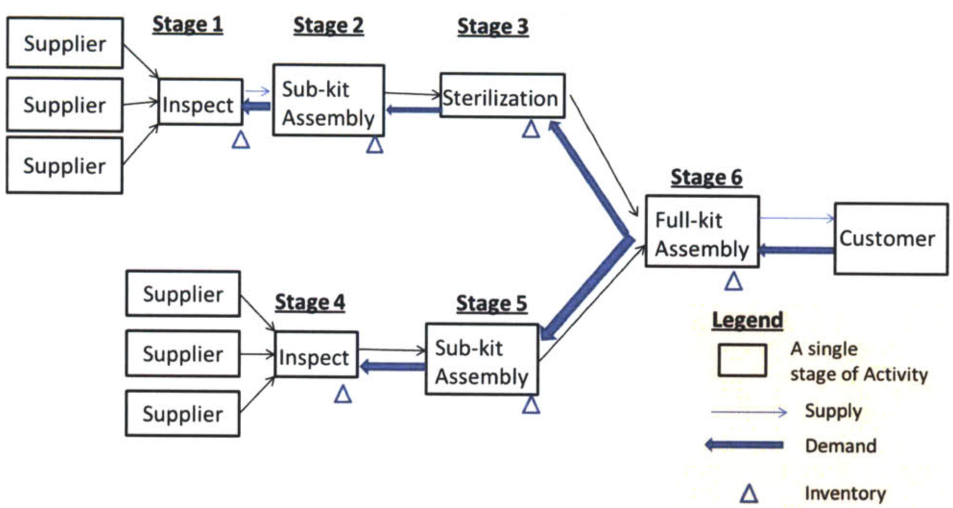


Figure 3-2: A Simplified Model representing the Supply Chain of MedCo

The input to the final assembly stage (Stage 6) are the sum of the demands of the four SKUs from the customers and the lead times for each SKU, and the outputs are the inventory management policy with the quantity of specific sub-kits to be ordered, the inventory levels and the various associated cost components. As for the upstream stages (Stage 3 and Stage 5), the inputs, which are the demands and variation of the demands for the sub-kits, will depend on the demands for the specific higher assemblies/full kits that the sub-kits are part of. The types of outputs for Stage 3 and Stage 5 are similar to that of Stage 6. The same concept is applicable for Stage 1, 2 and 4 as well.

The sub-sections below detail the assumptions used, the specific methods and the formulae used in our analysis.

3.3.2 Assumptions for Scenario Analysis

We made the following assumptions for analyzing the various scenarios we developed:

- **Demands for final SKUs are independent**

  In our analysis of the demands of the SKUs, we found that all the coefficients of correlation of demands are near to 0. Hence, we assumed that the demands for the four final SKUs are independent.

- **Demands are normally distributed**

  Given a large number of data points and the resemblance of the actual demand distribution to the normal distribution, we assumed that the demands follow normal distribution.

- **Lead times are constant**

  Processes are fairly regularized in the medical devices industry and the number of suppliers is limited, resulting in a fairly stable lead time. We hence assumed that lead times information provided by the firm remain constant. In most cases, the lead times were based on close to the worst case (maximum) scenarios.

- **Cycle Service Level (CSL) is 95%**

  Based on MedCo's requirement, we assumed CSL as 95%. Hence, the safety factor, k, equals 1.64 and the unit loss function, G_{uk}, equals 0.021.

- **Ordering cost is $30/order**

  We only included a minimal labor cost of $30 per order since the firm utilizes best-in-class IT systems to issue purchase orders to suppliers. We did not include shipping costs in this case.

- **Shortage cost is 10% of value per item**

  We assumed that the shortage cost is equal at all the stages and includes the cost of air-lifting the product to the stage that requires the item.

- **Holding cost rates are higher after value addition**

  We estimated the holding cost rates for the different stages based on risk of obsolescence of the items and assume 1% probability that an item would require re-work while still in storage.

3.3.3 Analytical Method

3.3.3.1 Demand Analysis of Final Products

With inputs of three years' worth of monthly demand data for the different SKUs, we analyzed the pattern and computed the monthly mean and standard deviation. We also computed the correlation coefficient between different pairs of demands for the four SKUs to determine whether there is correlation between any pair using equations (3-1) and (3-2). This allowed us to determine the SD of the individual component.

$$\textbf{Covariance}\ (\mathbf{X},\mathbf{Y}) = \sum_i^N P(X = x_i, Y = y_i)[(x_i - \mu_x)(y_i - \mu_y)] \qquad (3\text{-}1)$$

$$\textbf{Correlation}\ (\mathbf{X},\mathbf{Y}) = \frac{\text{Covariance}(\mathbf{X},\mathbf{Y})}{\sigma_x \sigma_y} \qquad (3\text{-}2)$$

where X and Y are Random Variable, and x_i and y_i are specific values of X and Y random variables. N is the total number of products. μ_x and μ_y are the means of X and Y, respectively.σ_x and σ_y are the standard deviations of X and Y, respectively.

3.3.3.2 Estimation of Holding Cost

There will invariably be cost incurred to hold inventory. Inventory holding cost includes the capital cost and non-capital cost components. The non-capital cost component includes warehousing space, labor, insurance and/or obsolescence. For this medical device company, we expected that the different stages of the supply chain will incur different holding costs due to the amount of obsolescence and associated rework labor needed, with all else being equal. Due to lack of specific data on the holding cost, the company estimated the annual holding cost of the finished SKUs to be 15% of the costs. Notwithstanding the lack of data, for the purpose of having a more meaningful analysis, we attempted to estimate the annual holding costs for the different stages.

Analyzing person-hours information required at final stages of assembly for both sterilized and non-sterilized kits, we estimated the components of the annual holding cost rate for the final stage (Stage 6) as:

Holding cost due to obsolescence = Re-work cost per unit/Value of item (3-3)

where,

Re-Work Cost per unit = 1% of Cost of labor + Cost of material per unit (3-4)

This analysis led us to the following result:

Annual Holding cost due to risk of obsolescence for the sterilized (S) kit = 1.3%

Annual Holding cost due to risk of obsolescence for the non-sterilized (NS) kit = 1.2%

Given that the annual holding cost rate for finished products is 15%, the estimated annual holding cost rates for all the stages, accounting for the risk of obsolescence, are shown in Table 3-3.

Table 3-3: Annual Holding Cost Rates for the Various Stages

Stage	Type	Annual Holding Cost Rate (r)
6	Final SKU	0.15
3	Sterilized sub-kit	0.138
2, 5	Sub-kit for sterilization, non-sterilized sub-kit, partial kit	0.137
1, 4	Individual components	0.125

3.3.3.3 Establishing better kitting architecture

Using the postponement concept mentioned in the Literature Review section, we then tried to establish other possible kitting architectures that likely result in inventory reduction. One alternative was to put items that are common to different full kits together in the same partial kit prior to full kitting. This we believed will result in risk pooling, and hence lower the standard deviation (SD) of the demand. Another alternative was to combine similar full kits into a single kit. More discussion on this area will be made in Section 3.4.

.

3.3.3.4 Computation of Demand Mean and Standard Deviation of individual components

We then computed the monthly mean and SD of the individual components of the SKUs, which depend on the mean and SD of the SKUs. The same step was repeated for the sub-components of the components. We used the following equations:

$$\mu_i = \sum_{j=1}^{j=N} I_j * \mu_j \tag{3-5}$$

$$\sigma_i = \sqrt{\sum_{j=1}^{j=N} {I_j}^2 * {\sigma_j}^2} \tag{3-6}$$

where μ_j is the mean annual demand of SKU j. μ_i is the mean annual demand of Component i. σ_i is the annual SD of component i. σ_j is the annual SD of SKU j. I_j is the number of Component i in SKU j. *N* is the number of SKUs that Component i is part of (≤ 4 in our case).

The equations are only valid with the assumption that the demands between any pair of SKUs are not correlated. We have shown earlier that the assumption is generally valid.

3.3.3.5 Average Demand and Standard Deviation of Demand over lead time and review period

We then computed the average demand and SD over lead time and review period for each of the SKUs, components and sub-components using the monthly mean and SD that we had calculated earlier, based on the following formulae (Silver et al., 1998):

$$\mu_{L+R} = \mu\,(L + R) \tag{3-7}$$

$$\sigma_{L+R} = \sigma\,\sqrt{L + R} \tag{3-8}$$

where μ_{L+R} is the average demand over lead time, L, and review period, R;

σ_{L+R} is the SD of demand over lead time, L, and the review period, R.

The lead time of the individual SKUs or components, L, will be equal to the longest lead time of getting the individual components or sub-components from the last inventory position in the upstream stages, i.e. $L = \max(L_1 \ldots L_j)$; where j is the total number of components or sub-components from which the SKU or components are assembled. L is assumed to be deterministic in this case, as explained in the Section 3.3.2.

3.3.3.6 Safety Stock

We then computed the safety stock for each of the SKUs, components, and sub-components for each of the stages for different scenarios. Safety stock was calculated using the following formula (Silver et al., 1998):

$$\boldsymbol{Safety\ Stock = k\,\sigma\sqrt{L+R}} \tag{3-9}$$

where k is the Safety Factor corresponding to a specific Cycle Service Level (CSL), σ is the SD of the demand per year, L is the lead time in year, and R is the review period in year.

3.3.3.7 Cycle Stock

The cycle stock was then computed using the formulae (Silver et al., 1998):

$$\boldsymbol{Q = \mu * R} \tag{3-10}$$

$$\boldsymbol{Cycle\ Stock = \frac{Q}{2}} \tag{3-11}$$

where μ is the average annual demand, R is the review period in year, and Q is the average Re-order Quantity.

3.3.3.8 Inventory value and Total Relevant Cost

With the information on the safety stock and cycle stock, we then calculated the inventory for individual SKUs, components and sub-components, the inventory value at different stages, and the Total Relevant Cost (TRC) for different scenarios. The answers were compared and analyzed to draw insights and to determine the best scenario. The formulae for the calculation of the inventory value and Total Relevant Cost are given below (Silver et al., 1998):

$$\textbf{Inventory Value} = \textbf{v(Cycle Stock + Safety Stock)} \tag{3-12}$$

TRC = Cycle Stock Holding Cost + Safety Stock Holding Cost + Pipeline Holding Cost + Stock-out Cost + Ordering Cost (3-13)

$$TRC = vr(Cycle\ Stock) + vr(Safety\ Stock) + vr\mu L + C_{stock-out}P(Stock - out) + \frac{A}{R} \quad (3\text{-}14)$$

where v is the cost per unit of the inventory, r is the holding cost per item per year, $C_{stock-out}$ is the annual cost of stock-out per item, P(Stock-out) is the probability of stock-out, μ is the average annual demand per item and L is the lead time in year.

3.3.3.9 Sensitivity Analysis

We also performed a sensitivity analysis by varying a few parameters and analyzing the outputs for certain scenarios. The parameters included the review period I, lead time and the Cycle Service Level (CSL). We then drew insights from the outputs and considered the practicality of implementation.

3.3.4 Strategic Inventory Placement (SIP)/Guaranteed-Service Model

As mentioned in our Literature Review section, Graves et al.(2000) considered a multi-stage production/distribution supply chain subject to stochastic demands and derived an optimization method to determine the locations of the supply chain for placing de-coupling inventories, or so-called strategic inventories. The broad formulae are given in the Literature Review section (See Section 2.4: Supply Chain Network Optimization). This sub-section presents the method and formulae that we use for optimization.

3.3.4.1 Formulae

As mentioned in our Literature Review, there is a limitation in directly applying formulae from Graves et al. in our context, as it assumes a single end product with a single average demand and SD of demand (i.e. demand variation) and all the safety stock of components at the upstream stages will be subjected to the same average demand and variation. In our case, we have multiple finished products with different average demands and standard deviations and different components at upstream stages will therefore have different demands and standard deviations as well. In our thesis research, we adapted their mathematical formulation for optimization to our context and they are shown below.

$$\boldsymbol{min \sum_{i=1}^{N} \sum_{k=1}^{k=K} h_{ik} * I_{ik}} \qquad (3\text{-}15)$$

The following are the constraints:

$$\boldsymbol{I_{ik} = Z\, \sigma_{ik} \sqrt{\max(S_{in\_ik} + T_{ik}) - S_{out\_ik}} \qquad i = 1,\ \ldots,\ N \quad k = 1,\ \ldots,\ K}$$

$$\boldsymbol{h_{ik} = v_k r_i}$$

$$\boldsymbol{0 \le S_{out\_ik} \le S_{in\_ik} + T_{ik}}$$

where S_{out_ik} is the Service Time (out) and S_{in_ik} is the Service Time (in), respectively, for Stage i and Component k; N is number of stages (the larger the number, the more downstream the stage is); K is the total number of components, T_{ik} is Production Lead Time of Stage i for Component k; h_{ik} is the annual holding cost rate per item per unit time for Component k at Stage i; v_k is the unit cost for component k; r_i is the holding cost per unit cost $at\ Stage\ i$; and lastly, Z is the Safety Factor.

The formulations were programmed in Excel spreadsheet and we employed certain strategies for determining the decision variables: S_{out_ik} and S_{in_ik}. We discuss the strategies in the Section 3.4.8: Strategic Inventory Placement (SIP). Using the results, the inventory level at different stages can be determined using the formula:

$$\boldsymbol{Safety\ Stock_{ik} = Z\, \sigma_k \sqrt{\max(S_{in\_ik} + T_{ik}) - S_{out\_ik} + R_{ik}} \qquad i = 1, \ldots, N \quad k = 1, \ldots, K} \qquad (3\text{-}16)$$

where R_i is review period of Stage i. The other notations are the same as those mentioned above. We adapted the formula above from that originally given by Graves et al. (2000) by including the review period in the calculation when using the Base Stock Policy, which required the review period to be included for calculating safety stock.

3.4 Scenarios

Based on our Literature Review, we know that the inventory control policy, placement of the decoupling safety stock strategically at different locations, the type of postponement used and the kitting architecture will affect the inventory level and associated costs. Based on this understanding, we derived five scenarios, each depicting a specific strategy that will be described later, together with the base case and enhanced base case scenarios, which are based on the current supply chain, to study the effects of each strategy on inventory levels at the different stages and to determine the best strategy for inventory management of the surgical kits.

3.4.1 Base Case Scenario – Current Supply Chain

3.4.1.1 Description

The Base Case scenario is based on the existing supply chain without any change to the placement of the inventory. Figure 3-3 below depicts the current supply chain.

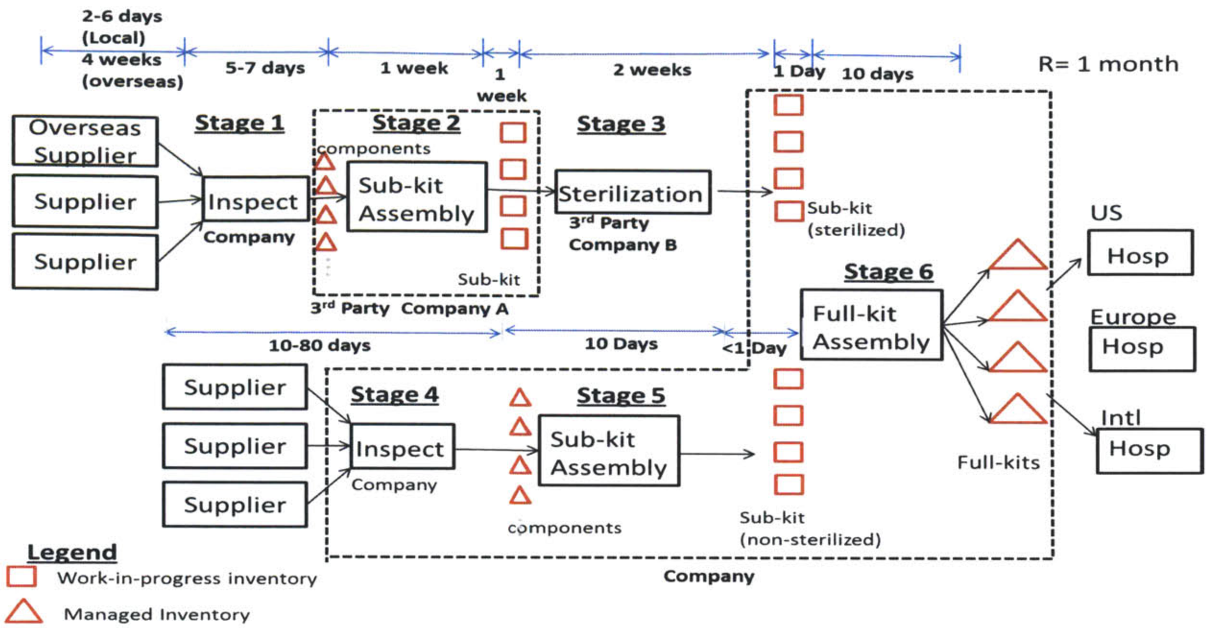


Figure 3-3: Base Case Scenario

The description of the Base Case Scenario can be found in Section 3.2.1: Existing Supply Chain. Lead times for individual components feeding into Stage 1 and Stage 4 are different depending on the location of the suppliers. Lead times for the remaining stages are calculated from the information provided by the firm as shown in Table 3-4.

