A SPREADSHEET MODEL THAT ESTIMATES THE IMPACT OF REDUCED
DISTRIBUTION TIME ON INVENTORY INVESTMENT SAVINGS: WHAT IS A
DAY TAKEN OUT OF THE PIPELINE WORTH IN INVENTORY?

THESIS

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Abstract

In most of the literature dealing with inventory problems, either with a deterministic or probabilistic model, lead time is viewed as a prescribed constant or a stochastic variable, which therefore, is not subject to control. But, in many practical situations, lead time can be reduced by an extra crashing cost; in other words it is controllable.

This study proposes a repeatable spreadsheet optimization model that estimates the impact of reduced replenishment lead time on inventory investment savings at forward and strategic locations to motivate decision makers to support enterprise-wide distribution process improvement. The contribution of this study is that a means of automatically calculating the inventory control parameters such as safety stocks and reorder points, and estimated savings caused by lead time mean or variability reduction is provided to the user. So, a trade-off analysis can be done as to whether reducing lead time would override the lead time crashing cost.

First, the model finds the optimal safety factor of an item based on a fill rate goal using Excel Solver. Then, Excel's VBA automates the process of finding safety factors for other items before and after lead time reduction. Finally, the model is applied to three different supply support activities to show the superior features of the model that also allow the user to change and upgrade it for future research.

To Wife, Mother and Brother

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I owe gratitude to my wife. Her patience, understanding and unconditional love have been tremendously valuable to me. She fully supported me and sacrificed so much so that this final product is as much hers as it is mine.

I dedicate this thesis to "my beautiful and lonely country, which I love passionately" and to our great leader, Atatürk. Without him, Turkey wouldn't be where it is today and I wouldn't be here accomplishing this research effort.

Serhat SAYLAM

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List of Abbreviations

DOD	Department of Defense
USTRANSCOM	The United States Transportation Command
DPO	Distribution Process Owner
VBA	Visual Basic for Applications
OPTEMPO	Operation Tempo
DOS	Days of Supply
SS	Safety Stock
ROP	Reorder Point
CSL	Cycle Service Level
FCUS	Fractional Charge per Unit Short
CCLIS	Charge per Customer Line Item Short
FCSO	Fractional Charge per Stock-out Occasion
FR	Fill Rate
FCUSUT	Fractional Charge per Unit Short per Unit Time
DLA	Defense Logistics Agency
JIT	Just in Time
NIIN	National Item Identification Number
EOQ	Economic Order Quantity
ID	Infantry Division
BCT	Brigade Combat Team
DCB	Dollar Cost Banding
SSA	Supply Support Activities

List of Notations

A = Ordering cot, in $

D = Annual demand, in units

Q = Order quantity, in units

v = Unit variable cost, in $/ units

r = Inventory carrying charge, in $/ $/ units

d = Daily demand, in units

LT = Lead time, in days

σ_d = Standard deviation of daily demand, in units

σ_{LT} = Standard deviation of lead time, in days

σ_{dLT} = Standard deviation of demand during lead time, in units

k = Safety factor

ETC = Expected total cost

ETS = Expected total saving

$G_u(k)$ = The loss function, a special function of unit normal (mean 0, std. dev. 1)

$p_{u\geq}(k)$ = Probability that a unit normal variable takes on a value of k, or larger

B_2 = Specified Fractional Charge per unit short

P_2 = Fill rate

A SPREADSHEET MODEL THAT ESTIMATES THE IMPACT OF REDUCED DISTRIBUTION TIME ON INVENTORY INVESTMENT SAVINGS: WHAT IS A DAY TAKEN OUT OF THE PIPELINE WORTH IN INVENTORY?

I.   Introduction

"Logisticians are a sad and embittered race of men who are very much in demand in war, and who sink resentfully into obscurity in peace. They deal only in facts, but must work for men who merchant in theories. They emerge during war because war is very much a fact. They disappear in peace because peace is mostly theory. The people who merchant in theories, and who employ logisticians in war and ignore them in peace, are generals.

Generals are a happy blessed race who radiate confidence and power. They feed only on ambrosia and drink only nectar. In peace, they stride confidently and can invade a world simply by sweeping their hands grandly over a map, point their fingers decisively up train corridors, and blocking defiles and obstacles with the sides of their hands. In war, they must stride more slowly because each general has a logistician riding on his back and he knows that, at any moment, the logistician may lean forward and whisper: "No, you can't do that." Generals fear logisticians in war and, in peace, generals try to forget logisticians.

Romping along beside generals are strategists and tacticians. Logisticians despise strategists and tacticians. Strategists and tacticians do not know about logisticians until they grow up to be generals--which they usually do.

Sometimes a logistician becomes a general. If he does, he must associate with generals whom he hates; he has a retinue of strategists and tacticians whom he despises; and, on his back, is a logistician whom he fears. This is why logisticians who become generals always have ulcers and cannot eat their ambrosia." Unknown Author (Bowersox, Closs, & Helferich, 1986)

Background

In most of the literature dealing with inventory problems, either with a deterministic or probabilistic model, lead time is viewed as a prescribed constant or a stochastic variable, which therefore, is not subject to control. But, in many practical situations, lead time can be reduced by an extra crashing cost, in other words it is controllable.

There is a rapidly growing literature on modeling the effects of changing the lead time in inventory control model problems. The literature on lead time reduction almost all deal with deterministic lead times and cycle service level objectives, and include a lead time cost in the objective function.

Lead time reduction is described as the process of decreasing lead time at an additional cost in order to reduce the inventory cost. If the reduction in inventory cost overrides the investment in lead time reduction, then the lead time reduction strategy would be viable. Lead time reduction has two components: reducing mean and reducing the variability. By reducing lead time, customer service and logistics response time can be improved and reduction in safety stocks can be achieved.

In most business situations management must be able to deal with variability in demand and lead time. Demand and lead time variability are a fact of life. Forecasting is rarely accurate enough to predict demand, and demand is rarely constant. In addition, transportation delays along with supplier and production problems make lead time variability a fact of life (Stock & Lambert, 2001, p. 233). Inventory is associated with time and depends on lead time variability. Methods of decreasing inventory related costs include such measures as reducing the number of backorders or expedited shipments (Stock & Lambert, 2001, p. 232). When the replenishment lead time reduced, it leads not only to expedited shipment but also to less number of backorders.

Many firms have focused on reducing safety stocks by reducing the replenishment lead time itself. Choosing a supplier that is closer to the facility is not always possible. However shipping via a faster transportation mode and improving the distribution process are just two ways of reducing the lead time.

Cycle service level cannot be recommended for inventory control in real-world situations. The fill rates make the determination of the corresponding safety stock (SS) and reorder points (ROP) a bit more complex, but on the other hand, will give a much better picture of customer service (Axsäter, Inventory Control, 2006, p. 95). Fill rate is a more relevant measure than cycle service level because it allows the retailer to estimate the fraction of demand that turns to sales.

It is not possible to give a formula that provides the value of safety factor based on fill rate, because the loss function , $G_u(k)$, is a special function of the unit normal variable. (Chopra, Reinhardt, & Dada, 2004, p. 192). In most of the textbooks there is a

table that shows the values of safety factor, k, that most closely approximates the calculated loss function values. However, the appropriate safety factor can be obtained directly using Excel Solver. To do that, one needs to calculate the loss function and solve it for the optimal safety factor of an item in Excel Solver.

However, it is cumbersome to do this manually for each item in Excel Solver, because most of the time there are hundreds of items. Thus, evaluating required safety inventory, given desired fill rate is limited relatively to evaluating required safety inventory, given desired cycle service level. The solution to deal with this problem is to write a Visual Basic for Applications (VBA) code to solve any number of items in a loop. Fortunately it is easy to write a simple macro in Excel to carry out this process automatically with a click button.