Table 3-4: Lead Time and Review Period (Base Case Scenario) (MedCo)

Stage	Type	Total Lead Time (Days)	Review Period (Days)
Stage 1	Sterilized Components	Unique to item	30
Stage 4	Non-Sterilized Components	Unique to item	30
Stage 6	4 Final SKUs	50	30

3.4.1.2 Formulae

We estimated the monthly average and standard deviation (SD) of demand for each item in this case from known average monthly demand, monthly SD of the four final SKUs and the given BOM information using the following formulae:

$$\mu_i = \sum_{j=1}^{j=4} \mu_j * B_{ij} \qquad (3\text{-}17)$$

$$\sigma_i = \sqrt{(\sum_{j=1}^{j=4} \sigma_j * B_{ij})^2} \qquad (3\text{-}18)$$

where μ_i and σ_i are the average annual demands and SD of demands for each item, μ_j is the average annual demand for each of four final SKUs, σ_j is the SD of the demands for each of four final SKUs. B_{ij} is the number of item i to final SKU j.

The various cost components in this case are derived by using the formulae shown in Table 3-5.

Table 3-5: Formula for Safety Stock, Cycle Stock, and Relevant Costs (Base Case)

Order quantity	**(Q)**	Max ($\mu_i * R$, min order quantity)
Safety Stock	**(SS)**	Average Inventory – $Q/2$
Cycle Stock	**(CS)**	$Q/2$
Inventory Value		$(CS + SS) * v_i$
Annual Holding Cost		$v_i * h_i * (CS + SS)$
Annual Stock-Out Cost		$P_i * v_i * \sigma_{L+R} * G_{uk} * (1/R)$
Annual Ordering Cost		$A * N_s * (1/R)$

where μ_i is the average annual demand, R is the review period (in year), v_i is the cost of Component i, h_i is the annual holding cost of Component i (in $/$/year), P_i is the annual stock-out cost per item (in $/item/year), σ_{L+R} is the standard deviation of demand over lead time and review period (in units/year), G_{uk} is the unit loss function, A is the ordering cost per order ($/order).

3.4.2 Enhanced Base Case Scenario – Applying Base Stock Policy to the Base Case

3.4.2.1 Motivation and Purpose

As MedCo's current inventory management policy differs from the traditional ones that are mentioned in the Literature Review section, we examined whether, by just changing the inventory management policy to one of those above mentioned inventory management policies, we could achieve substantial improvements to the various cost components.

3.4.2.2 Description

The same base case supply chain model as shown earlier (see 3.4.1.1 Description) was adopted.

3.4.2.3 Formulae

The average demand and SD of the demand for all items, except the sterilized sub-kit and non-sterilized partial kits were calculated as described in the base case scenario.

Using the average demand and the SD of demand for each item, the optimal inventory levels and relevant costs associated with each stage can be determined using the formulae (Silver et al., 1998) summarized in Table 3-6, which is based on Base Stock Policy.

Table 3-6: Formulae for Safety Stock, Cycle Stock, and Relevant Costs (Enhanced Base Case)

Demand over L+R (μ_{L+R})	$(\mu_i) * (L + R)$
SD of demand over L+R (σ_{L+R})	$\sigma_i * \sqrt{(L+R)}$
Safety Stock (SS)	$z * \sigma_{L+R}$
Order up to level	$\mu_{L+R} + SS$
Cycle Stock (CS)	$(\mu_i * R)/2$
Inventory Value	$(CS + SS) * v_i$
Annual Holding Cost	$v_i * h_i * (CS + SS)$
Annual Stock-Out Cost	$P_i * v_i * \sigma_{L+R} * G_{uk} * (1/R)$
Annual Ordering Cost	$A * N_s * (1/R)$

where μ_i is the average annual demand (units/year), L is the lead time (in year), R is the review period (in year), v_i is the cost of Component i, h_i is the annual holding cost (in \$/\$/year), P_i is the annual stock-out cost per item (in \$/item/year), σ_{L+R} is the standard deviation of demand over lead time and review period (in units/year), G_{uk} is the unit loss function, A is the ordering cost per order (\$/order), N_s is the number of suppliers at the previous upstream stage.

3.4.3 Scenario 1 – Forward Placement with and without Partial Kits

3.4.3.1 Motivation and Purpose

We found that the four SKUs share several common components. Using the postponement concept mentioned in the Literature Review, we identified that by putting together common components that contribute to different set of SKUs, we could allow risk pooling of demand variation across final products, reduce lead time to final products and hence intuitively lead to lower inventory. We wished to study the benefits, if any, of combining the common sub-components together into partial kits that can contribute to the assembly of one or more final SKUs and stock them right before assembly. Furthermore, by establishing the inventory of sub-kits and partial kits right before the full-assembly process, it may reduce the replenishment lead time of the full-kits (SKUs) and hence reduce safety stock. On the other hand, this increased the lead times of Stages 3 and 5 and stocking items at an extra stage also increased the overall inventory in the system. We wished to study the effect of these countering arguments and analyze the trade-offs in terms of the various relevant cost components and the overall effect on the inventory value.

3.4.3.2 Description

In Scenario 1, inventories are maintained at Stages 1, 3, 4, 5 and 6. Inventory of the to-be-sterilized sub-kit right after the sub-kit process (Stage 2) is removed. Scenario 1 can be further broken down into two sub-scenarios – Scenario 1a and Scenario 1b. In Scenario 1a, inventories of both the current sterilized sub-kits and non-sterilized sub-kits are placed at Stage 3 and Stage 5, respectively. In Scenario 1b, a new form of non-sterilized **partial kits**, each comprising components that are common to the same set of various final kits, instead of the original non-sterilized sub-kits, is established in the distribution center at Stage 5, just prior to the full kit assembly stage (Stage 6).

As an illustration on the concept of partial kit, with reference to the BOM shown in

Table 3-1 3-1, Non-sterilized Component 3 (NS Comp 3), NS Comp 4 and NS Comp 11 are common to all the four final kits and they can be put into the same partial kit. NS Comp 5 and NS Comp 6 are common to three of the four final kits and they can be kitted as another partial kit.

For both sub-scenarios, we apply the Base Stock Policy for the inventory management in this case. Please see Figure 3-4 below.

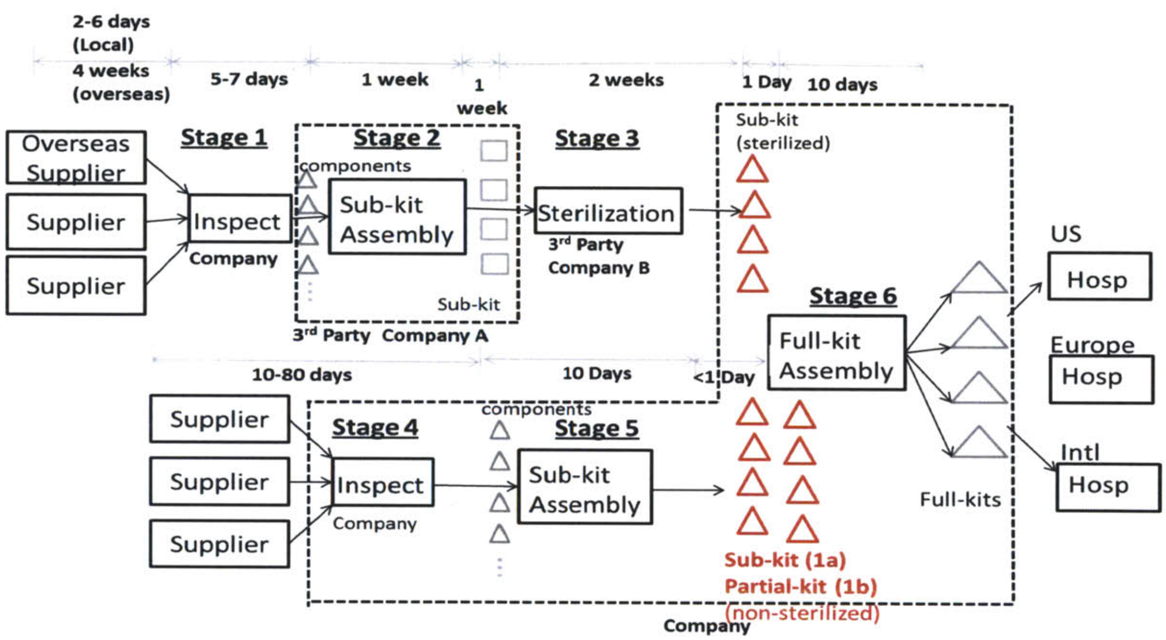


Figure 3-4: Scenario 1 – Forward placement; 1a (no partial kit) and 1b (with partial kits)

The lead time and review period of the various stages are the same as the Base Case Scenario.

3.4.3.3 Formulae

The average demand and SD of the demand for all items, except the sterilized sub-kit and non-sterilized partial kits are calculated as described in the Base Case. However, for the partial kits, we determined which partial kit can contribute to which of the SKUs, instead of using the existing Bill of Material (BOM). The formulae can be modified as shown:

$$\mu_i = \sum_{j=1}^{j=4} \mu_j * P_{ij} \quad (3\text{-}19)$$

$$\sigma_i = \sqrt{\left(\sum_{j=1}^{j=4} \sigma_j * P_{ij}\right)^2} \quad (3\text{-}20)$$

where μ_i and σ_i are the average annual demand and annual SD of demand for each item, respectively, μ_j is the average annual demand for each of four final SKUs. σ_j is the SD for each of four final SKU j, P_{ij} is the binary variables for Partial Kit i that can contribute to the assembly of final SKU j.

Using the average demand and the SD of demand for each item, the optimal inventory levels and relevant costs associated with each stage can be determined using the formulae (Silver et al., 1998) summarized in Table 3-6, which is based on Base Stock Policy.

3.4.4 Scenario 2 – Reduced Lead Time and Review Period of Stage 6

3.4.4.1 Motivation and Purpose

It emerged during our discussions with the firm that the final assembly of the finished products can be accomplished in 1.5 days instead of the regular 10 days. The extra time was due to the awaiting labor period, and could be potentially eliminated by detailed manpower scheduling. In addition, based on our literature review on Periodic Review, Order-Up-To (Base Stock) System, we noted that shorter review period should also lead to reduced relevant costs and smaller inventory. We wished to study the effect of reducing lead time and review periods on the various relevant costs and the inventory value. We incorporated this capability of the firm into the model to demonstrate the benefits of reducing lead time to Stage 6 on the overall relevant costs. We also altered the review period to a fortnight instead of a month to study the combined effects of these changes using this scenario. Here, we used the original sub-kits (as in Base Case scenario) instead of newly proposed partial kits, so as to not convolute our study of the specific effect with the other effect.

3.4.4.2 Description

As in the Base Case Scenario, the same types of inventories are maintained at Stages 1, 4 and 6. Lead time of Stage 6 is reduced to 1.5 days, based on the possibility that we described above, and the review period of Stage 6 is reduced from 30 days to 14 days. Please see the Figure 3-5 below.

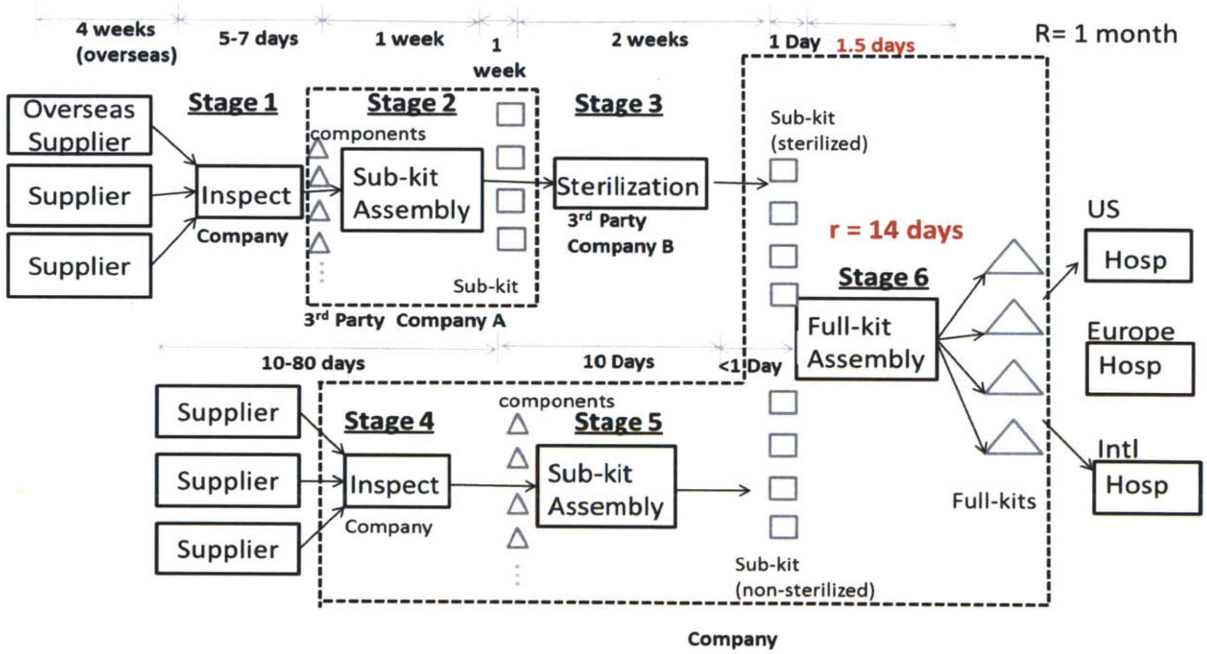


Figure 3-5: Scenario 2 – Reduced Lead Time and Review Period

The lead times and review periods are shown in the Table 3-7.

Table 3-7: Lead Times and Review Periods of the Various Stages (Scenario 2)

Stage	Type	Total Lead Time (Days)	Review Period (Days)
Stage 1	Sterilized Components	Unique to item	30

Stage 4	Non-Sterilized Components	Unique to item	30
Stage 6	4 Final SKUs	41.5	14

3.4.4.3 Formulae

The same set of formulae used for Enhanced Base Case scenario as shown in the Table 3-6 is used for Scenario 2 as well.

3.4.5 Scenario 3 – Combined Kits

3.4.5.1 Motivation and Purpose

We observed that SKU 1 and SKU 2 share many common components (~80% of their list of components are common), and they could be potentially combined. As discussed in our Literature Review, by combining the two SKUs into one SKU, the point of differentiation for the final product is pushed from Stage 6 downstream to the customer's end. This is, in effect, application of the **form postponement** strategy (Lee & Tang, 1997). The average monthly demands for the two products are very different with the average demand of SKU 1 being low and the coefficient of variation being very high for SKU 1. This grouping will pool demand variation across these SKUs and lead to lower overall inventory levels.

However, an increase in the material cost of the SKUs and marginal wastage are expected, as there would be additional components in the new SKU given to the customers that originally ordered either SKU 1 or SKU 2. We wished to utilize Scenario 3 to study the effect of combining these final products on the total relevant costs for the system.

3.4.5.2 *Description*

In Scenario 3, the two final SKUs – SKU 1 and SKU 2 – are combined and a new SKU, SKU 12. SKU 12 will contain all the components from the non-sterilized and sterilized sub-kit of both the SKU 1 and SKU 2. Customers who originally require SKU 1 will instead order SKU 12. With this, they will receive components of the original SKU 1 and also additional items that belong to the original SKU 2. Likewise, customers who originally require SKU 2 will order SKU 12 instead, and receive components of the original SKU 2 and also additional items that belong to the original SKU 1.

Inventories are maintained at Stages 1, 4 and 6 similar to the Base Case. The Base Stock Policy is used, and the lead times and review period are also kept the same as those in the Base Case to uniquely identify the effect of only merging two SKUs. Please see the Figure 3-6.

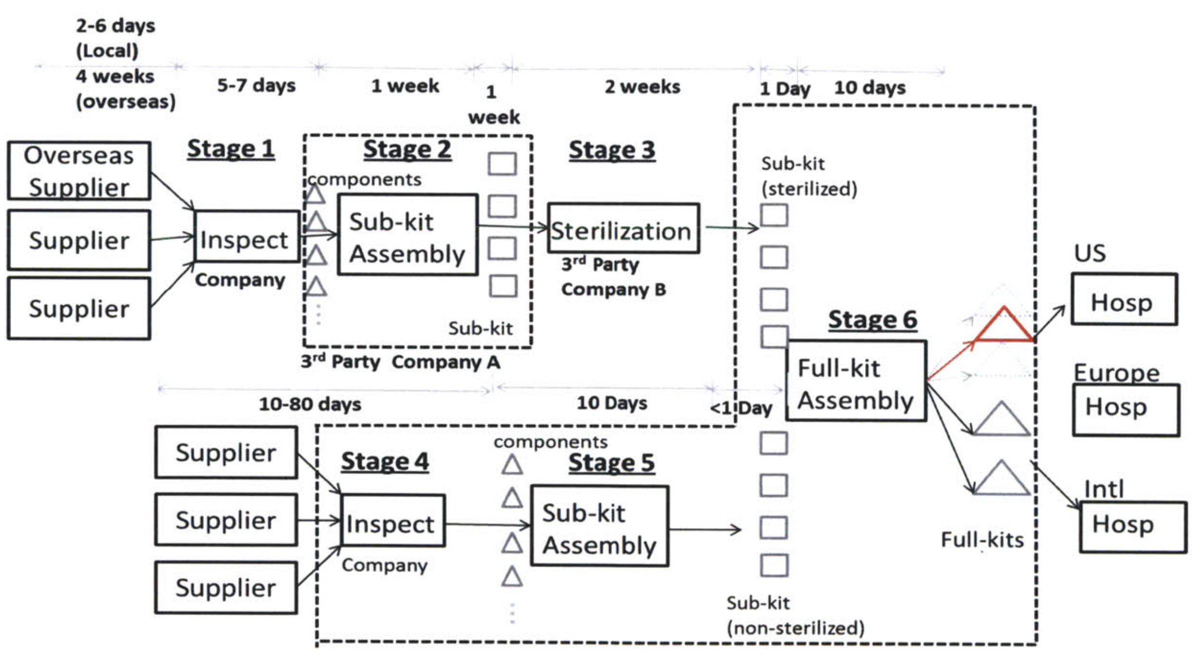


Figure 3-6: Scenario 3 – Combined Kit

3.4.5.3 Formulae

The formulae to derive the average demand and the SD of demand for each component in this case were modified from that of Scenario 1 and are shown below.

$$\mu_i = \sum_{j=1}^{j=3} \mu_j * C_{ij} \tag{3-21}$$

$$\sigma_i = \sqrt{\left(\sum_{j=1}^{j=3} \sigma_j * C_{ij}\right)^2} \tag{3-22}$$

where μ_i and σ_i are the average demand and SD of demands, respectively, for each component; μ_j is the average demand for each of the three final SKUs; σ_j is the SD for each of three final SKUs; C_{ij} is the number of Item i contributed to one of the new set of final SKU j. The rest of the calculations of the cost components are the same as those for the Enhanced Base Case Scenario. See Table 3-6.

3.4.6 Scenario 4 – Continuous Review System

3.4.6.1 Motivation and Purpose

As highlighted in our Literature Review section, there are two traditional inventory management models – one of them being the Periodic Review, Order-up-to (aka Base Stock) Model, which was used in the previous scenarios, and the other being the Continuous Review, Re-order Point (aka "two bins") Model. The latter system would theoretically achieve a lower inventory value given the same Cycle Service Level (CSL). However, the savings in inventory value may be offset by a certain extent by increased ordering costs. In addition, this scenario is difficult to manage in the real world, with each item having its own re-order point, though it can be made much easier to do so using IT system. MedCo has recently introduced a new IT system for inventory management, and hence this provides an opportunity for using the Continuous Review model. Notwithstanding the challenges of implementation, we wished to study the use of Continuous Review, Re-order Point (Q, s) model, in order to quantify the trade-offs between inventory value and ordering cost, and the effect on the Total Relevant Cost and the inventory value.

3.4.6.2 Description

In this scenario, we adopt the (Q, s) (aka "two bins") System, as described in our Literature Review section. Inventory policy is changed from the Base Stock Policy to the Continuous Review, Re-Order Point Policy for all stages. While the placement of the inventories and the lead times remain unchanged vis-à-vis the Base Case (see the diagram depicting the Base Case scenario for reference to Scenario 4), the review period is reduced to zero and orders are placed for each item once the inventory position drops below the designated re-order point. The lead times and review periods are shown Table 3-8.

Table 3-8: Lead Times and Review Periods of the Various Stages (Scenario 4)

Stage	Type	Total Lead Time (Days)	Review Period (Days)
Stage 1	Sterilized Components	Unique to item	0
Stage 4	Non-Sterilized Components	Unique to item	0
Stage 6	4 Final SKUs	50	0

The average demand and SD of demands for the items are determined as in the Base Case Scenario. For Continuous Review policy, the various relevant costs in the system are derived by using the formulae (Silver et al., 1998) shown in the Table 3-9.

Table 3-9: Formulae for Inventory value and Relevant Costs (Scenario 4)

Demand over Lead Time (L) (μ_L)	$\mu_i * L$
SD over Lead Time (σ_L)	$\sigma_i * \sqrt{L}$
Safety Stock (SS)	$z * \sigma_L$
Re-Order Point (s)	$\mu_L + SS$
Cycle Stock (CS)	$(\sqrt{2 * A * \mu_i/(h_i * v_i})/2$
Inventory Value	$(CS + SS) * v_i$
Annual Holding Cost	$v_i * h_i * (CS + SS)$
Annual Stock Out Cost	$P_i * v_i * \sigma_{L+R} * G_{uk} * (\mu_i * 12)/(CS * 2)$
Annual Ordering Cost	$A * (\mu_i * 12)/(CS * 2)$

where μ_i is the average annual demand (units/year), L is the lead time (in year), R is the review period (in year), v_i is the cost of Component i, h_i is the annual holding cost (in \$/\$/year), P_i is the annual stock-out cost per item (in \$/item/year), σ_{L+R} is the standard deviation of demand over lead time and review period (in units/year), G_{uk} is the unit loss function, A is the ordering cost per order (\$/order), N_s is the number of suppliers at the previous upstream stage.

3.4.7 Scenario 5 – Combined Scenario 2 (Reduced Lead Time and Review Period) and Scenario 3 (Combining kits)

3.4.7.1 Motivation and Purpose

We wished to bring the best inputs from all scenarios together in this scenario. Scenario 5 is the combination of Scenario 2 and Scenario 3, and not the others, for several reasons. Firstly, since the use of partial kits would require the placement of inventory at Stage 3 and Stage 5, which results in worse off TRC and inventory value (See Section 4), it is not being used. The Continuous Review system is also not adopted because the system may be difficult to implement. Henceforth, we only chose to reduce the lead time and review period for Stage 6 (Scenario 2) and combine two of the SKUs (Scenario 3) that allowed risk pooling of demand variation across the final products.

3.4.7.2 Description

Inventories are maintained at Stages 1, 4 and 6. SKU 1 and 2 are merged into SKU 12. The lead time of Stage 6 is reduced to 1.5 days and the review period for Stage 6 is changed to 14 days, which was determined to be close to optimal by a sensitivity analysis on the review period. Please see Figure 3-7 that depicts the supply chain of Scenario 5.

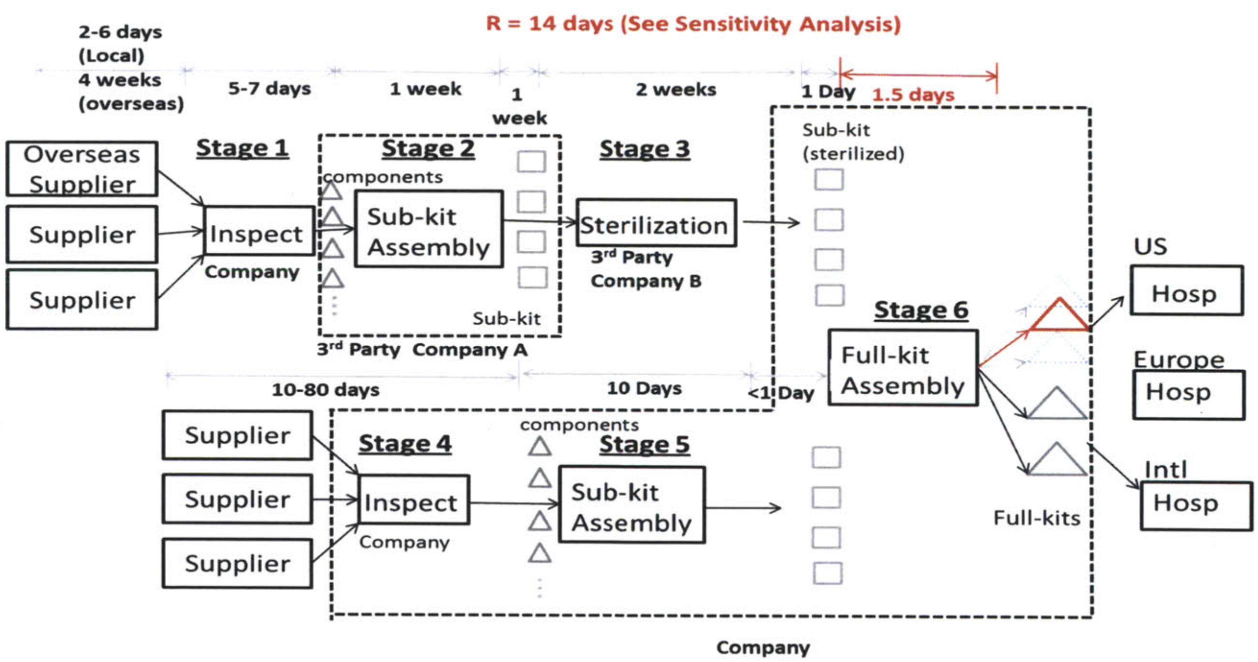


Figure 3-7: Scenario 5 - Combined Scenario 2 and Scenario 3

The lead times and the review periods of the various stages are shown in the Table 3-10.

Table 3-10: Lead Times and Review Periods for the Various Stages (Scenario 5)

Stage	Type	Total Lead Time (Days)	Review Period (Days)
Stage 1	Sterilized Components	Unique to item	30
Stage 4	Non-Sterilized Components	Unique to item	30
Stage 6	3 Final SKUs	41.5	14

3.4.7.3 Formulae

The average demands and SD of demands for all items are calculated using the formulae below.

$$\mu_i = \sum_{j=1}^{j=3} \mu_j * C_{ij} \quad (3\text{-}23)$$

$$\sigma_i = \sqrt{\left(\sum_{j=1}^{j=3} \sigma_j * C_{ij}\right)^2} \quad (3\text{-}24)$$

where μ_i and σ_i are the average annual demand and annual SD of demands for each item, respectively, μ_j is the average annual demands for the three final SKUs, σ_j is the annual SDs for the three final SKUs, C_{ij} is the number of Item i that contributes to one of the final SKU j.

The same set of formulae used for the Enhanced Base Case Scenario as shown in Table 3-6 is used for Scenario 5 as well.

3.4.8 Strategic Inventory Placement (SIP)

3.4.8.1 Motivation and Purpose

Although we have discussed possible changes to inventory management policies and kitting techniques in the above scenarios, we have not yet looked at placement of inventory from a strategic perspective – whether it is indeed the best strategy to keep inventory at Stages 1, 4 and

6; if yes, what are the items we should stock; whether stocking all or none at a stage yields the lowest costs; what are the service times that a stage works with; and whether it is the best technique to let stages guarantee the lowest service times they can to their successors. In this sub-section, we examine the above questions using the SIP /Guaranteed Service Model described in the Literature Review and Methodology sections.

3.4.8.2 Description

We chose to optimize two scenarios: Enhanced Base Case and Scenario 5. While the former represents optimal inventory levels for the current supply chain strategy, the latter synthesizes the best of all scenarios discussed above and represents the optimal inventory levels for an improved supply chain strategy.

First, we identify the service times various stages work with before optimization using the proposed safety stock levels for both the Enhanced Base Case and Scenario 5. The following figure showcases the current inventory placement strategy and depicts inventory levels graphically.

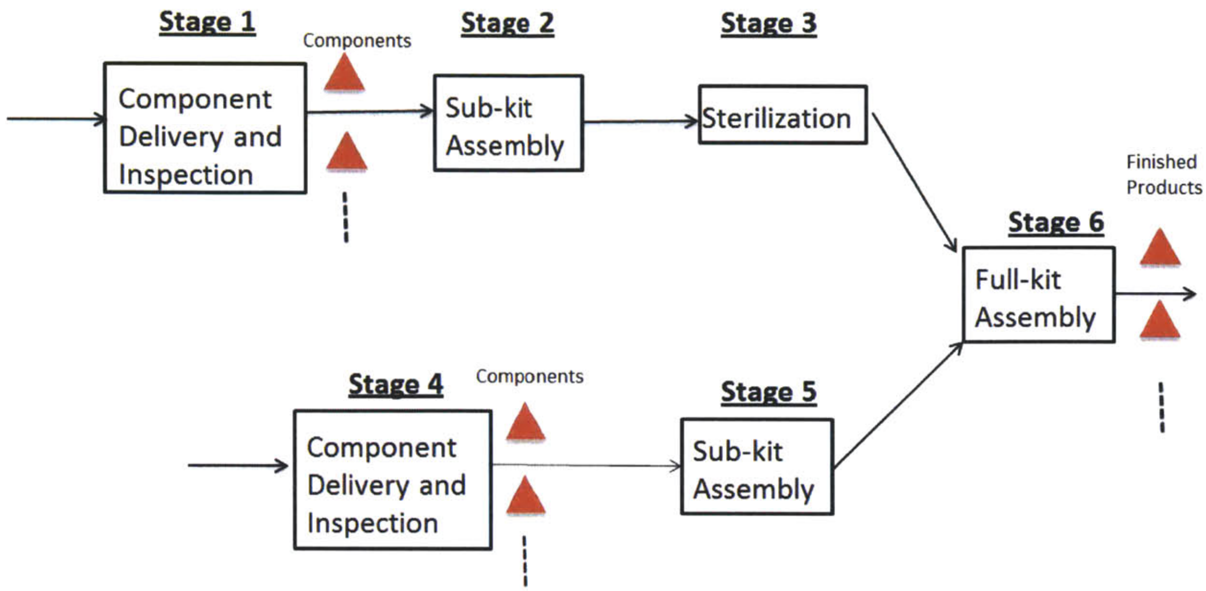


Figure 3-8: Graphical representation of inventory levels before optimization

Next, we consider two strategies to optimize the network:

1. Keep only partial inventory of components at Stages 1 and 4 (those with longer lead times) and increase inventory level at final assembly stage, Stage 6. This strategy is graphically represented in the diagram below.