Managers are under pressure to decrease inventories as supply chains attempt to become leaner. The goal is to reduce inventories without hurting the level of service provided to customers. Lean thinking in supply chain management shows that there are advantages and benefits associated with the efforts to control lead time.

Supply chain managers' focus is shifting from buying inventory to buying response time. It should be evident that supply chain is not an army or air force initiative in military. In fact, it is very much a joint concept. Sometimes, army or navy becomes supplier or distributor, and air force becomes retail, or vice versa. Reducing the replenishment lead time requires significant effort from the supplier and distributor, whereas reduction in safety inventory occurs at the retail. Therefore, it is important to share the resulting benefits.

This study, just like those mentioned above, deals with lead time reduction in mean and standard deviation. Where it differs is that a normally distributed lead time is used, where most of the research papers have modeled deterministic lead times. Also, the expression for the cost of lead time reduction is not included in the objective function. Rather, the savings caused by reducing the mean and the standard deviation of the normally distributed lead time are calculated.

The main impact of the lead time reduction is on carrying cost function since it contains the safety stock function. But also one gets backordering cost savings when there is no need for the safety stock. If there is no need for the safety stock, lead time reduction will automatically increase the fill rate, so the backordering cost will drop.

By using such models, it should not be hard to convince the decision makers and managers that the lead time is critical to success, but convincing these decision makers and managers by a visual model is more convenient. It is estimated that most people learn by seeing and that visual model is worth a thousand words.

Since it is aimed to develop a model that estimates the impact of reduced distribution time on inventory investment savings, the best way to model is to use a spreadsheet. Although, spreadsheet models have a huge popularity in academic and business world, little has been written on the topic of implementing an optimization model in spreadsheets. According to Ragsdale, most of the businessmen would rate spreadsheets as their most important analytical tool after their brains. He defines the spreadsheet model as a set of mathematical relationships and logical assumptions

implemented in a spreadsheet as a representation of some real world decision problem (Ragsdale, 2008, p. 1).

The proposed model is applied to Department of Defense (DOD) supply chain. The United States Transportation Command (USTRANSCOM), as Distribution Process Owner (DPO) for DOD is responsible for coordinating /synchronizing the DOD distribution system, and developing/implementing distribution process improvements that enhance the DOD supply chain. To that end, there is interest in the "payoff" of distribution process improvements that reduces lead time for ordering/shipping materiel. Specifically, there is interest in estimating the benefits to inventory investment at forward and strategic storage sites as an outcome of reduced distribution lead time through process improvements.

Research Question

Can a valid repeatable model that estimates the impact of reduced distribution time on inventory investment savings be developed?

Investigative Questions

To help answer the research question, this research must answer the following investigative questions:

1. How can the potential depth of inventory in the proposed model?
2. How can the potential breadth of inventory be determined in the proposed model?
3. Which one is to be focused on first? Reducing mean or variability?
4. Can the investment opportunities be prioritized by using the proposed model?

Assumptions and Notations

In general many real-world inventory control problems are so complicated that one cannot represent the real-world situation 100% accurately. Assumptions are used when constructing a mathematical inventory control model of a real world system. Without such assumptions, the models become unmanageable. The assumptions in this study are as follows.

1. Crossing of orders is not permitted. Orders cannot cross over time.

2. For slow moving items, demand generally follows a Poisson distribution. In this study, the most frequently used normal distribution is assumed.

3. Daily demand follows a normal distribution with mean d and variance $\sigma_d{}^2$.

4. Lead time follows a normal distribution with mean l and variance $\sigma_l{}^2$.

5. Lead time and demand are statistically independent. When the lead time changes all other parameters are assumed to be unchanged.

6. Inventory is continuously reviewed. Replenishments are made whenever the inventory position falls under the reorder point.

7. Units are demanded one at a time so that there will be no overshoot of the reorder point.

8. Safety stock is established based on the fill rate goal.

9. Stock-outs are backordered.

Organization

In this study, a spreadsheet model that calculates the estimated annual savings caused by lead time reduction is described. In Chapter 2, the relevant researches

pertaining to the lead time mean and variability, inventory control methods, inventory cost functions and the impact of a reduction in lead time mean and variance are presented. In Chapter 3, the main issues, mathematical model and the details of implementing a large-scale model in an Excel spreadsheet using Excel Solver and VBA techniques are described. In Chapter 4, the implementation and the results of a real-world example are presented by using the proposed model. Finally, Chapter V discusses recommendations and suggestions for related future research.

II.   Literature Review

Normally Distributed Demand and Lead Time

In many situations the demand comes from several independent customers. This is also true for supply support activities of the military. It is known from the central limit theorem that, under very general conditions, a sum of many independent variables will have a distribution that is approximately normal. So, it is reasonable to let the demand be represented by a normal distribution. Provided that the demand is reasonably low, it is then natural to use a discrete demand model, which resembles the real demand. However, if the demand is relatively large, it is more practical to use a continuous demand model as an approximation. Furthermore, if the time period considered is long enough, the discrete demand will become approximately normally distributed (Axsäter, Inventory Control, 2006, p. 76). The normal distribution has been common in practice for a long time and is easy to deal with.

Ordering Cost

In the calculation of expected total relevant cost of inventory, there are three different costs. These are ordering cost, carrying cost and stock-out cost. A company's ordering costs typically include the cost of transmitting and processing the inventory transfer; the cost of handling the product if it is in stock, or the cost of setting up production to produce it, and the handling cost if the product is not in stock; the cost of receiving at the field location; and the cost of associated documentation (Stock & Lambert, 2001, p. 236). When ordering from international suppliers there are also various additional costs.

Inventory Carrying Cost

Inventory carrying costs, the costs associated with the quantity of the inventory stored, include a number of different cost components and generally represent one of the highest costs of logistics. By carrying stock, there is an opportunity cost for capital tied up in inventory. The capital cost is usually regarded to be the dominating part of the holding cost. Other parts can be material handling, storage, damage and obsolescence, insurance, and taxes (Axsäter, Inventory Control, 2006, p. 44). In many companies inventory carrying cost percentages have never been calculated. Most managers use estimates or traditional industry benchmarks. Table 1 contains different estimates of inventory carrying cost percentages that are widely referenced in logistics and inventory management literature (Stock & Lambert, 2001, p. 195). According to Dollar Cost Banding (DCB) study of RAND Corporation, the carrying cost as a percentage of unit price is 22% in the United States Army (Girardini, et al., 2004, p. 98).

Table 1. Estimates of Inventory Carrying Cost (Stock & Lambert, 2001, p. 195)

Author	Publication	Estimate of Carrying Costs as a % of Inventory Value
L.P. Alford & John R. Bangs (eds.)	*Production Handbook*, (New York: Ronald Press, 1955) p. 397.	25%
George W. Aljian	*Purchasing Handbook*, (New, York: McGraw-Hill, 1958), pp. 9-29.	12-34%
Dean S. Ammer	*Materials Management*, (Homewood, Ill.: Richard D. Irwin, 1962), p. 137.	20-25%
Donald J. Bowersox, David J. Closs and Omar K. Helferich	*Logistics Management*, 3rd ed., (New York: Macmillan, 1986), pp. 189-97.	20%*
Joseph L. Cavinato	*Purchasing and Materials Management*, (St. Paul, MN.: West Publishing, 1984), p. 284.	25%
J.J. Coyle and E. J. Bardi	*The Management of Business Logistics*, 3rd ed. (St. Paul, MN.: West Publishing, 1984), p. 144.	25-30%
Gordon T. Crook	"Inventory Management Takes Teamwork," *Purchasing*, March 26 1962, p. 70.	25%
Thomas W. Hall	"Inventory Carrying Costs: A Case Study," *Management Accounting*, January 1974, pp. 37-39	20.4%
J. L. Heskett, N.A. Glaskowsky, Jr., and R. M. Ivie	*Business Logistics*, 2nd ed. (New York: Ronald Press, 1973), p. 20.	28.7%
James C. Johnson and Donald F. Wood	*Contemporary Physical Distribution and Logistics*, 3rd ed. (Tulsa, OK.: PenWell Publishing, 1986), p. 253.	25%
John F. Magee	"The Logistics of Distribution," *Harvard Business Review*, July-August 1960, p. 99.	20-35%
Benjamin Melnitsky	*Management of Industrial Inventory* (Conover-Mast Publication, 1951), p. 11.	25%
Thomson M. Whitlin	*The Theory of Inventory Management*, (Princeton, NJ.: Princeton University Press, 1957), p. 220.	25%