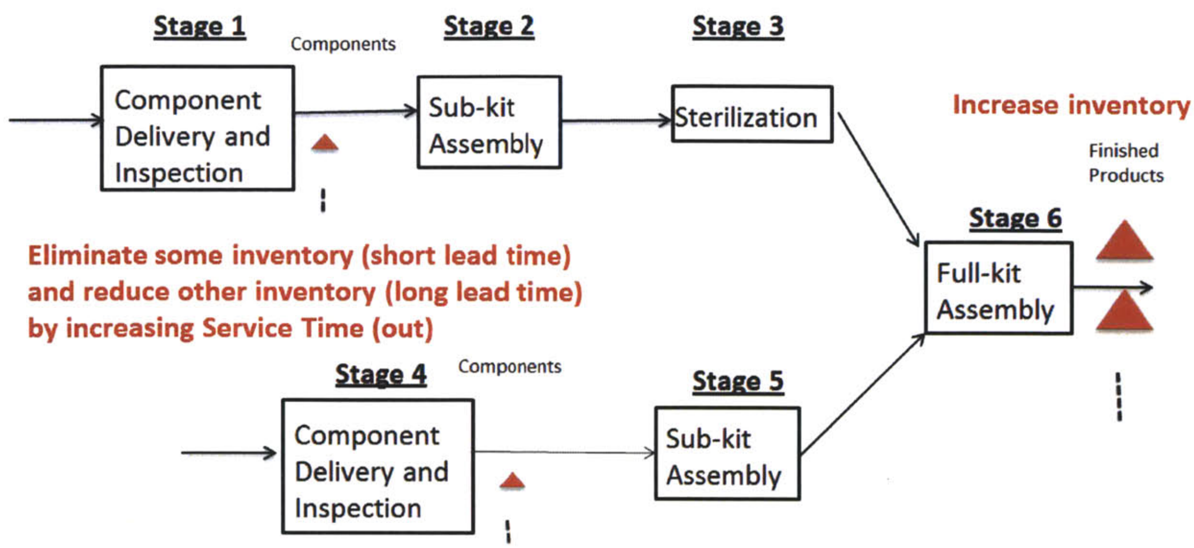


Figure 3-9: Graphical Representation of Inventory Levels after Optimization – Alternative A

2. Eliminate all component inventories from the network and keep only finished products inventory at Stage 6. This strategy is depicted diagrammatically in Figure 3-10.

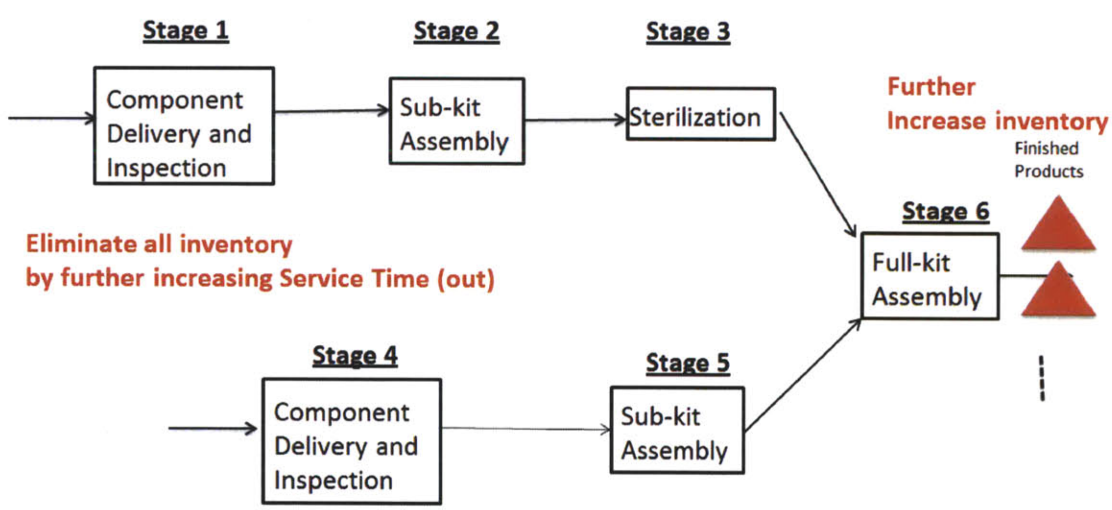


Figure 3-10: Graphical Representation of Inventory Levels after Optimization – Alternative B

We consider the two alternatives to weigh the benefits and risks associated in each case. While Alternative B suggests easier inventory management and the lowest Total Relevant Cost, it also introduces some risk into the network by maintaining a flow-through system. Alternative A, in this perspective serves as a near optimal strategy with low Total Relevant Cost while still keeping some inventory upstream to manage risk.

We developed an MILP based on the SIP model with the objective to minimize the total safety stock holding cost for the entire network, as described in Section 3.3.4 above. Although we could have used Microsoft Excel Solver to optimize the problem, we used the business logic described in the SIP model to identify the best combination of service times since the Excel solver has limited capabilities in handling non-linear equations.

The key parameters to the SIP model are recorded in Table 3-11.

Table 3-11: Input parameters to the SIP Model

Stage	S_{in} (days)	T (days)	S_{out} (days)
1	0	Unique to item	Decision Variable
2	$S_{out\text{-}Stage1}$	T_{Stage2}	$S_{out\text{-}Stage1} + T_{Stage2}$
3	$S_{out\text{-}Stage2}$	T_{Stage3}	$S_{out\text{-}Stage2} + T_{Stage3}$
4	0	Unique to item	$S_{out\text{-}Stage2} + T_{Stage3} - T_{Stage5}$
5	$S_{out\text{-}Stage4}$	T_{Stage5}	$S_{out\text{-}Stage2} + T_{Stage3}$
6	$S_{out\text{-}Stage5}$	T_{Stage6}	0

We assume that the external suppliers to Stages 1 and 4 maintain enough inventories so as to respond immediately to the network's demand and hence set S_{in} for both these stages to be 0 days. S_{out} of Stage 6 is constrained to 0 days because of the customer's requirement. We vary S_{out} of Stage 1 to switch between Alternatives A and B and derive the remaining service times based on the constraints. S_{out} of Stage 4 derived from the total lead times only defines the maximum allowable limit of S_{out} for all individual components. The details on how the service times are derived are given in Section 4.11.

4 Data Analysis and Results

In this section, we first present the demand analysis for the four SKUs, recap the strategies, and then state the assumptions for our analysis. Subsequently, we present the results, analysis and also key insights drawn from every scenario described in Section 3.

4.1 Demand Analysis

We calculated the average monthly demand and the Standard Deviation (SD) of the demand for the four final SKUs using the methods described in Section 3. Table 4-1 records the Coefficient of Variation (COV) for these products.

Table 4-1: Coefficient of Variation of Demand for 4 SKUs

	SKU 1	SKU 2	SKU 3	SKU 4
COV	0.794	0.175	0.242	0.891

Since COV values greater than 0.5 typically indicate high variation, we identified that demands for SKU 2 and 3 are stable while demands for SKU 1 and 4 are highly variant. Table 4-2 records the Coefficients of Correlation between pairs of demands of the final SKUs.

Table 4-2: Coefficient of Correlation between Demands for all the 4 SKUs

	SKU 1	SKU 2	SKU 3	SKU 4
SKU 1	-	0.129	0.096	0.033
SKU 2		-	0.379	-0.173
SKU 3			-	0.045
SKU 4				-

As the Coefficients of Correlation are close to 0, we noted that the demands for the products are independent from each other. Hence the SDs of the demands for individual items were determined in the following scenarios.

4.2 Recap of Strategies Used

Before we discuss the results, we would like to recap the strategies that we used in our research. Table 4-3 gives a brief description of the strategies that were explained previously in Section 3.4.

Table 4-3: Brief Description of Strategies

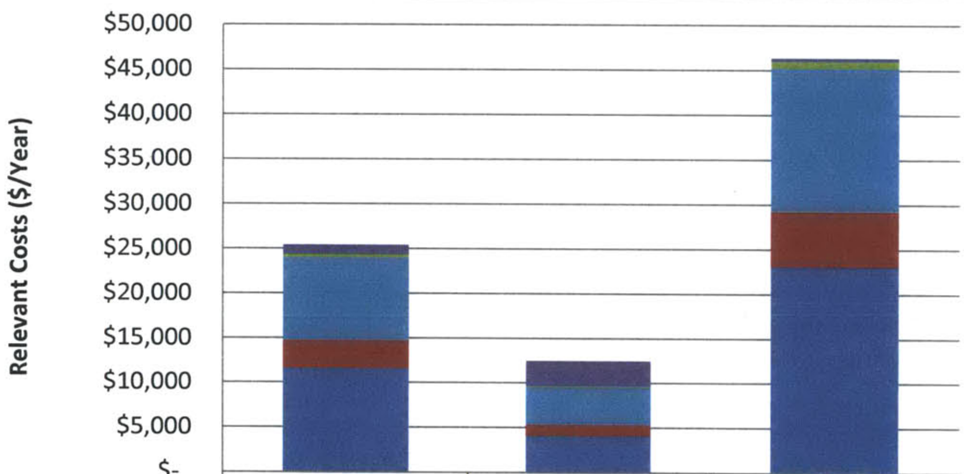
Strategy Number	Strategy (Scenario)	Description of Strategy
0	**Base Stock Policy** (Enhanced Base Case)	Apply Base Stock Policy for the whole supply chain with safety stock and cycle stock calculations using formulae given by Silver et al. (1998)
1a	**Forward placement of inventory without Partial Kits** (Scenario 1a)	Placement of sterilized sub-kits and **non-sterilized sub-kits** inventory before Full Kit Assembly at Stage 3 and Stage 5, respectively.
1b	**Forward placement of inventory with Partial Kits** (Scenario 1b)	Placement of sterilized sub-kits and non-sterilized **partial kits** inventory before Full Kit Assembly at Stage 3 and Stage 5, respectively.
2	**Reduced Review Period and Lead Time of Stage 6** (Scenario 2)	Reduce review period to 14 days and shorten lead time to 1.5 days for Stage 6.
3	**Combined Kits** (Scenario 3)	Combine two of the four full kits which have 80% of their components in common.
4	**Continuous Review System** (Scenario 4)	Use Continuous Review System across the whole supply chain.
5	**Combined Scenario 2 and Scenario 3** (Scenario 5)	Reduce review period to 14 days and shorten lead time to 1.5 days for Stage 6. Combine two of the four full kits which have 80% of their components in common.

A	**Strategic Inventory Placement Alternative A (SIP A)** (Enhanced Base Case–Alternative A and Scenario 5 – Alternative A)	Reduce inventory of components at Stage 1 and Stage 4 only. Increase inventory of finished products at Stage 6.
B	**SIP B** (Enhanced Base Case–Alternative B and Scenario 5– Alternative B)	Eliminate inventory of components at Stage 1 and Stage 4 only. Further increase inventory of finished products at Stage 6.

4.3 Base Case

4.3.1 Results

The sum of the safety stock (SS), cycle stock (CS) and pipeline (PL) holding costs, stock-out costs and ordering costs for all items at the three stages of inventory is presented in Figure 4-1.



	Stage 1	Stage 4	Stage 6
Ordering Cost	$1,095	$2,920	$365
Stock-Out Cost	$358	$113	$807
PL Holding Cost	$9,239	$4,157	$15,943
CS Holding Cost	$3,154	$1,233	$6,202
SS Holding Cost	$11,596	$4,129	$23,075

Figure 4-1: Baseline – Relevant Costs Distribution across Stages of Inventory

We noted that the different holding costs form a major part of the Total Relevant Cost (TRC) for all stages. The pipeline holding costs for Stages 2, 3 and 5 are added to those of Stage 6, because inventory keeps flowing through the chain. However, the ordering costs are higher for Stages 1 and 4 since they depend on the number of suppliers for each stage. The total inventory investment and relevant costs for the Base Case are recorded in Table 4-4.

Table 4-4: Base Case – Comparison of Costs

	Base Case
Inventory Value	$355,745
Total Relevant Cost	$84,386

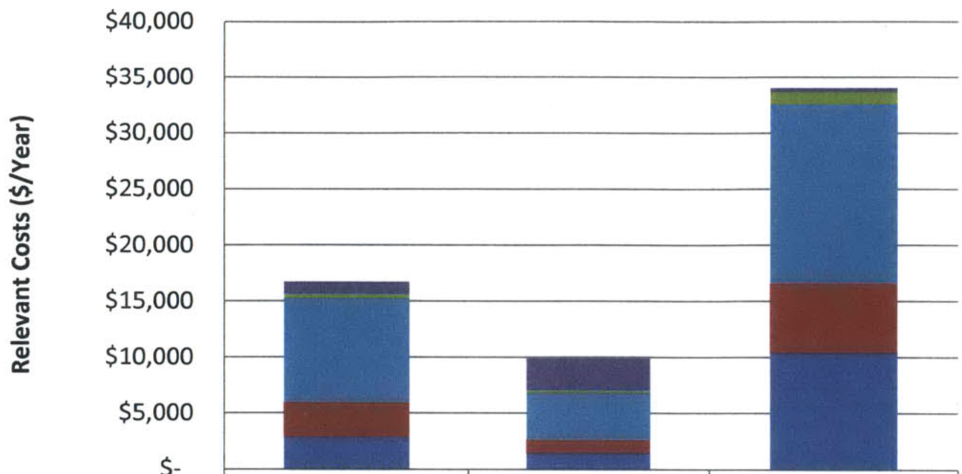
4.3.2 Insights

There is almost as much pipeline inventory across the supply chain as the total cycle stock and safety stock inventory being held at various stages. The safety stock holding cost and stock-out cost are greater at Stage 6 than at earlier stages because of the value-added to the inventory through sterilization and kitting across the network.

4.4 Enhanced Base Case – Applying Base Stock Policy

4.4.1 Results

The sum of relevant costs for all items at each of the four stages is calculated and the results are presented in Figure 4-2.



	Stage 1	Stage 4	Stage 6
Ordering Cost	$1,095	$2,920	$365
Stock-Out Cost	$358	$184	$1,077
PL Holding Cost	$9,239	$4,157	$15,943
CS Holding Cost	$3,154	$1,233	$6,206
SS Holding Cost	$2,895	$1,488	$10,450

Figure 4-2: Enhanced Base Case – Relevant Costs Distribution across Stages of Inventory

We observed that although the safety stock holding costs and ordering costs remain the same as in the Base Case, the holding costs of cycle stock and pipeline inventory go down in this scenario. These savings are expected to contribute to about 28% reduction in Total Relevant Cost from the Base Case. Table 4-5 records the improvements over the Base Case in terms of inventory value and the Total Relevant Costs required in the two cases.

Table 4-5: Enhanced Base Case – Comparison of Costs from Base Case

	Base Case	Enhanced Base Case	Improvement over Base Case
Inventory Value	$355,745	$181,191	49%
Total Relevant Cost	$84,386	$60,763	28%

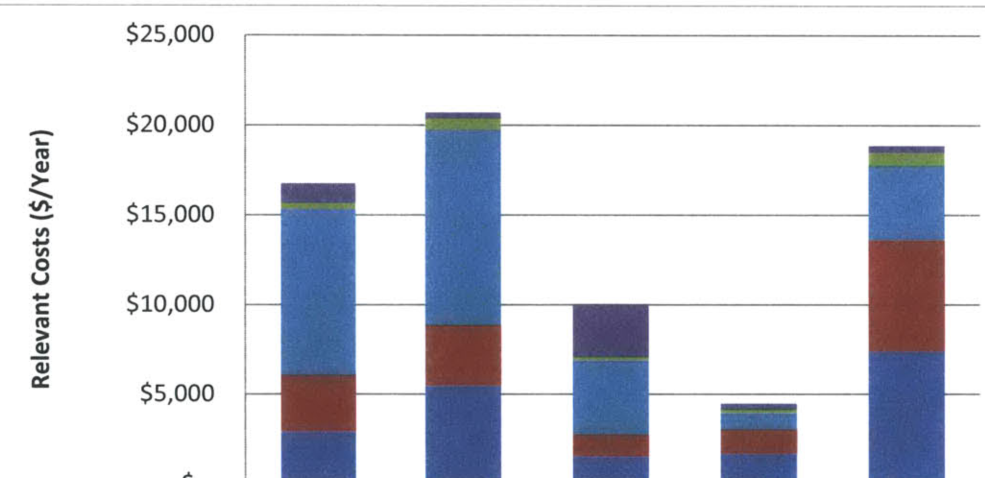
4.4.2 Insights

We noted that calculating safety stock based on the variation of demand rather than the demand itself leads to large cost reductions. The inventory value can almost be halved and TRC reduced by nearly one-third by simply applying the formulae of the Base Stock policy. The stock-out costs are higher because of leaner inventory carried through the supply chain. However, the benefits achieved in costs compensate for the marginal increase of the risk of stocking out.