Stock-Out Cost

The numerical value of the safety stock depends on what happens to demands when there is a stock-out. If an item is demanded and cannot be delivered due to a stock-out, various costs can occur. What happens to demands when an item is temporarily out of stock is of paramount importance in inventory control. There are two extreme cases. These are complete backordering and complete lost sales. In this study, complete backordering is assumed when an item is temporarily out of stock. That is, any demand, when out of stock, is backordered and filled as soon as adequate-sized replenishment arrives and the customer does not go elsewhere to satisfy the need. This situation corresponds to a captive market, common in government organizations (particularly

military) (Silver, Pyke, & Peterson, 1998, p. 234). If the customer order is backordered, there are often price discounts for late deliveries, extra costs for administration, material handling, and transportation (Axsäter, Inventory Control, 2006, p. 45). Most of these costs are difficult to estimate. Moreover, backordering costs in military operations are even more difficult to estimate. If a component is missing in a high operational tempo (OPTEMPO), this can cause a chain of negative consequences. As Silver states in his book;

> "Inventory management can be a matter of life and death. Imagine a hospital stocking out of blood, or the air force stocking out of a mission-critical part when the enemy is attacking (Silver, Pyke, & Peterson, 1998, p. 3)."

But there are also situations when backordering costs are easy to evaluate. If a missing component can be bought at a higher cost in a store next door, that additional cost can be assumed as the backordering cost. In military there is no known backorder cost factor and military risks associated with stock-out positions have no commercial parallel (DoD, 2009, p. 4). Part unavailability in supporting supply support activities not only leads to long customer wait times, extended repair times, and reduced equipment availability but also could lead to increase maintenance workload if maintenance chose to work around a problem by removing needed parts from other pieces of inoperable equipment. When no workaround was possible, repairs could not be completed until all needed parts had arrived, thus reducing equipment readiness (Girardini, et al., 2004, p. 1). Equipment readiness is the percentage of weapon systems that are operational.

The backorder cost considered has a structure that is very similar to the carrying cost. The only difference is that the backorder cost is charged when the inventory level is

negative and the carrying cost when it is positive. Holding cost, h, can similarly be interpreted as a penalty cost of carrying a unit. Since holding cost, h, is the product of unit price and carrying cost as a percentage of unit price $(v \times r)$, backorder cost can be the product of unit price and a fractional charge per unit short $(B_2 \times v)$. This fractional charge per unit short increases when there is a high OPTEMPO, and decreases when there is a low OPTEMPO. One problem with stock-out cost is that practitioners usually find it difficult to determine how high it should be. It is, on the other hand, an advantage that a given stock-out cost makes it possible to balance stock-out and holding costs and find the optimal customer service (Axsäter, Inventory Control, 2006, p. 96).

When army equipment fails, the speed of the maintenance technicians to restore it to mission-ready conditions depends on the availability of needed spare parts. When these parts are available at maintainer's supporting supply support activity (SSA), maintainer receives it quickly. On the contrary, parts that are unavailable at SSA level might not arrive for weeks. Despite the advantages of having parts available from SSAs, inventory managers determining what and how many to stock on SSAs cannot be simply based on their desire to achieve a higher level of customer service by stocking inventory as many as possible (Girardini, et al., 2004, p. 1). Instead, they must make tradeoffs among the cost functions mentioned above.

Safety Stock

Safety stock is the average inventory remaining when the replenishment lot arrives. The appropriate level of safety stock is determined by the following three factors:

- The uncertainty of demand

- The uncertainty of replenishment lead time

- The desired level of service

In most business situations management must be able to deal with variability in demand and lead time. Demand and lead time variability are a fact of life. Forecasting is rarely accurate enough to predict demand, and demand is rarely constant. In addition, transportation delays along with supplier and production problems make lead time variability a fact of life (Stock & Lambert, 2001, p. 233).

When demand and replenishment lead time are probabilistic, there is a definite chance of not being able to satisfy some of the demand on routine basis directly from shelf. If the demand during replenishment lead time is unusually large and the replenishment lead time is unusually long, a stock-out may occur. On the other hand if the demand is lower and the replenishment lead time is relatively short, extra inventory is carried unnecessarily.
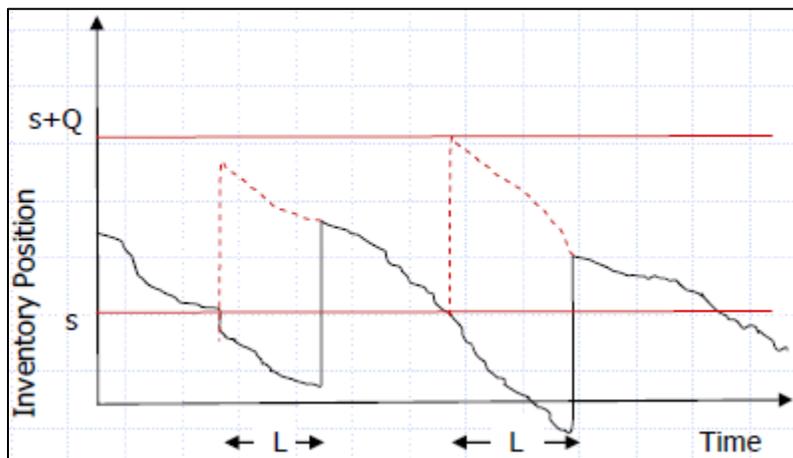

Figure 1. (s Q) System and Safety Stock

In calculating safety stock levels it is necessary to consider the joint impact of demand and replenishment lead time variability. If demand and replenishment lead time are assumed to be independent random variables, then it can be shown that

$$Safety\ Stock = k \times \sigma_{dLT} \tag{2.1}$$

where k is safety factor and σ_{dLT}, is standard deviation of demand during lead time.

$$\sigma_{dLT} = \sqrt{(Average\ lead\ time \times \sigma^2{}_d) + (Average\ daily\ demand)^2\sigma^2{}_{LT}} \tag{2.2}$$

where σ_d, is standard deviation of daily demand and σ_{LT}, is standard deviation of lead time.

When determining a suitable safety stock, it can be set based on a prescribed service constraint or a certain backordering factor. In practice it is often regarded to be easier to specify a service level, since it is almost impossible to calculate a 100% accurate backordering factor (Axsäter, Inventory Control, 2006, p. 94).

According to Silver, managers have four different methods of modeling in order to balance these two types of risks (Silver, Pyke, & Peterson, 1998, p. 241). But, common inventory optimization models generally fall into two categories. One of them minimizes the expected total cost function summing three components, namely, expected annual ordering cost, carrying cost, and stock-out cost. Silver calls this approach "safety stock based on minimizing cost". In the second category one minimizes a cost function containing only the first two components, but subject to a target service level constraint. This approach is called "safety stock based on customer service". Table 2 summarizes these approaches (Caplice, 2006).

Table 2. Framework for (s, Q) Systems (Caplice, 2006)

Stockout Types	Key Element	Cost	Service
Event based	Probability of a stock out event	$B_1(Prob[SO])(D/Q)$	$P_1 = 1 - Prob[SO]$
# of Units Short	Expected # units short	$(B_2 v)(\sigma_L G_u(k))(D/Q)$	$P_2 = ItemFillRate$ $= 1 - (\sigma_L G_u(k)/Q)$
Units Short per Time	Expected duration time for each unit stocked out	$(B_3 v)(\sigma_L G_u(k) d_{SO})(D/Q)$ Where $d_{SO} =$ avg duration of stockout	
Line Items Short	Expected number of lines shorted	$(B_4 v)(\sigma_L G_u(k)/z)(D/Q)$ where $z =$ avg items / order	

According to Silver these four methods are:

1. Safety Stocks Established through the Use of a Simple-Minded Approach:

This approach typically assigns a common safety factor or a common time supply as the safety stock of each item. The U.S. Army used traditional "days-of-supply" (DOS) algorithm until 2002 (Girardini, et al., 2004). According to Silver, a large U.S. based international consulting firm estimates that 80-90 percent of its customers use this approach for setting safety stock. The main shortcoming of this approach as in DOS method is the underlying assumption that demands are uniformly distributed throughout the year. Unfortunately the assumption of a uniform distribution is almost never the case, due to highly variable OPTEMPO of deployable units, the variable nature of equipment failure, and the distribution of quantity requested per requisition (Girardini, et al., 2004, p. 21).

2. Safety Stock Based on Minimizing Cost:

This approach involves specifying a way of costing the stock-out and then minimizing it. The cost-minimization approach trades off inventory cost and stock-out cost to find the lowest cost policy. There are four different cases.

a. Specified Fixed Cost (B₁) per Stock-out Occasion (FCSO)

$$ETC = \left(A\frac{D}{Q}\right) + \left(\frac{Q}{2} + k\sigma_{dLT}\right)vr + \left(\frac{D}{Q}B_1 p_{u\geq}(k)\right) \qquad (2.3)$$

Where ETC is the expected total cost, A is the ordering cost, D is the annual demand, Q is the lot size, v is the unit price, r is the inventory carrying charge,

$$k = \sqrt{2ln(\frac{DB_1}{\sqrt{2\pi}Qvr\sigma_{dLT}})} \qquad (2.4)$$

b. Specified Fractional Charge (B₂) per Unit Short (FCUS)

$$ETC = \left(A\frac{D}{Q}\right) + \left(\frac{Q}{2} + k\sigma_{dLT}\right)vr + \sigma_{dLT}G_u(k)\left(\frac{D}{Q}B_2v\right) \qquad (2.5)$$

where $G_u(k)$ is the special function of unit normal and,

$$p_{u\geq}k = \frac{Qr}{DB_2} \qquad (2.6)$$

c. Specified Fractional Charge (B₃) per Unit Short per Unit Time (FCUSUT)

$$ETC = \left(A\frac{D}{Q}\right) + \left(\frac{Q}{2} + k\sigma_{dLT}\right)vr + \sigma_{dLT}G_u(k)\left(\frac{D}{Q}B_3v\right)t_{so} \qquad (2.7)$$

where t_{so} is average duration of stock-out (Caplice, 2006) and,

$$G_u(k) = \frac{Q}{\sigma_{dLT}}\left(\frac{r}{B_3+r}\right) \qquad (2.8)$$

d. Specified Charge (B_4) per Customer Line Item Short (CCLIS)

$$ETC = \left(A\frac{D}{Q}\right) + \left(\frac{Q}{2} + k\sigma_{dLT}\right)vr + B_4\left(\frac{D\sigma_{dLT}G_u(k)}{Q\hat{z}}\right) \qquad (2.9)$$

Where $\hat{z}$ is the average number of units ordered per customer line and,

$$p_{u\geq}(k) = \frac{Qrv\hat{z}}{B_4 D} \qquad (2.10)$$

For the proposed model, the specified fractional charge (B_2) per unit short model is used because it is the simplest and thus the most popular one. Also, if an item is missing the backorder cost will be proportional to its unit value, so that the criticality of the item will be under consideration.

3. Safety Stocks Based on Customer Service:

Since costing the stock-out situation is very difficult, an alternative approach is to provide a certain level of service and establish the safety stock based on this certain service level.

a. Probability (P_1) of No Stock-out per Replenishment Cycle- Cycle Service Level (CSL)

$$ETC = \left(A\frac{D}{Q}\right) + \left(\frac{Q}{2} + k\sigma_{dLT}\right)vr \qquad (2.11)$$

Where

$$p_{u\geq}(k) = 1 - P_1 \qquad (2.12)$$

The corresponding spreadsheet formulas are computed as follows;

$$k = NORM.S.INV(P_1) \qquad (2.13)$$

$$P_1 = NORM.S.DIST(k,1) \qquad (2.14)$$

b. Fraction (P_2) of Demand Satisfied from the Shelf- Fill Rate (FR)

$$ETC = \left(A\frac{D}{Q}\right) + \left(\frac{Q}{2} + k\sigma_{dLT}\right)vr \qquad (2.15)$$

Where

$$G_u(k) = \frac{Q}{\sigma_{dLT}}(1 - P_2) \qquad (2.16)$$

c. Fraction of Time (P_3) During Net Stock is Positive- Ready Rate

The Department of the United States Army uses fill rate service level method and SSA fill rate goal is 85 percent stock availability given current demand level (Girardini, et al., 2004, p. 38). SSA fill rate is the percentage of requests that are immediately filled from supporting SSA. The remaining 15 percent of requisitions will generally be placed on backorder status. Some weapon systems attain a higher stock availability rate, but it is cost prohibitive to attempt to attain a customer service level above 85 percent because the safety stock investment would have to be much larger (LaFalce, 2009). Figure 2 summarizes how to set safety stocks based on a given objective.
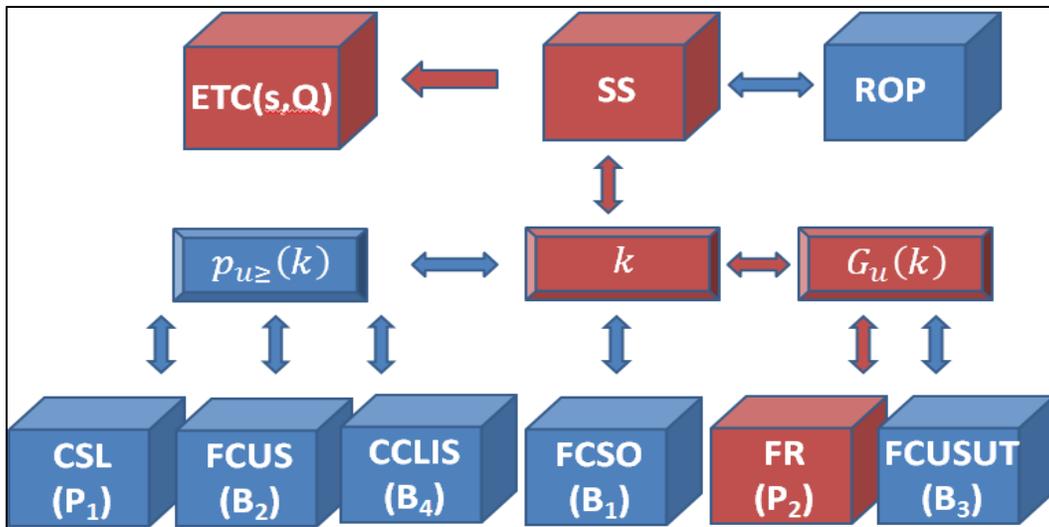

Figure 2. Safety Stock Logic

Minimizing the level of inventories based on cycle service level is not an adequate criterion for selecting safety stocks in that it does not take account of the impact of stock-outs. Also, to set a fill rate goal can be reasonable for a specific item but if there are several items like in this case, to set a cycle service level goal is a simpler method. However, cycle service level also has some important disadvantages. The problem is that cycle service level, P_1 does not take the batch size into account. If the batch size is large and covers the demand during a long time, it doesn't matter much if P_1 is low. Most of the time there is still plenty of stock on hand due to the large batch size. On the other hand, when the batch quantity is small, the real service can similarly be very low even if P_1 is high. Silver gives a good example for this case;

> "Consider two items, the first being replenished twenty times a year, the other once a year. If they both are given the same safety factor based on cycle service level so that both have a probability of 10% of stock-out per replenishment cycle, then we would expect $20 \times (0.10)$, or two stock-outs per year for the first item and only one stock-out every ten years (0.1 per year) for the second item. Therefore, depending on management's definition of service level, we, in fact, may not be giving the same service on these two items (Silver, Pyke, & Peterson, 1998, p. 269)."