4.5 Scenario 1a - Forward Placement of Inventory without Partial Kits

4.5.1 Results

The sum of the costs for the five inventorying stages is presented in Figure 4-3.



	Stage 1	Stage 3	Stage 4	Stage 5	Stage 6
Ordering Cost	$1,095	$365	$2,920	$365	$365
Stock-Out Cost	$358	$611	$184	$188	$762
PL Holding Cost	$9,239	$10,896	$4,157	$910	$4,137
CS Holding Cost	$3,154	$3,364	$1,233	$1,365	$6,206
SS Holding Cost	$2,895	$5,460	$1,488	$1,664	$7,381

Figure 4-3: Scenario 1a – Relevant Costs Distribution across Stages of Inventory

We observed that since inventory is maintained at Stages 3 and 5 now, the stock-out costs and the holding costs for Stage 6 go down in comparison with the Base Case and the Enhanced Base Case scenarios. However, the impact is offset by the increase in inventory at both Stages 3 and 5, resulting in an overall cost increase, as compared with the Enhanced Base Case Scenario. The costs are compared in Table 4-6 below.

Table 4-6: Scenario 1a – Comparison of Costs from Base Case and Enhanced Base Case

	Base Case	Enhanced Base Case	Scenario 1a	Improvement over Base Case	Improvement over Enhanced Base Case
Inventory Value	$355,745	$181,191	$246,780	31%	-36%
Total Relevant Cost	$84,386	$60,763	$70,760	16%	-16%

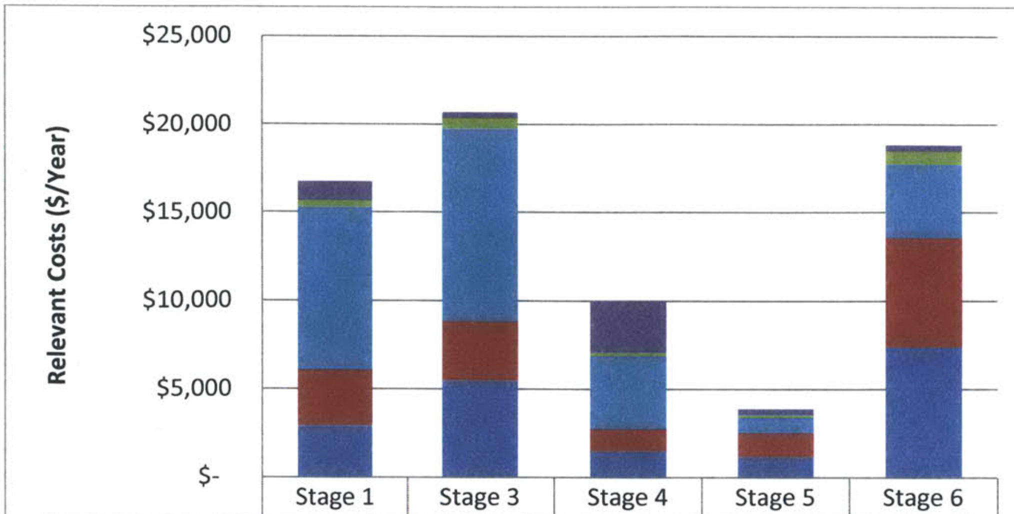
4.5.2 Insight

This scenario is only utilized in combination with the next one, Scenario 1b, to determine the benefits of using partial kits. The benefits of reducing risk of stock-out are outweighed by the rise in Total Relevant Costs when inventory is maintained at additional stages.

4.6 Scenario 1b - Forward Placement of Inventory with Partial Kits

4.6.1 Results

The sum of the costs for the five inventorying stages is presented in Figure 4-4.



	Stage 1	Stage 3	Stage 4	Stage 5	Stage 6
Ordering Cost	$1,095	$365	$2,920	$365	$365
Stock-Out Cost	$358	$611	$184	$130	$762
PL Holding Cost	$9,239	$10,896	$4,157	$910	$4,137
CS Holding Cost	$3,154	$3,364	$1,233	$1,333	$6,206
SS Holding Cost	$2,895	$5,460	$1,488	$1,150	$7,381

Figure 4-4: Scenario 1b – Relevant Costs Distribution across Stages of Inventory

We noted that the relevant costs remain the same for all stages as those in Scenario 1a, except for Stage 5. This stage incurs a 13% reduction in combined holding and stock-out costs since we can better forecast demand by pooling the risk across different SKUs. However, the overall cost results still remain higher than in the Enhanced Base case scenario as shown in Table 4-7.

Table 4-7: Scenario 1b – Comparison of Costs from Base Case and Enhanced Base Case

	Base Case	Enhanced Base Case	Scenario 1b	Improvement over Base Case	Improvement over Enhanced Base Case
Inventory Value	$355,745	$181,191	$242,804	32%	-34%
Total Relevant Cost	$84,386	$60,763	$70,157	17%	-15%

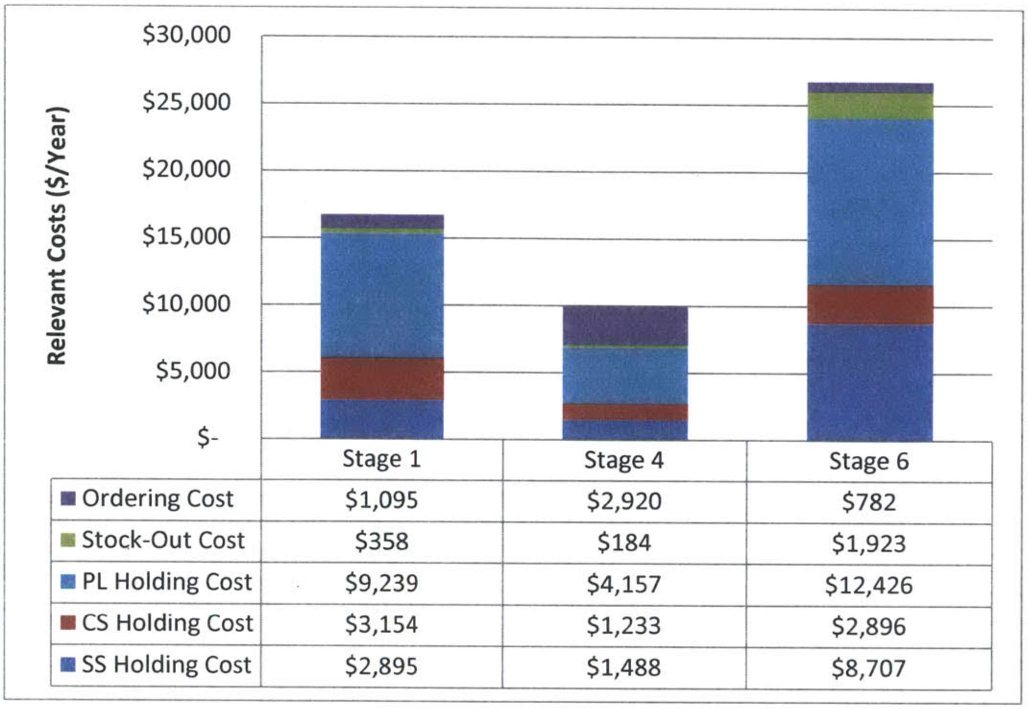
4.6.2 Insight

Using partial kits instead of sub-kits reduces the overall relevant costs to a very small extent compared with the Base Case and even increases them relative to the Enhanced Base Case. Since the COV of the two final SKUs are relatively high, the combined SD for partial kits does not reduce the costs by much. Hence, the forward placement of these partial kits to additional stages did not emerge as a good idea due to the increase of costs for that stage. Therefore, we did not consider it further in combination with other techniques discussed below.

4.7 Scenario 2 - Reduced Lead Time and Review Period of Stage 6

4.7.1 Results

Figure 4-5 presents the sum of the relevant costs for all items at each of the three stages of inventorying in this case.



	Stage 1	Stage 4	Stage 6
Ordering Cost	$1,095	$2,920	$782
Stock-Out Cost	$358	$184	$1,923
PL Holding Cost	$9,239	$4,157	$12,426
CS Holding Cost	$3,154	$1,233	$2,896
SS Holding Cost	$2,895	$1,488	$8,707

Figure 4-5: Scenario 2 – Relevant Costs Distribution across Stages of Inventory

We noticed that this scenario gives the best TRC when compared to all scenarios discussed earlier. Stage 6 contributes the most reduction to the overall costs. Specifically, even though the ordering costs and stock-out costs increase relative to the earlier cases, the holding cost for Stage 6 drops by about 46% relative to the Base Case to cause this effect. We tabulated the improvements from the Base Case and Enhanced Base Case in Table 4-8.

Table 4-8: Scenario 2 – Comparison of Costs from Base Case and Enhanced Base Case

	Base Case	Enhanced Base Case	Scenario 2	Improvement over Base Case	Improvement over Enhanced Base Case
Inventory Value	$355,745	$181,191	$147,507	59%	19%

Total Relevant Cost	$84,386	$60,763	$53,642	36%	12%

4.7.2 Insight

Reducing the lead time and review period has a significant impact on the relevant costs, more so than using partial kits or forward placing the inventory of sub-kits. The full kitting process can be aligned to the review period of 14 days, since, on average, 600 full kits can be assembled in 1.5 days. Hence, the total monthly demand for all SKUs of about 1200 can be assembled twice a month or every 14 days.

4.7.3 Sensitivity Analysis of TRC and Inventory Value Using Review Period

We did a sensitivity analysis of the Total Relevant Cost and the inventory values using different review periods to identify the range of review periods that lead to lowest overall costs in the system. Figure 4-6 below plots these costs for review periods from 1 to 30 days.

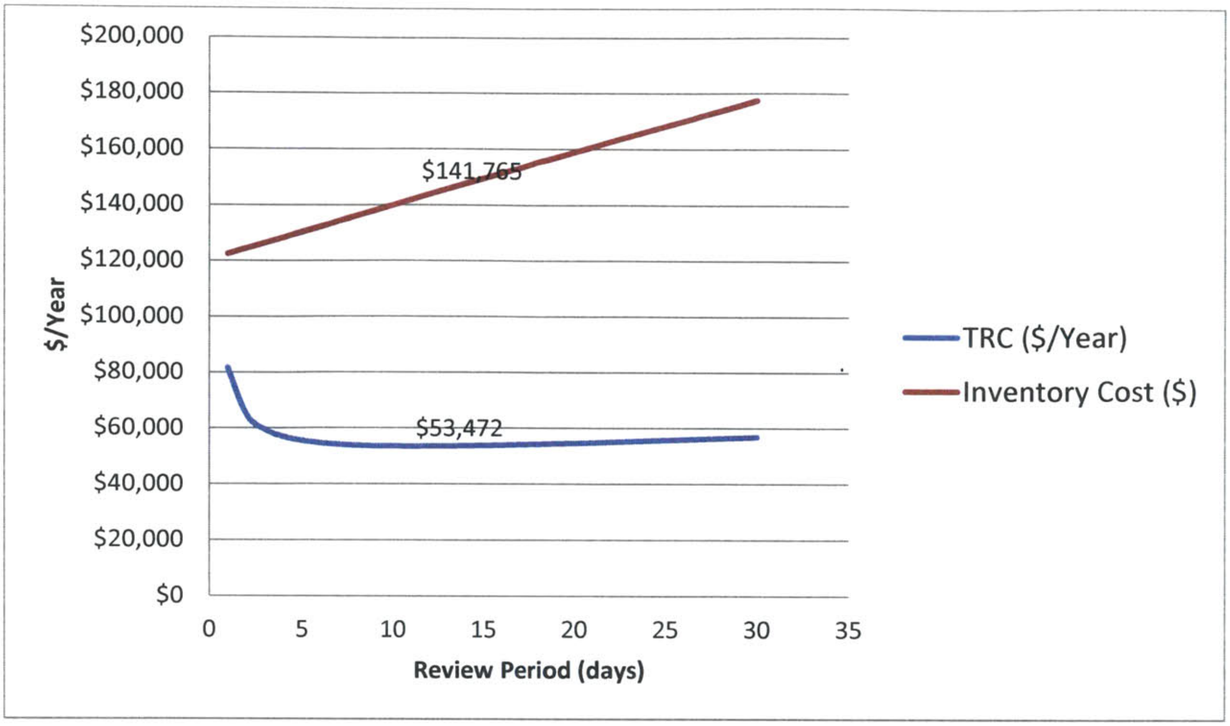


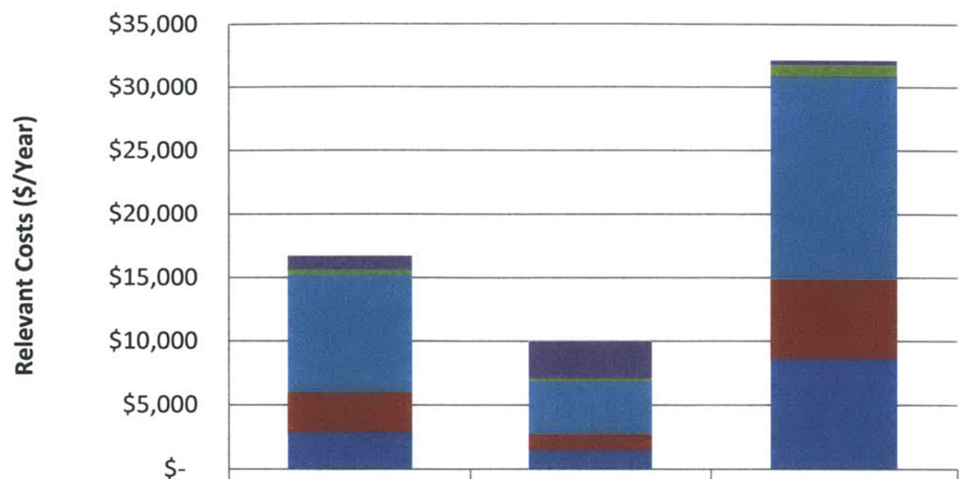
Figure 4-6: Sensitivity Cost of Inventory Value and TRC to Review Period (Scenario 2)

The TRC curve remains fairly flat over the review period range from 5 to 15 days and the lowest point is obtained at R=11 days. Although the lowest Total Relevant Cost occurs at a review period of 11 days, we choose a near optimal review period of 14 days because it not only provides near optimal costs but also serves as a more manageable time period (fortnightly) to review inventory.

4.8 Scenario 3 - Combined Kits

4.8.1 Results

The sum of relevant costs for all items at the three stages of inventory is shown in Figure 4-7.



	Stage 1	Stage 4	Stage 6
Ordering Cost	$1,095	$2,920	$365
Stock-Out Cost	$358	$187	$889
PL Holding Cost	$9,239	$4,157	$15,997
CS Holding Cost	$3,154	$1,273	$6,287
SS Holding Cost	$2,895	$1,510	$8,634

Figure 4-7: Scenario 3 – Relevant Costs Distribution across Stages of Inventory

We observed that the stock-out cost is lower in Scenario 3 when compared with all the scenarios since there is one less final SKU. However, the safety stock and pipeline holding costs are higher than those in Scenario 2 because of the difference in lead time. The percentage improvements over Base Case and Enhanced Base Case are presented in Table 4-9.