As a result, cycle service level cannot be recommended for inventory control in real-world situations. The fill rates make the determination of the corresponding safety stock and reorder points a bit more complex, but on the other hand, will give a much better picture of the customer service (Axsäter, Inventory Control, 2006, p. 95). In another study, Axsäter minimizes holding and ordering costs under a fill rate constraint by using a two-step procedure (Axsäter, 2006).

4. Safety Stocks Based on Aggregate Considerations:

The idea of this general approach is to establish the safety stocks of individual items, using a given budget, to provide the best possible aggregate service across a population of items.

According to Lau, specified fixed cost per stock-out occasion (B_1) and specified fractional charge per unit short (B_2) models can become "degenerate" even with quite plausible parameters. Also fill rate (P_2) models have potential to become degenerate but unlike the first two, does not produce nonsensical optimal solutions (Lau, Lau, & Pyke, 2002)

Also, Janssens and Ramaekers show how decisions regarding inventory management in case of incomplete information on the demand distribution can be supported by making use of a linear programming formulation of the problem (Janssens & Ramaekers, 2011).

Impact of Reduction in Replenishment Lead Time and Variability

Inventory is associated with time and depends on lead time variability. Methods of decreasing inventory related costs include such measures as reducing the number of backorders or expedited shipments (Stock & Lambert, 2001, p. 232). When the replenishment lead time is reduced, it leads not only to expedited shipment but also to less number of backorders. Many firms have focused on reducing safety stocks by reducing the replenishment lead time itself. Choosing a supplier that is closer to the facility is not always possible. However shipping via a faster transportation mode and improving the distribution process are just two ways of reducing the lead time.

The Defense Logistics Agency (DLA) is an agency in the United States Department of Defense, with more than 26,000 civilian and military personnel throughout the world. Located in 48 states and 28 countries, DLA provides supplies to the military services and supports their acquisition of weapons repair parts and other materiel.

> "DLA's focus is shifting from managing inventories to managing information across the supply chain; from managing supplies to managing suppliers; from buying inventory to buying response time."

Since the quote above is from the commander of a DOD agency rather than an Army agency, it should be evident that distribution-based logistics is not just an Army initiative. In fact, it is very much a joint concept (Stuart, 2004, p. 8).

According to Silver, every reasonable effort should be made to eliminate variability in the lead time. In return for firm commitments well ahead of time, a reasonable supplier should be prepared to promise a more dependable lead time (Silver, Pyke, & Peterson, 1998, p. 281). According to Axsäter, a significant way to increase the supply chain efficiency is to apply Just-In-Time (JIT) philosophy. Applications of JIT philosophy often leads to shorter lead times. The supply chain which best succeeds in reducing uncertainty and variability is likely to be the most successful in improving its competitive position (Towill & McCullen, 1999). However, there may also be significant costs associated with such changes. Most of the time researchers analyze two steady situations, before and after lead time reduction. Axsäter, in his study, tries to minimize holding and backordering cost during the change. That is, he considers a transient

problem of bringing the system from its original steady state to the new steady state (Axsäter, Inventory Control when the Lead-time Changes, 2011).

Although, lead time reduction is taken into consideration in the proposed model, the main goal must be to reduce the variability of demand during replenishment lead time. Since safety stock is the product of safety factor and standard deviation of demand during replenishment lead time, this is the only way of reducing safety stock without hurting the service level provided to customers. The standard deviation of demand during replenishment lead time is dependent on average demand, demand variability, average lead time and lead time variability. That is, reducing replenishment lead time is important only because it reduces the variability of demand during replenishment lead time. Reducing the replenishment lead time requires significant effort from the supplier and distributor, whereas reduction in safety inventory occurs at the retail. Therefore, it is important to share the resulting benefits.

There is a rapidly growing literature on modeling the effects of changing the givens such as setup cost, quality level, and lead time in inventory control model problems. Almost all of the literature on lead time reduction deal with deterministic lead times and cycle service level objectives, and include a lead time cost in the objective function.

Liao and Shyu have initiated a study on lead time reduction by presenting an inventory model in which lead time is a decision variable and the order quantity is predetermined. They decomposed lead time cost into three distinct components: administrative, transport, and supplier's speed up cost. This model aims to determine the

length of lead time and, therefore, minimizes the total expected cost for a continuous review policy. Liao and Shyu present the following cost function:

$$ETC(L) = k\sigma_{dLT}vr + R(L) \qquad (2.17)$$

Where $\sigma_{dLT} = \sigma_d\sqrt{L}$ since lead time is deterministic, safety factor k is based on cycle service level (P$_{1)}$ and

$$R(L) = \frac{360d}{Q}\left\{c_i(L_{i-1} - L) + \sum_{j=1}^{i-1} c_j(b_j - a_j)\right\} \qquad (2.18)$$

Where $R(L)$ denotes the lead time reduction cost with a_j the minimum duration of lead time component j, b_j the normal duration lead time component j, c_i the lead time reduction cost of lead time component i, L is the length of the lead time

$$\sum_{i=1}^{n} a_i \leq L \leq \sum_{i=1}^{n} b_i \qquad (2.19)$$

L_{i-1} is the total lead time when components 1 through $i - 1$ have been crashed to their minimum, with $i = 1,2,...,n; j = 1,2,...,i-1$. The expression for the ordering and stock-out costs is missing in the cost function above (Liao & Shyu, 1991).

Ben-Daya and Raouf have extended the Liao and Shyu model by allowing both lead time and order quantity as decision variables where the stock-outs are still neglected and the safety factor k is predetermined (Daya & Raouf, 1994):

$$ETC(Q,L) = \frac{AD}{Q} + ((Q/2) + k\sigma_{dLT})vr + \frac{D}{Q}R(L) \qquad (2.20)$$

Ouyang have generalized the Ben-Daya and Raouf model by allowing backorders and lost sales. The total amount of stock-out is considered a mixture of backorders and lost sales and safety factor k is based on cycle service level (P$_1$). A backorder cost

captured by a fixed penalty per unit short and a lost sales cost captured by the profit

contribution per unit (Ouyang, Yeh, & Wu, 1996).

$$C(Q,L) = \frac{AD}{Q} + \left(\left(\frac{Q}{2}\right) + k\sigma_{dLT}\right)vr + \{(1-\beta)vr + D[\pi + \pi_0(1-\beta)]\}\frac{G_u(k)*\sigma_{dLT}}{Q} + \frac{D}{Q}R(L) \qquad (2.21)$$

Here β is the fraction of the demand during the stock-out period will be

backordered, π is the fixed penalty cost per unit short and π_0 is the marginal profit per

unit. In this model, they make a crucial mistake by adding the stock-out cost expression

but calculating safety factor based on a cycle service level (P_1). To find the minimum

expected cost where stock-out cost expression is included, safety factor has to be

calculated based on stock-out cost factor (safety stock based on minimizing cost).

Moon and Choi point out this flaw in the Ouyang model and improve their model

by simultaneously optimizing both the order quantity and the reorder point. However,

instead of using a safety factor based on stock-out cost factor, they use the reorder point

to calculate the safety stock (Moon & Choi , 1998). Lam proposes a simple solution

procedure to improve the model of Quyang (Lan, Chu, Chung, Wan, & Lo, 1999).

In many practices, the stock-out cost includes intangible components such as loss

of goodwill and potential delay to the other parts of the inventory system. In military

applications it is much more difficult to determine the cost of stock-outs. Thus, many

authors replace the stock-out cost by a condition on the service level. Ouyang and Wu

suggested a mixture inventory model with a service level constraint for lead time. They

relax the assumption on the form of the cumulative distribution function of the lead time

demand and calculate the safety factor k based on cycle service level (P_1). That is, the

service level they chose implies the stock-out level per replenishment cycle is bounded

(Ouyang & Wu, Mixture Inventory Model Involving Variable Lead Time with a Service Level Constraint, 1997).

Pan makes the lead time reduction cost not only a function of lead time components, but also of the order quantity while safety factor k is still based on cycle service level (P_1) (Pan, Hsiao, & Lee, 2002). Hoque and Goyal highlight the misleading behavior of the formulas used to obtain the optimal order quantity on the paper by Pan (Hoque & Goyal, 2004). Chang have extended Ben-Daya and Raouf's model by using the same cost function as an objective cell in a linear programming method. He uses the same inventory model except that the number of orders, D/Q, is an integer (Chang, 2005). Wu, Lee and Tsai extend the model of Ouyang by considering the lead time demand with the mixture of normal distributions while they still assume the shortages are allowed and safety factor is based on cycle service level (Wu, Lee, & Tsai, 2007).

So far, research on lead time reduction has dealt only with deterministic lead times. Hayya relaxes this assumption and uses an exponential lead time model, and thus reducing lead time implies reducing variance. But this time deliveries are subject to order crossover because of lead time variability. Hayya considers effective lead times rather than actual lead times because order crossover are accepted in his model. He uses the cost per unit short model (B_2) of Silver, because it is the most popular model that stock-outs are allowed.

$$C(Q, k) = \left(A \frac{D}{Q} \right) + \left(\frac{Q}{2} + k\sigma_{dLT} \right) vr + \sigma_{dLT} G_u(k) \left(\frac{D}{Q} B_2 v \right) \qquad (2.22)$$

In the Hayya model, the optimal lot size is

$$Q = \sqrt{\frac{2D(A+\sigma_{dLT}B_2 vG_u(k))}{vr}} \qquad (2.23)$$

And the safety factor is based on the backorder cost per unit short:

$$p_u \geq k = \frac{Qr}{DB_2} \qquad (2.24)$$

Hayya, in his model writes the optimal cost, optimal order quantity and the optimal safety factor as regression functions in the problem parameters. Thus he provides the practitioner a means (through regression equations) of directly calculating the inventory policy parameters (Hayya, Harrison, & Chatfield, 2009).

Again, Hayya uses his previous regression model, but this time deals with the net effect of reducing mean lead time on inventory cost. Most importantly, he doesn't include the cost of lead time reduction expression into the total inventory cost function because he wants to see the inventory cost savings of reducing the lead time. Table 3 summarizes the Hayya's lead time reduction chronology (Hayya, Harrison, & He, 2011).

Table 3. Lead Time Reduction Chronology (Hayya, Harrison, & He, 2011)

Authors	Cost equation	Reduction cost per cycle
Liao and Shyu (1991)	$C(L) = hz_o\sigma_x + R(L)$, Q constant, and $C(L)$ concave in L	$R(L) = c_i(L_{i-1} - L) + \sum_{j=1}^{i-1} c_j(b_j - a_j)$ (a piecewise linear function).
Ben-Daya and Raouf (1994)	$C(Q,L) = \frac{AD}{Q} + h\left(\frac{Q}{2} + z_o\sigma_x\right) + \frac{D}{Q}\left(c_i(L_{i-1} - L) + \sum_{j=1}^{i-1} c_j(b_j - a_j)\right)$ Convex in Q for fixed L; concave in L for fixed Q	$R(L) = c_i(L_{i-1} - L) + \sum_{j=1}^{i-1} c_j(b_j - a_j)$ a piecewise linear function.
	$C(Q,L) = \frac{AD}{Q} + h\left(\frac{Q}{2} + z_o\sigma_x\right) + \alpha\frac{D}{Q}e^{-\beta L}$ Convexity or concavity depends on the Hessian	$R(L) = \alpha e^{-\beta L}$, α, β constants.
Ouyang et al. (1996)	For normally distributed LTD: $MinC(Q,L) = \frac{AD}{Q} + h\left[\frac{Q}{2} + z_o\sigma_x + (1-\beta)\sigma_x G(z_o)\right] + \frac{D}{Q}[\pi + \pi_o(1-\beta)G(z_o)] + \frac{D}{Q}R(L)$ Convex in Q for fixed L; concave in L for fixed Q	$R(L) = c_i(L_{i-1} - L) + \sum_{j=1}^{i-1} c_j(b_j - a_j)$ a piecewise linear function.
Ouyang and Wu (1997)	For normally distributed LTD: $Min\ C(Q,L) = \frac{AD}{Q} + h\left[\frac{Q}{2} + z_o\sigma_x + (1-\beta)\sigma_x G(z_o)\right] + \frac{D}{Q}R(L)$ s.t. $\frac{\sigma_x G(z_o)}{Q} \leqslant \alpha$ Does not satisfy the Kuhn–Tucker conditions	Same as in Ouyang et al. (1996).
Ouyang and Wu (1998)	Distribution-free: the same as in Ouyang et al. (1996), except that now the safety stock, $r - \mu L$ replaces $z_o\sigma_x$ and the ESPRC, $E[X - r]^+$, replaces $\sigma_x G(z_o)$	
Moon and Choi (1998)	They correct a redundancy flaw (service level and a unit shortage cost in the same formulation) in Ouyang et al. (1996)	
Hariga and Ben-Daya (1999)	Lead time reduction models as in the above, but with full and partial information about the LTD	
Lan et al. (1999)	Same as in Ouyang et al. (1996), but a 'refinement' of the solution	Same as in Ouyang et al. (1996).
Pan et al. (2002)	For normally distributed lead time demand, $C(Q,\pi_x,L) = \frac{AD}{Q} + h\left[\frac{Q}{2} + z_o\sigma_x + (1-\beta)\sigma_x G(z_o)\right] + \frac{D}{Q}R(L)$. The same as for Ouyang et al. (1996), except for the structure of $R(L)$. C is convex in Q, concave in L	$R(L) = (a_i + b_i Q)(L_{i-1} - L) + \sum_{j=1}^{i-1}(a_j + b_j Q)(T_j - t_j)$, $L_i \leqslant L \leqslant L_{i-1}$ The same as in Ouyang et al. (1996), except that $c_j = a_j + b_j Q$, $c_j = a_j + b_j Q$.
Hoque and Goyal (2004)	They argue that the formulas in Pan et al. (2002) are incorrect and they offer an alternative solution. The Pan et al. model is extended to include a constraint on Q. They extend the Pan et al. model to include a constraint on Q	
Pan and Hsiao (2005)	Backorder unit price discount, π_x, introduced. For normally distributed LTD: $C(Q,\pi_x,L) = \frac{AD}{Q} + h\left[\frac{Q}{2} + z_o\sigma_x + (1-\beta)\sigma_x G(z_o)\right] + \frac{D}{Q}[\pi_x\beta + \pi_o(1-\beta)]\sigma_x G(z_o) + \frac{D}{Q}R(L)$	The same as in Pan et al. (2002). The distribution-free case is on the lines in Ouyang and Wu (1998). An algorithm used to produce (Q^*, π_x^*, L^*).
Chang (2005)	A linear programming (objective function analogous to the one in Ben-Daya and Raouf (1994)) minimized subject to resource constraints	As in Ben-Daya and Raouf (1994), except that D/Q is an integer.