Table 4-9: Scenario 3 – Comparison of Costs with Base Case and Enhanced Base Case

	Base Case	Enhanced Base Case	Scenario 3	Improvement over Base Case	Improvement over Enhanced Base Case
Inventory Value	$355,745	$181,191	$170,126	52%	6%
Total Relevant Cost	$84,386	$60,763	$59,325	30%	2%

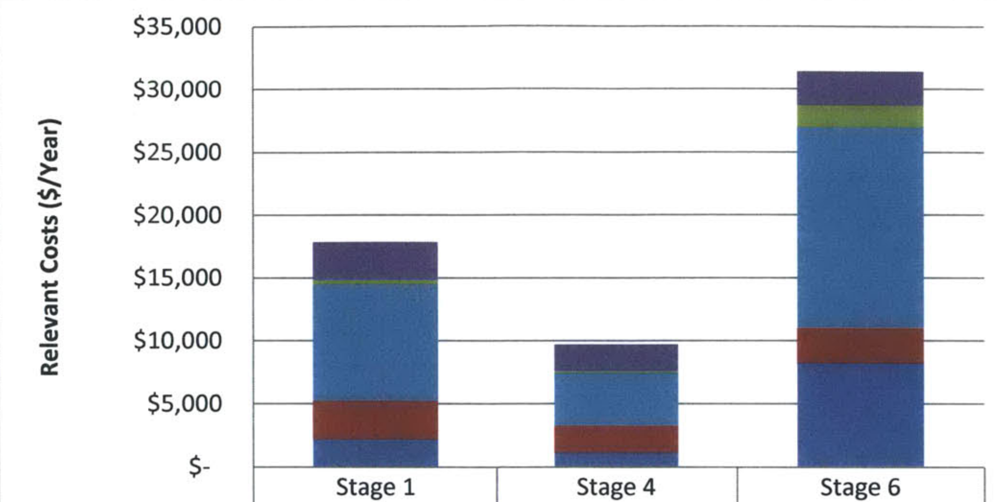
4.8.2 Insight

Combining the two SKUs does achieve significant inventory value reductions by pooling demand variation for the products. However, the results are not as significant as obtained by reducing the lead time and review periods in Scenario 2. Hence, although an advantageous alternative, the strategy of combining kits should be complemented by other changes to make best use of the combined kit.

4.9 Scenario 4 - Continuous Review System

4.9.1 Results

The sum of the relevant costs for all items at the three different stages of inventorying is presented in Figure 4-8.



	Stage 1	Stage 4	Stage 6
Ordering Cost	$3,049	$2,130	$2,768
Stock-Out Cost	$301	$136	$1,716
PL Holding Cost	$9,239	$4,157	$15,943
CS Holding Cost	$3,049	$2,130	$2,768
SS Holding Cost	$2,228	$1,170	$8,261

Figure 4-8: Scenario 4 – Relevant Costs Distribution across Stages of Inventory

We observed that although the holding costs go down in Scenario 4 relative to all the scenarios above, the Total Relevant Costs are offset by the increase in ordering costs. In this Scenario, the number of order cycles has increased, and it thereby results in higher stock-out costs. These costs are comparatively lower than those from most of the scenarios discussed above. They are shown in Table 4-10.

Table 4-10: Scenario 4 – Comparison of Costs from Base Case and Enhanced Base Case

	Base Case	Enhanced Base Case	Scenario 4	Improvement over Base Case	Improvement over Enhanced Base Case
Inventory Value	$355,745	$181,191	$142,145	60%	22%
Total Relevant Cost	$84,386	$60,763	$59,045	30%	3%

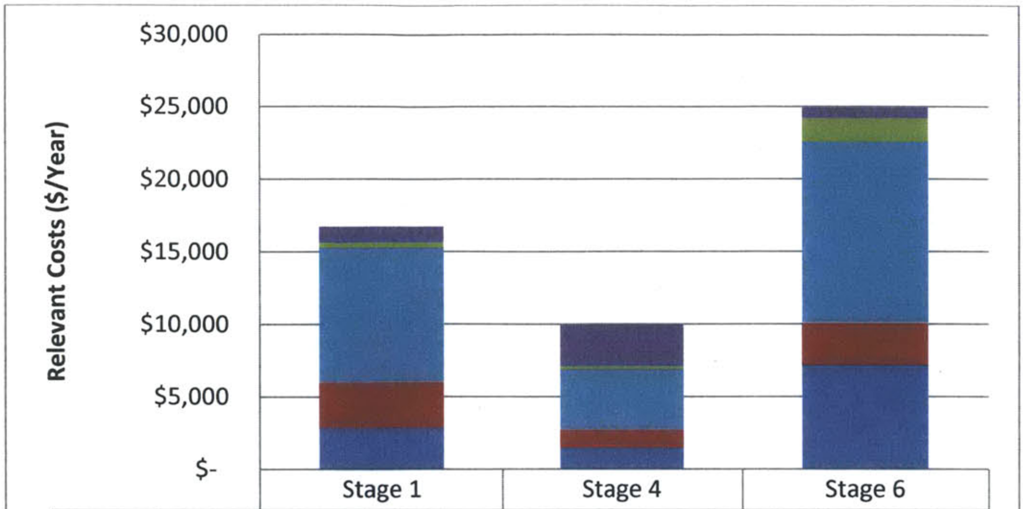
4.9.2 Insight

While a continuous review system enables good reduction in inventory value, the reduction in TRC is small. Furthermore, it may be challenging to implement in the real world due to coordinating issues since every item has its own order cycle. Notwithstanding this challenge, this scenario provides us with a good strategy for comparison with what the best case can achieve.

4.10 Scenario 5 - Combined Scenario 2 (Reduced Lead Time and Review Period) and 3 (Combining kits)

4.10.1 Results

The relevant costs are calculated for every item and summed up for the three different stages of inventory. The results are recorded in Figure 4-9.



	Stage 1	Stage 4	Stage 6
Ordering Cost	$1,095	$2,920	$782
Stock-Out Cost	$358	$187	$1,587
PL Holding Cost	$9,239	$4,157	$12,480
CS Holding Cost	$3,154	$1,273	$2,934
SS Holding Cost	$2,895	$1,510	$7,190

Figure 4-9: Scenario 5 – Relevant Costs Distribution across Stages of Inventory

We noted that since we reduce the review period of Stage 6 by more than half in this scenario, the number of order cycle almost doubles. Hence, the ordering costs increase for all stages, more so for Stage 4 since the higher number of suppliers has a multiplicative effect on the amount. The comparison with the Base Case and Enhanced Base Case are presented in Table 4-11.

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Table 4-11: Scenario 5 – Comparison of Costs from Base Case and Enhanced Base Case

	Base Case	Enhanced Base Case	Scenario 5	Improvement over Base Case	Improvement over Enhanced Base Case
Inventory Value	$355,745	$181,191	$138,145	61%	24%

Total Relevant Cost	$84,386	$60,763	$51,761	39%	15%

4.10.2 Insight

Reducing the review period and lead time of Stage 6 (as in Scenario 2) or combining two similar kits (as in Scenario 3) does not reduce the inventory values in the network as significantly as using continuous review (as in Scenario 4) when exercised as independent concepts. However, when applied together (as in Scenario 5), the concepts achieve better results than using continuous review. Furthermore, it is a more practical solution to review inventory at fixed intervals rather than triggering different orders for each individual item.

4.10.3 Sensitivity Analysis of TRC and Inventory Value Using Review Period

We did a sensitivity analysis similar to the one we did for Scenario 2 – calculating Total Relevant Cost and inventory values using different review periods to identify the range of review periods that lead to lowest overall costs in the system. Figure 4-10 below plots these costs for review periods from 1 to 30 days. In this scenario, on the TRC curve, the lowest point is obtained at R=11 days as well. The TRC curve remains fairly flat over the review period range from 5 to 15 days.

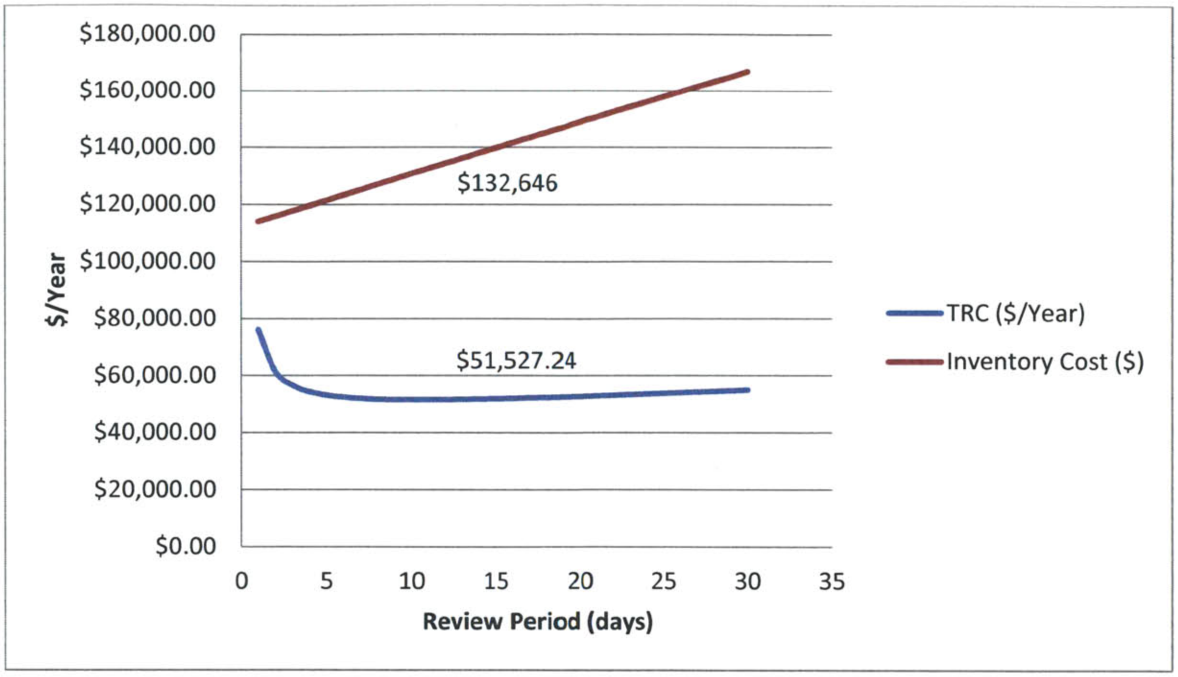


Figure 4-10: Sensitivity Cost of Inventory Value and TRC to Review Period (Scenario 5)

As in Scenario 2, we selected a review period of 14 days, although the lowest Total Relevant Cost occurs at a review period of 11 days, since it is a more manageable unit of time to review inventory and it also gives near optimal costs.

4.11 Strategic Inventory Placement (SIP)/Guaranteed Service Model

4.11.1 Service Times for Enhanced Base Case

Using the proposed safety stock levels in the Enhanced Base Case scenario, we calculated the service times that each stage would require when the network is not optimized. The results are presented in Table 4-12.

Table 4-12: Service Times for Enhanced Base Case Scenario

Stage	S_{in} (days)	T (days)	S_{out} (days)
1	0	40 to 52	0
2	0	19	19
3	19	21	40
4	0	10 to 80	0
5	0	10	10
6	40	10	0

We made the service times (in) (S_{in}) of Stages 1 and 4 to be 0, as we assumed that the external suppliers guarantee no delay in service. The S_{in}s of the remaining stages are equal to the Service Time (out) (S_{out}) of the previous stage. The total lead times (T) for Stages 1 and 4 vary for the different items and Table 4-12 records the range between minimum and maximum lead times. Total lead time values (T) for all other stage were calculated from the information given in Table 4-12 above. The shipment time from one stage to the next was included in the lead time of the latter stage.

4.11.1.1 Insights

Stage 5 guarantees a Service Time (out) (S_{out}) of 10 days although its successor Stage 6 has to wait until 40 days for Stage 3 to begin assembly. For Stage 5 to do so, Stage 4 has to hold high inventory levels and guarantee a S_{out} of 0 days. This is an opportunity to increase S_{out} of Stage 5 to equal to that of Stage 3 and consequently decrease inventory levels at Stage 4. We also observed that, with a lead time of only 10 days to Stage 5, Stage 4 does not need to guarantee a service time (out) of 0 days, but can wait until 10 days in order to align to the S_{out} time of Stage

5. Similarly, Stage 1 need not promise a S_{out} time of 0 days since it can afford to wait until 19 days to align with the S_{out} time of Stage 2. We noted that the current inventory levels allow Stage 6 to guarantee immediate service and balance inventory between Stages 1, 4 and 6 in the network.

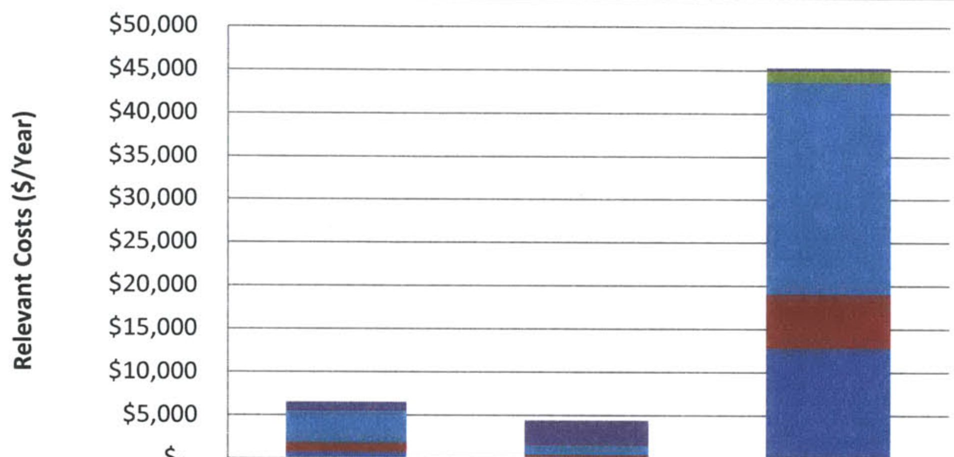
4.11.2 Service Times for the Optimized Enhanced Base Case – Alternative A (Reduced Inventory of Components and Increased Inventory of Finished Products)

Applying the SIP model to the Enhanced Base Case, we calculated the optimal service times for all stages that would allow the network to operate with lower Total Relevant Cost. The results are recorded in Table 4-13 below.

Table 4-13: Service Times for Optimized Enhanced Base Case – Alternative A

Stage	S_{in} (days)	T (days)	S_{out} (days)
1	0	40 to 52	Maximum 40
2	40	19	59
3	59	21	80
4	0	10 to 80	Maximum 70
5	70	10	80
6	80	10	0

We allowed the S_{out} for Stage 1 to go up to the maximum total lead time of about 80% of all items at that stage, i.e. 40 days. All items having T greater than 40 days get inventoried at Stage 1 and no stock is maintained for the rest of the items. Since the lead time for Stage 2 is 19 days, we derived the S_{out} for Stage 2 to be 19 days after 40 days, i.e. 59 days. Stage 3 could then similarly guarantee a S_{out} time of 21 days after 59 days, i.e. 80 days. Since Stage 6 requires items from both Stage 3 and Stage 5, we safely set the S_{out} for Stage 5 to be 80 days and derived the S_{out} for Stage 4 to be equal to 10 days less than 80 days, i.e. 70 days. Since this serves as the maximum S_{out} time allowed for Stage 4, those items having T longer than 70 days get inventoried at this stage. There is no stock maintained for all other items having T less than 70 days. The sum of relevant costs for the optimized network is presented in Figure 4-11.