Chopra focuses on the relationship between lead time uncertainty and safety stock. He questions the use of normal approximation of lead time. In his model the safety factor is based on cycle service level, but for the first time in research on lead time reduction, using fill rate (P_2) is suggested instead of cycle service level (P_1). In practice managers often focus on the fill rate as a service quality measure, rather than the cycle service level. In his paper, he suggests that most firms aim for fill rates of between 97 and 99%. This implies cycle service levels of between 50 and 70%. To him, in this range of cycle service levels, a manager who wants to decrease inventory cost should focus on decreasing lead times rather than lead time variability and this contradicts the conclusion drawn using the normal approximation (Chopra, Reinhardt, & Dada, 2004).

Then He, Xu and Hayya presents a paper that is a criticism of Chopra, where the optimal safety factor was derived based upon a predetermined Q, instead of solving the optimal safety factor and lot size Q simultaneously. They find that the discrepancy is due to the fact that Chopra only focuses on safety factor, k, without taking into consideration the joint effect on the total inventory cost of both safety factor, k, and lot size, Q (He, Xu, & Hayya, 2011).

This study, just like those mentioned above, deals with lead time reduction in mean and standard deviation. Where it differs is that a normally distributed lead time is used, where most of the research papers have modeled deterministic lead times. Also, the expression for the cost of lead time reduction is not included in the objective function. Rather, the savings by reducing the mean and the standard deviation of the normally distributed lead time are calculated.

Fill Rate

Fill rate represents the magnitude of the stock-out, not the probability of stock-out (Stock & Lambert, 2001, p. 249). The equation to calculate the fill rates is (Silver, Pyke, & Peterson, 1998, p. 299);

$$Fraction\ Backordered = \frac{Expected\ shortage\ per\ replenishment\ cycle, ESPRC}{Q} \quad (2.25)$$

$$1 - P_2 = \frac{ESPRC}{Q} = \frac{G_u(k) \times \sigma_{dLT}}{Q} \quad (2.26)$$

$$P_2 = 1 - \frac{G_u(k) \times \sigma_{dLT}}{Q} \quad (2.27)$$

To select the safety stock based on fill rates;

$$G_u(k) = \frac{Q}{\sigma_{dLT}}(1 - P_2) \qquad\qquad (2.28)$$

Thus it is expected that the required safety stock would increase if Q decreased (more opportunity for stock-out), σ_{dLT} increased (higher uncertainty), or P_2 increased (better service desired) (Silver, Pyke, & Peterson, 1998, p. 269).

It is not possible to give a formula that provides the value of safety factor because the loss function , $G_u(k)$, is a special function of the unit normal variable. (Chopra, Reinhardt, & Dada, 2004, p. 192). In most of the textbooks there is a table that shows the values of safety factor, k, that most closely approximates the calculated loss function values. However, the appropriate safety factor can be obtained directly using Excel Solver. To do that, one needs to calculate the loss function, $G_u(k)$, from the equation above and then use the equation below to solve it for the optimal safety factor for an item in Excel Solver.

$$G_u(k) = (NORMDIST(k, 0,1,0) - k * (1 - NORMDIST(k, 0,1,1))) \qquad (2.29)$$

However, it is cumbersome to do this manually for each item in Excel Solver, because most of the time there are hundreds of items. Thus, evaluating required safety inventory, given desired fill rate, P_2, is limited relatively to evaluating required safety inventory, given desired cycle service level, P_1. The solution to deal with this problem is to write a VBA code to solve any number of items in a loop. Fortunately it is easy to write a simple macro in Excel to carry out this process automatically with a click button.

Fill rate is a more relevant measure than cycle service level because it allows the retailer to estimate the fraction of demand that turns to sales. These two measures are

very closely related because raising the cycle service level will also raise the fill rate for an item (Chopra & Meindl, 2001, p. 186). The relationship between fill rate and cycle service level when safety factor is based on cycle service level is as follows;

Since,
$$P_2 = 1 - \frac{G_u(k) * \sigma_{dLT}}{Q} \tag{2.30}$$

$$P_2 = 1 - \frac{[f_x(x_0) - k * (prob(x_0 \geq k))] * \sigma_{dLT}}{Q} \tag{2.31}$$

$$P_2 = 1 - \frac{[f_x(x_0) - k * (1 - P_1)] * \sigma_{dLT}}{Q} \tag{2.32}$$

The corresponding spreadsheet formula are computed as follows

$$P_2 = 1 - \frac{[NORM.S.DIST(NORM.S.INV(P_1),0) - NORM.S.INV(P_1) * (1 - P_1)] * \sigma_{dLT}}{Q} \tag{2.33}$$

Fill rate is a more relevant measure also because it can be easily seen that the stock-out cost can be written as a function of fill rate. According to Silver, stock-out cost is composed of the expected shortage per replenishment cycle, $\sigma_{dLT} G_u(k)$, the number of cycles per year D/Q, and the cost per unit short $B_2 v$ (Silver, Pyke, & Peterson, 1998, p. 263).

$$C_s = \boldsymbol{\sigma_{dLT} G_u(k)} \left(\frac{D}{Q} B_2 v \right) \tag{2.34}$$

Since,
$$Fraction\ Backordered = \frac{G_u(k) \times \sigma_{dLT}}{Q} = 1 - P_2 \tag{2.35}$$

So,
$$C_s = (1 - P_2)(DB_2 v) \tag{2.36}$$

III.   Modeling

Background

Why a spreadsheet is preferred for modeling? "Spreadsheet modeling" refers to the use of a spreadsheet as a platform for solving problems. Today, spreadsheets such as Microsoft Excel™ are effective modeling, prototyping, analysis and presentation tools. Spreadsheets are also available for all major computers even for frontline employees. The most common spreadsheet that is used today is Microsoft Excel™. Since the idea of the spreadsheets are accounting, it is widely used in military and business organizations. Although there are more powerful tools such as MATLAB or Arena, a spreadsheet model is simpler and easier to use and understand. The spreadsheets are not only easy to understand but also they can be effectively used, maintained and updated by the front-line managers. That is, front-line managers tend to think in terms of spreadsheets rather than linearity functions (Powell, 1997). Spreadsheets are always ready to be updated for further changes.

Since a model that estimates the impact of reduced distribution time on inventory investment savings is needed, the best way to model is to use a spreadsheet. According to Ragsdale, most of the businessmen would rate the spreadsheets as their most important analytical tool after their brains. He defines the spreadsheet model as a set of mathematical relationships and logical assumptions implemented in a spreadsheet as a representation of some real world decision problem (Ragsdale, 2008, p. 1). So, it is preferred building a spreadsheet model in this study rather than using a specialized programming modeling packages.

The best way to start modeling a spreadsheet is to maintain the primary data in the spreadsheet and use the appropriate formulas to calculate the required dependent variables. So, whenever it is necessary, the primary data can be updated and appropriate changes will be made automatically for dependent variables.

That is why; firstly the mathematical equations that define the dependent variables are written, then separate cells in the spreadsheet are reserved to represent each dependent variable and finally spreadsheet formulas that correspond the dependent variable functions are created in the reserved cells.

The purpose in this study is to calculate the estimated annual savings caused by lead time reduction. This reduction can be both in mean and variance. To calculate the savings, one needs to calculate the values of cost functions before and after the lead time reduction.

It is seen in literature review chapter that most of the research papers take ordering cost, carrying cost and backordering cost into account while some of them dismiss backordering cost since they calculate the safety stock based on customer service. In this study ordering cost, carrying cost and backordering cost are taken into consideration as the cost functions. Moreover there are different backordering cost factors that are used in calculating expected backordering cost as mentioned in literature review chapter. The specified fractional charge (B_2) per unit short model is preferred because it is the simplest and thus the most popular one. Also, if an item is out of stock, the backorder cost will be proportional to its unit value, so that the criticality of the item will be under consideration.