	Stage 1	Stage 4	Stage 6
Ordering Cost	$1,095	$2,920	$365
Stock-Out Cost	$89	$21	$1,319
PL Holding Cost	$3,593	$1,096	$24,650
CS Holding Cost	$1,036	$206	$6,206
SS Holding Cost	$718	$170	$12,791

Figure 4-11: Relevant Costs Distribution for Optimized Enhanced Base Case – Alternative A

This alternative of optimization proposes that we maintain inventory for only a few components at Stages 1 and 4 while increasing inventory levels at Stage 6. In comparison with the Enhanced Base Case (EBC), this optimization alternative reduces the total cycle stock holding cost and the safety stock holding cost. Since much of the inventory is closer to the customers, the stock-out costs are also reduced. The pipeline holding costs get redistributed between stages while the total value remains the same. Comparison of costs after this optimization versus before optimization is made in Table 4-14.

Table 4-14: EBC (Non-Optimized) vs. EBC (Optimized) – Alternative A

	Non-Optimized Enhanced Base Case (EBC)	Optimized EBC-Alternative A	Improvements
Inventory Value	$181,191	$143,687	21%
Total Relevant Cost	$60,763	$56,275	7%

The costs are compared with the Base Case and the Enhanced Base Case in Table 4-15.

Table 4-15: Optimized Enhanced Base Case – Alternative A - Comparison of Costs with Base Case and Enhanced Base Case

	Base Case	Enhanced Base Case	Optimized EBC – Alt A	Improvement over Base Case	Improvement over Enhanced Base Case
Inventory Value	$355,745	$181,191	$143,687	60%	21%
Total Relevant Cost	$84,386	$60,763	$56,275	33%	7%

4.11.2.1 Insights

Keeping partial inventory for components at Stages 1 and 4 instead of keeping inventory for all items helps to reduce the Total Relevant Cost and the total inventory value for the overall supply chain. The network becomes more efficient when a few of the stages are made to guarantee longer service times even though they can work with shorter service times since the final assembly depends on the slower stages.

4.11.3 Service Times for the Optimized Enhanced Base Case – Alternative B (Removed Inventory of Components and Increased Inventory of Finished Products)

Applying the SIP model to the Enhanced Base Case, we calculated the optimal service times for all stages that would allow the network to operate with the lowest Total Relevant Cost. The results are recorded in Table 4-16 below.

Table 4-16: Service Times for Optimized Enhanced Base Case – Alternative B

Stage	S_{in} (days)	T (days)	S_{out} (days)
1	0	40 to 52	Maximum 52
2	52	19	71
3	71	21	92
4	0	10 to 80	Maximum 80
5	80	10	90
6	92	10	0

We allowed S_{out} for Stage 1 to go up to the maximum total lead time of all items at that stage, i.e. 52 days. Since the lead time for Stage 2 is 19 days, we derived S_{out} for Stage 2 to be 19 days after 52 days, i.e. 71 days. Stage 3 could then similarly guarantee an S_{out} time of 21 days after 71 days, i.e. 92 days. Although we can allow Stage 5 to quote 92 days service time, it projects no further inventory savings for upstream Stage 4, and it violates the mathematical constraints. Hence, we set S_{out} for Stage 5 to be 90 days and derived S_{out} for Stage 4 to be 10 days less than 90 days, i.e.

80 days. Since this is the maximum S_{out} time feasible, all items are guaranteed S_{out} times of 80 days or less, depending on the lead times at Stage 4. The sum of relevant costs for the optimized network is presented in Figure 4-12.

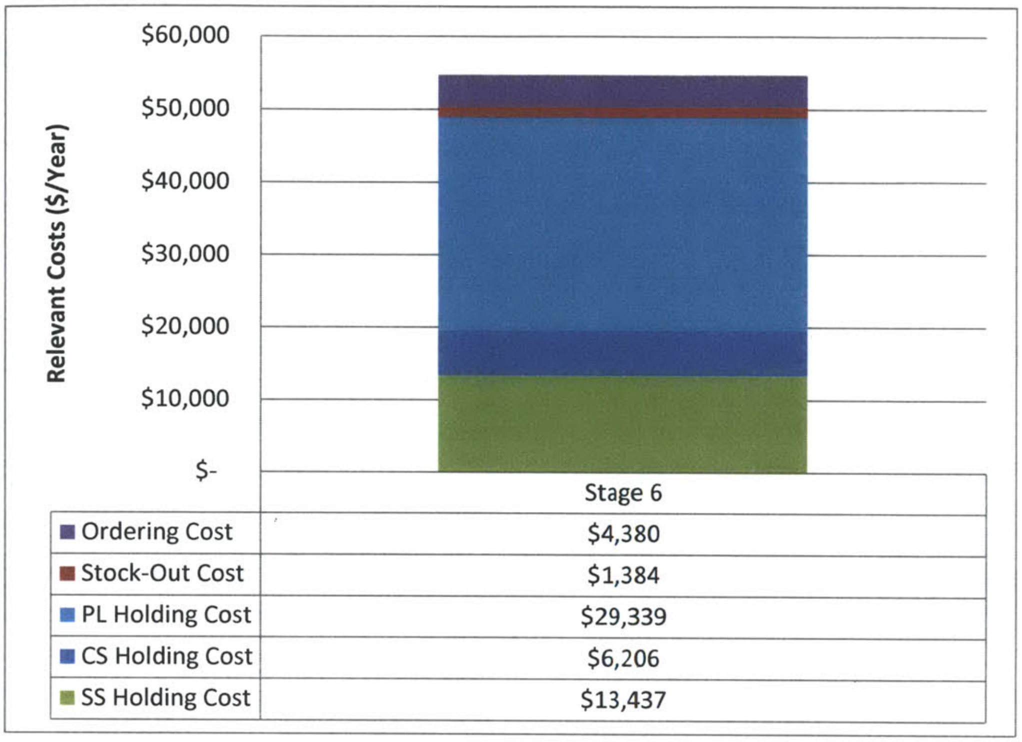


Figure 4-12: Relevant Costs Distribution for Optimized Enhanced Base Case – Alternative B

This alternative of optimization proposes that we maintain inventory only at Stage 6 to minimize the Total Relevant Cost and inventory values, as compared with maintaining partial inventory of components at Stages 1 and 4 as described in the previous alternative. While safety stock and cycle stock holding costs decrease further, all other relevant costs get redistributed to Stage 6. Comparison of costs after this optimization versus before optimization is made in Table 4-17.

Table 4-17: EBC (Non-Optimized) vs. EBC (Optimized) – Alternative B

	Non-Optimized EBC	Optimized EBC - Alternative B	Improvements
Inventory Value	$181,191	$130,954	28%
Total Relevant Costs	$60,763	$54,746	10%

The costs are compared with the Base Case and the Enhanced Base Case in Table 4-18.

Table 4-18: Optimized Enhanced Base Case - Alternative B - Comparison of costs with Base Case and Enhanced Base Case

	Base Case	Enhanced Base Case	Optimized EBC – Alt B	Improvement over Base Case	Improvement over Enhanced Base Case
Inventory Value	$355,745	$181,191	$130,954	63%	28%
Total Relevant Cost	$84,386	$60,763	$54,746	35%	10%

4.11.3.1 Insights

Eliminating component inventory at Stages 1 and 4 gives the best results in terms of Total Relevant Cost and total inventory value. However, maintaining only finished products stock introduces greater risk in the supply chain. Since few components are sourced from overseas, not maintaining some buffer inventory upstream will reduce the network's capability to handle surges in demand. Though this alternative tends towards an extreme, it emphasizes the significance of strategically increasing inventory downstream close to customer in this supply chain. Counter to the common postponement proposition that more inventories should be placed upstream than downstream, it is better in this supply chain to increase inventory downstream. This is because the cost of value-add to the components and the cost of re-packing the sub-kits are very low compared to the material cost of the components themselves. Therefore, the cost of increasing inventory downstream is lower than the savings from reducing inventory upstream.

4.11.4 Service Times for Scenario 5

Using the proposed safety stock levels in Scenario 5, we calculated the service times that each stage would require when the network is not optimized. Results are presented in Table 4-19.

Table 4-19: Service Times for Scenario 5

Stage	S_{in} (days)	T (days)	S_{out} (days)
1	0	40 to 52	0
2	0	19	19
3	19	21	40
4	0	10 to 80	0
5	0	10	10
6	40	1.5	0

All service times are similar to those in the Enhanced Base Case. The only difference here is that the total lead time to Stage 6 is reduced from 10 days to 1.5 days, but the proposed safety stock levels account for this change and the S_{out} time for Stage 6 remains 0.

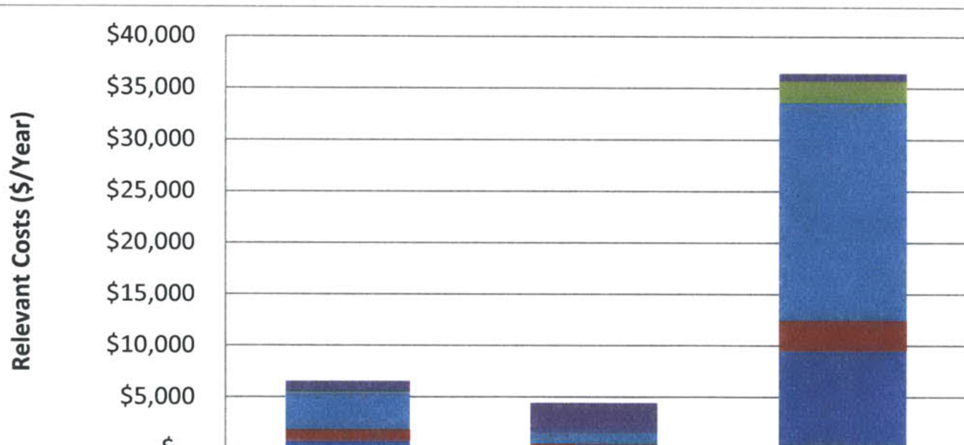
4.11.4.1 Insights

While reducing lead time and review period and combining kits lower the inventory levels at the various stages, as in the Enhanced Base Case, they do not provide the benefits of strategically placing inventory across the whole supply chain.

4.11.5 Service Times for the Optimized Scenario 5 – Alternative A (Reduced Inventory of Components and Increased Inventory of Finished Products)

The service times in this case are similar to those of the Optimized Enhanced Base Case – Alternative A. Reducing the total lead time for Stage 6 to 1.5 days does not affect any service times and Stage 6 is constrained to operate with a S_{out} time of 0 days.

The sum of relevant costs for this optimized network is presented in Figure 4-13.



	Stage 1	Stage 4	Stage 6
Ordering Cost	$1,095	$2,920	$782
Stock-Out Cost	$89	$21	$2,082
PL Holding Cost	$3,593	$1,096	$21,188
CS Holding Cost	$1,036	$208	$2,934
SS Holding Cost	$718	$173	$9,444

Figure 4-13: Relevant Costs Distribution for Optimized Scenario 5 – Alternative A

Similar to the Optimized Enhanced Base Case – Alternative A strategy, this alternative proposes that we maintain inventory for only a few components at Stages 1 and 4 while increasing inventory levels at Stage 6. However, the savings in cycle stock holding costs and the safety stock holding costs are even greater since we base this optimization on the modified inventory strategy of Scenario 5. The stock-out costs increase marginally compared to Scenario 5 as the network operates on leaner inventory levels. Comparison of costs after this optimization versus before optimization is made in Table 4-20.

Table 4-20: Scenario 5 (Non-Optimized) vs. Scenario 5 (Optimized) – Alternative A

	Non-Optimized Scenario 5	Optimized Scenario 5 - Alternative A	Improvements
Inventory Value	$138,145	$99,600	28%
Total Relevant Costs	$51,761	$47,379	8%

The total costs are compared with the Base Case and the Enhanced Base Case in Table 4-21.

Table 4-21: Optimized Scenario 5 – Alternative A - Comparison of costs with Base Case and Enhanced Base Case

	Base Case	Enhanced Base Case	Optimized Scenario 5 – Alt A	Improvement over Base Case	Improvement over Enhanced Base Case
Inventory Value	$355,745	$181,191	$99,600	72%	45%
Total Relevant Cost	$84,386	$60,763	$47,379	44%	22%

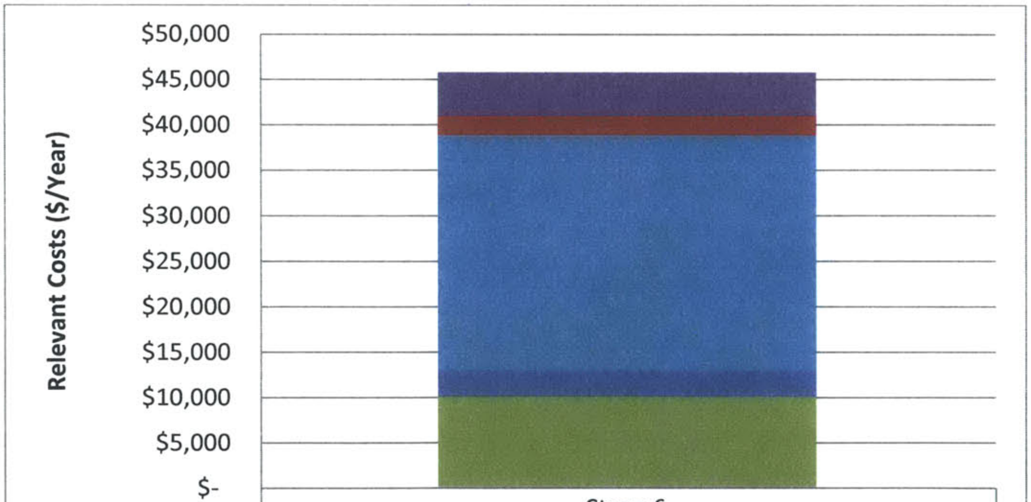
4.11.5.1 Insights

Using inferences from the Optimized Enhanced Base Case – Alternative A, we noticed that significant improvements in costs can be achieved by optimizing an already improved inventory strategy by maintaining stock of only a few components upstream and transferring the bulk of the stock to Stage 6.

4.11.6 Service Times for the Optimized Scenario 5 – Alternative B (Removed Inventory of Components and Increased Inventory of Finished Products)

The service times in this case are equal to those in the Optimized Enhanced Base Case – Alternative B. Although T reduces to 1.5 days for Stage 6, the S_{out} time is constrained to 0 days for that stage.

The sum of relevant costs for the optimized network is presented in Figure 4-14.



	Stage 6
Ordering Cost	$4,797
Stock-Out Cost	$2,209
PL Holding Cost	$25,877
CS Holding Cost	$2,934
SS Holding Cost	$10,013

Figure 4-14: Relevant Costs Distribution for Optimized Scenario 5 – Alternative B

This alternative of optimization offers the lowest Total Relevant Cost and the lowest total inventory value in the network. When compared with Scenario 5, the safety stock and cycle stock holding costs decrease whereas the stock-out costs increase because leaner inventory levels are maintained in the supply chain.

Comparison of costs after this optimization versus before optimization is made in Table 4-22.

Table 4-22: Scenario 5 (Non-Optimized) vs. Scenario 5 (Optimized) – Alternative B

	Non-Optimized Scenario 5	Optimized Scenario 5 - Alternative B	Improvements
Inventory Value	$138,145	$86,314	38%
Total Relevant Costs	$51,761	$45,830	11%

The costs are compared with the Base Case and the Enhanced Base Case in Table 4-23.

Table 4-23: Optimized Scenario 5 – Alternative B - Comparison of costs with Base Case and Enhanced Base Case

	Base Case	Enhanced Base Case	Optimized Scenario 5 – Alt B	Improvement over Base Case	Improvement over Enhanced Base Case
Inventory Value	$355,745	$181,191	$86,314	76%	52%
Total Relevant Cost	$84,386	$60,763	$45,830	46%	25%

4.11.6.1 Insights

This scenario gives the best results when compared with all other scenarios discussed above. The network incurs the lowest Total Relevant Cost when no inventory is maintained at any stage except at the finished products stage. Similar to the Optimized Enhanced Base Case, the cost of increasing inventory downstream is lower than the savings from reducing inventory upstream. Although this involves some risk, the firm may look at other opportunities to guarantee immediate service from external suppliers to operate just in time over most of the network. Reducing lead time to Stage 1 and 4 could further improve the reliability in the supply chain and the firm can maintain high CSLs with lower inventory levels.

4.12 Weighing the Alternatives

The Enhanced Base Case proposes simple changes but is still able to reduce TRC by 28%. Scenario 1a and 1b together suggest that using partial kits reduces TRCs only marginally over the Base Case while incurring higher costs when compared with the Enhanced Base Case itself. This is because the partial kits concept requires inventory to be kept at two extra stages which cancels out any benefits achieved. Hence, we do not consider the partial kit concept in synthesizing the best case.

Scenario 2 proposes shortening lead time from 10 days to 1.5 days in assembling the final SKUs and reviewing stock fortnightly instead of monthly. This yields substantial TRC and inventory value reductions, and hence, we included these ideas in developing the best case.

Combining SKUs in Scenario 3 as a stand-alone concept does not appear to create as much impact as shortening lead time and review period, because the variance in demand is higher for one of the products. However, the decrease in TRC cannot be ignored and we therefore use it along with Scenario 2 in forming the best case.

Scenario 4 recommends a continuous review policy for all stages and generates significant cost savings. However, this policy demands greater coordination and introduces ordering complexity in the system. Hence, we avoid utilizing this scenario to build the best case.

In Scenario 5, our best case, we therefore recommend combining two similar SKUs, reducing lead time to the final stage and reviewing inventory at Stage 6 more frequently. This strategy proves to deliver the lowest TRC and the lowest total inventory value in the network.

The two optimization alternatives highlight that it is better to build up inventory of finished inventory and reduce component inventory in Stages 1 and 4. While we do get the best results by completely eliminating component inventory, the risks involved with implementing such a system are subject to the company's discretion.

Based on the results discussed in the sub-sections above, we ranked the various strategies in terms of incurring the lowest Total Relevant Cost and the total inventory value. Figure 4-15 compares the scenarios based on Total Relevant Cost.

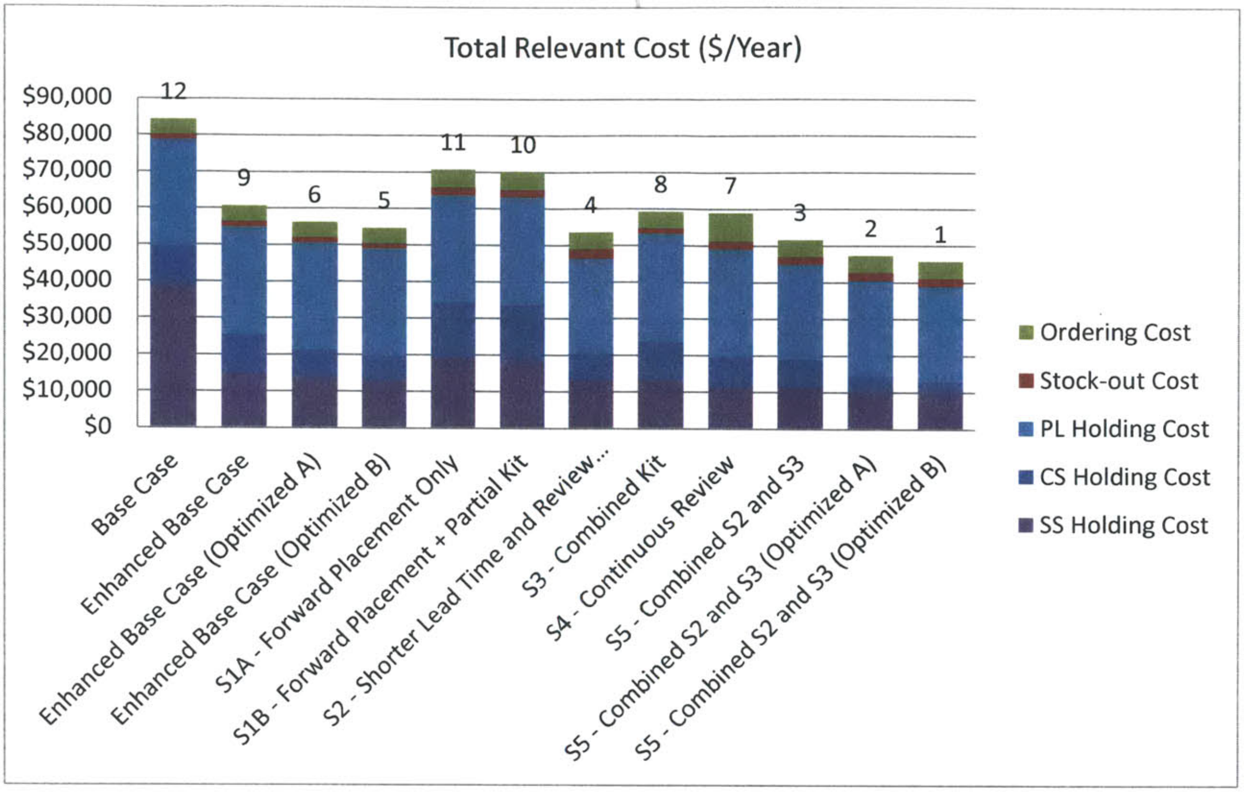


Figure 4-15: Comparison of Total Relevant Costs across all Stages

Scenario 5 optimized using Alternative B emerges as the clear winner closely followed by Scenario 5 optimized using Alternative A and the non-optimized Scenario 5. This indicates that changing the current inventory strategy by combining kits, reducing lead times and reviewing inventory more frequently yields significant cost reductions and it is highly recommended. Reducing component inventory in an improved supply chain further optimizes the Total Relevant Cost in the network.

Simply optimizing the current inventory strategy (with no changes to kitting, lead times and review periods) using Alternatives A and B surface as the next best alternatives. This suggests that increasing inventory levels at the finished products stage while reducing component inventory at Stages 1 and 4 can help lower the Total Relevant Cost substantially and is definitely advocated. Figure 4-16 compares the scenarios based on the total inventory value in the network.

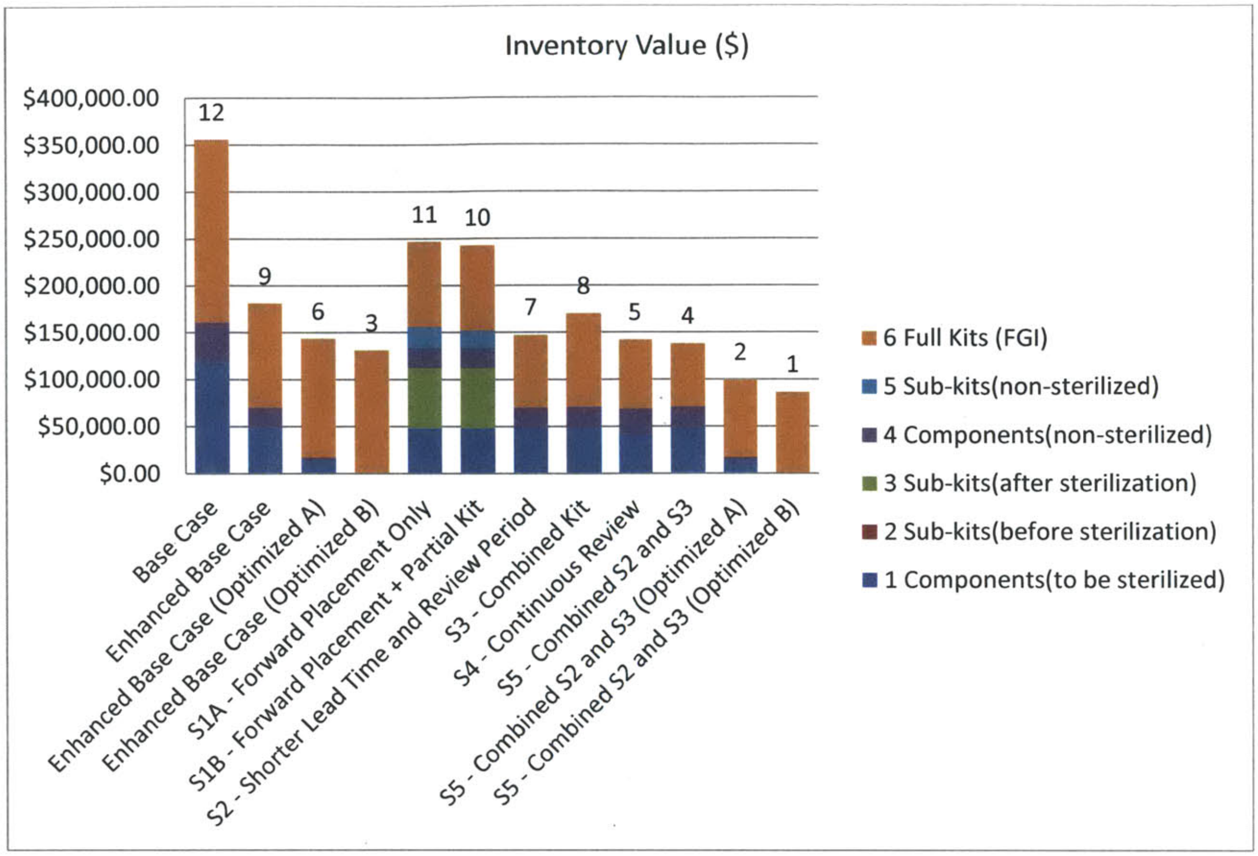


Figure 4-16: Comparison of Total Inventory Value across all Stages

While Scenario 5 optimized using Alternatives A and B still appear to be the best scenarios in terms of total investment in inventory, the Enhanced Base Case optimized using Alternative B ranks a close third – even above Scenario 5 – followed by Enhanced Base Case optimized using Alternative A. This highlights the significance of reducing component inventory at Stages 1 and 4 while increasing finished products inventory at Stage 6 and it is consistent with the results from comparing scenarios in terms of Total Relevant Cost.

5 Conclusion and Recommendation

This thesis generally contributes to a good understanding of how several possible inventory management strategies can be applied to the supply chain of MedCo and the effect of each of the strategies. This section discusses and compares the advantages and disadvantages of the various strategies more qualitatively and provides recommendations for implementation. It also identifies possible future research areas and opportunities for enhancement.

5.1 Conclusion

The results in Section 4 show that reducing the assembly lead time and review period at Stage 6, as well as adopting kitting architecture change by combining two of the SKUs result in better inventory value and Total Relevant Cost (TRC) reductions than the other strategies, such as the partial kit concept. Furthermore, the Strategic Inventory Placement (SIP) model reveals that increasing inventory of finished products can lead to the reduction and even the elimination of inventory of the components in upstream supply chain, and more importantly, overall reduction of total inventory.

Notwithstanding the quantitative results, there are other qualitative factors that should be considered when making the decisions on the adoption of the strategies. These could include the supplier's reliability risk and the ease of execution. For example, while the SIP (elimination of upstream inventory) model can produce the best TRC and inventory value results, it is not good in hedging against the supplier's reliability risk, especially that of the overseas suppliers. Another example is the strategy of adopting Continuous Review system. While it produces saving, the implementation would be more challenging due to the irregular frequency of ordering and higher amount of co-ordination effort required. Table 5-1 summarizes the pros and cons of the proposed strategies.

Table 5-1: Summary of Pros and Cons for the Strategies

Strategy Number	Brief Description of Strategy (Scenario)	Pros	Cons
0	Base Stock Policy with better safety stock and cycle stock calculation (Enhanced Base Case Scenario)	• Good improvement over the current base case. • Very easy to implement.	• Other strategies can yield better results.
1a	Forward placement of inventory to Stage 3 and 5, without Partial Kits (Scenario 1a)	• Good hedge against supplier's reliability risk.	• Increase in Total Relevant Cost (TRC) and overall inventory value.
1b	Forward placement of inventory to Stage 3 and 5, with Partial Kits (Scenario 1b)	• Reduce inventory at Stages 3 and 5 through risk pooling.	• Lowest saving in terms of Total Relevant Cost (TRC) and inventory value. • Difficult to manage, as there are more partial kits to be managed than Scenario 1a.
2	Reduction of Review Period to 14 days and shortening of Lead Time at Stage 6 to 1.5 days. (Scenario 2)	• Second most saving in terms of Total Relevant Cost (TRC) and inventory value.	• Need to study the processes to reduce labor awaiting time. • May incur extra labor overhead for reduction of the review period.
3	Combined two of the four SKUs (Scenario 3)	• Achieve some saving in terms of Total Relevant Cost (TRC) and Inventory value. • Straight-forward for implementation, as the kits are similar.	• Need to discuss with the customers regarding safety or other concerns.

4	Continuous Review System (Scenario 4)	• Higher savings in terms of TRC and inventory value than Strategy 1 and Strategy 3.	• Difficult to implement ➢ Requires change to IT system. ➢ Higher co-ordination effort for ordering due to irregular ordering interval.
5	Combined Strategy 2 and Strategy 3 (Scenario 5)	• Highest saving in TRC and inventory value among Strategy 1 to Strategy 5.	• Harder to implement than Strategy 0, 1, 2, and 3.
A	Strategic Inventory Placement Alternative A (SIP A) – partial inventory of components at Stage 1 and Stage 4 only; increase inventory of finished product (Enhanced Base Case Scenario – Alternative A, and Scenario 5 – Alternative A)	• Can further reduce the TRC and inventory value. • Less risky than Strategy 6, as there is some inventory present locally to hedge against supplier reliability risk, especially those from overseas.	• Reduction of TRC and inventory is not as good as Strategy 6.
B	SIP B – No inventory of components at Stage 1 and Stage 4; increase inventory of finished product (Enhanced Base Case – Alternative B, and Scenario 5 – Alternative B)	• Highest saving in terms of TRC and inventory value, when combined with Strategy 2 and 3.	• Risky, in view of the lack of inventory to hedge against supplier reliability risk, especially those from overseas.

5.2 Recommendation

Given the range of possible strategies, MedCo could adopt a spiral approach to implement the changes in stages depending on the ease of implementation and other considerations deemed important by MedCo. From the ease of implementation perspective, the company could consider implementing a different technique of calculating the safety stock and cycle stock by adopting the Base Stock System and adjusting their inventory accordingly (Enhanced Base Case/Strategy 0). This can be done without much process or product change. Subsequently, they could implement the combination of the SKUs (combined kits) as well as reduction of review period and lead time of Stage 6 (Scenario 5/Strategy 5), which are considered simple to implement, but it involve product change and process change. The two recommended SIP strategies (Strategy A or Strategy B) can also be implemented readily, but the company should weigh them against the supplier's risk involved, and choose the one that they deem more suitable.

5.3 Suggested Future Research and Enhancement

While our research provides a good understanding of the strategies that can be employed and their respective effects on the inventory value and TRCs, there are a few caveats for immediate applications and also a few suggested improvements that can be made.

5.3.1 Lead Time and Variability

As shown in Section 4, the pipeline holding cost is the largest component of the Total Relevant Cost (TRC) due to long lead times involved and hence, it is worth the effort to see how the lead times can be reduced. Furthermore, in this research, we assumed the delivery lead times to be constant and did not take the lead time variability into account for this study. This is partly because the lead times are somewhat stable and partly, due to a lack of detailed data on the lead time. To compensate this, the lead times that we used, however, are generally nearer to the longest possible times. This, however, leads to higher safety stock levels than actually required. For future enhancement to the research result, MedCo could consider tracking the lead times and their variability, and use that to better determine the safety stock levels.

5.3.2 Demand Forecasting

In calculating the re-order point, we used the actual demand variability instead of the forecast error because of two reasons. First, the amount of demand forecasting data was limited, and in addition, based on the comparison of the Root Mean Square Error (RMSE) of the demand forecast and the demand variability of the four SKUs, the demand variability is generally higher or close to the RMSE. Ideally, the forecast error, in terms of the RMSE, should be used for determining the safety stock level, as it is the forecast that drives the determination of the safety stock levels directly. Should MedCo use the RMSE for safety stock calculation, it could also look at other ways to improve its demand forecast, especially for the higher value items.

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