Why to use fill rate and backordering cost in the same model? According to Silver, safety stocks can be calculated based on minimizing cost or customer service. If cost minimization approach is chosen then backordering cost factor should be known and safety stock should be calculated based on backordering cost factor. Since it is very difficult to know or estimate the backordering cost factor, a specific customer service level goal makes it easier to calculate the safety stock. Most of the military and business organizations choose the second approach and state a cycle service level or a fill rate goal. That is, to reach to a service level goal is more important than minimizing cost.

Fill rate goal is the practical one that fits to the real world situations while academicians use cycle service level more in the academic papers since it is much easier to calculate and understand.

In this study, it is aimed to see the impacts of lead time reduction. Although military organizations use fill rate to calculate the safety stocks, there is a backordering rate that is not calculated as a cost function. Since the fill rate is a goal to reach, lead time reduction will not change this objective, but it will reduce the safety stocks to reach this objective. It means that backordering rate will not change and always be (*1-fill rate)*.

What if fill rate is already higher than the goal. In this case, lead time reduction will increase the fill rate, hence decrease the backordering rate. That means less backordering cost. That is why; backordering cost is added to the proposed model in order to see the expected savings in backordering cost.

Model Formulation

Basic Spreadsheet Model

The total expected annual cost is given by the relation

$$ETC = Ordering\ Cost + Carrying\ Cost + Backordering\ Cost \qquad (3.1)$$

When all cost functions are defined in terms of their dependent variables,

$$ETC = \left(A\frac{D}{Q}\right) + \left(\frac{Q}{2} + SS\right)vr + \sigma_{dLT}G_u(k)\left(\frac{D}{Q}B_2v\right) \qquad (3.2)$$

Safety stock, SS is the product of safety factor and the expected demand during lead time.

$$SS = k\sigma_{dLT} \qquad (3.3)$$

The expected demand during lead time is given by the relation

$$\sigma_{dLT} = \sqrt{(LT \times \sigma^2{}_d) + (d^2 \times \sigma^2{}_{LT})} \qquad (3.4)$$

The safety factor k is calculated based on fill rate goal.

$$G_u(k) = \frac{Q}{\sigma_{dLT}}(1 - P_2) \qquad (3.5)$$

As stated before, it is not possible to give a formula that provides the value of safety factor because the loss function, $G_u(k)$, is a special function of the unit normal variable. (Chopra, Reinhardt, & Dada, 2004, p. 192). In most of the textbooks there is a table that shows the values of safety factor, k, that most closely approximates the calculated loss function value. In this study it is preferred using Excel Solver to calculate the optimal safety factor that gives the stated fill rate goal. In Excel, the loss function value is given by the relation

$$G_u(k) = (NORMDIST(k, 0,1,0) - k * (1 - NORMDIST(k, 0,1,1))) \qquad (3.6)$$

By using the formulas above, all variables are defined as the functions of their independent variables. It is called primary data to the data related to independent variables. These variables are fixed ordering cost A, carrying cost as a percentage of unit price r, fill rate goal, P_2, specified fractional charge per unit short, B_2, and unit price, v, mean and standard deviation of lead time, and mean and standard deviation of daily demand.

Besides, the intended days of reduction in mean or variance of the lead time are required in order to calculate the total expected annual cost after lead time reduction. All the equations above are used to calculate the values such as safety stock and expected cost functions of only one item. Unit price, demand mean, and demand variance are the unique variables of an item.

Organization of the data is very important and must be laid out logically. The goal is to organize the data so meaning and purpose of the model are as clear as possible. The primary data cells are arranged in a way that parallels the structure of the data in order to simplify setting up formulas for the dependent variables such as safety stock and cost functions. The primary data cells are formed vertically in order to make primary data input easy for the end-user. It is much easier for end-user to perform only vertical scrolling rather than vertical and horizontal scrolling together (Cunha & Mutarelli, 2007). Table 4 summarizes the relationship between the independent variables and the corresponding cells in the spreadsheet.

Table 4. Summary of the Relationship Between the Decision Variables and Corresponding Spreadsheet Cells

Independent Variables	Order Cost	Carrying Cost %	Fill Rate Goal %	Fractional Charge	Unit Price	Demand		Lead Time		Lead Time Reduction	
						Average	Standard Deviation	Average	Standard Deviation	Average	Standard Deviation
Spreadsheet Cells	C1	C2	C3	C4	E10	G10	H10	H1	H2	C5	C6

Next, the spreadsheet formulas corresponding to the dependent variables, including the objective value of "estimated cost savings", are created by referring to the data cells where the corresponding coefficients have been entered (or calculated). These formulas are created by using the corresponding algebraic equations. When the spreadsheet formulas for the first item are created, they are copied for the other items since all of the item formulas have the same structure. So, hard-to-detect typing errors are prevented.

To do that, firstly the National Item Identification Number (NIIN) of the first item are entered starting from "Row 10". Each row represents an item. Then, the corresponding unit price and demand parameters are entered into the next columns of the same row. After that, the spreadsheet model is separated into three main groups of columns. These are "Before Lead Time Reduction", "After Lead Time Reduction", and "Savings" groups of columns.

In the "Before Lead Time Reduction" group of columns, the first column (column J) is reserved for the safety factor, k, since it is the decision variable that calculates the intended fill rate goal. Moreover, all other variables, including the safety stock and the estimated cost functions are dependent on this safety factor. The next column (column K) is the standard deviation of the demand during lead time. As stated before, the algebraic expression is given by the relation

$$\sigma_{dLT} = \sqrt{(LT \times \sigma^2{}_d) + (d^2 \times \sigma^2{}_{LT})} \qquad (3.7)$$

The corresponding spreadsheet formula is computed in the cell "K10" as follows;

$$Formula\ for\ cell\ K10 = SQRT((\$H\$1*(H10\char`^2)) + ((G10\char`^2)*(\$H\$2))) \quad (3.8)$$

Also, Economic Order quantity (EOQ) value is needed in order to calculate the estimated cost functions and the savings. The next column (column L) is reserved for EOQ formulation. The algebraic expression for EOQ is given by the relation

$$EOQ = \sqrt{\frac{2AD}{vr}} \qquad (3.9)$$

The corresponding spreadsheet formula is computed in the cell "L10" as follows;

$$Formula\ for\ cell\ L10 = SQRT(2*\$C\$1*365*G10/(E10*\$C\$2)) \quad (3.10)$$

The next value to calculate is safety stock which is a product of safety factor and the standard deviation of demand during lead time. The algebraic expression for the safety stock is given by the relation

$$SS = k\sigma_{dLT} \qquad (3.11)$$

The corresponding spreadsheet formula is computed in the cell "M10" as follows;

$$Formula\ for\ cell\ M10 = K10*J10 \qquad (3.12)$$

Although reorder point (ROP) is not a coefficient of the estimated cost and saving functions, it is a very helpful value that tells when to reorder. Since all the related coefficients to calculate ROP are available, the next column (column N) is reserved for ROP values of the items. The algebraic expression for the ROP is given by the relation

$$ROP = (d)(LT) + SS \tag{3.13}$$

The corresponding spreadsheet formula is computed in the cell "N10" as follows;

$$Formula\ for\ cell\ N10 = G10 * \$H\$1 + M10 \tag{3.14}$$

The next and the last column (column O) in the "Before Lead Time Reduction" group of columns is reserved to calculate the fill rate. This value is a function of the safety factor and must be equal to the intended fill rate goal. The algebraic expression for the fill rate is given by the relation

$$P_2 = 1 - \frac{G_u(k) * \sigma_{dLT}}{Q} \tag{3.15}$$

The corresponding spreadsheet formula is computed in the cell "O10" as follows;

$$Cell\ O10 = 1 - ((NORMDIST(J10,0,1,0) - J10 * (1 - NORMDIST(J10,0,1,1))) * K10/L10 \tag{3.16}$$

The next group of columns is created to calculate the same values as above, but this time the intended lead time reduction is taken into account in terms of both mean and variance. This group of columns is called the "After Lead Time Reduction" group of columns. The algebraic expressions regarding to the dependent variables are same except the lead time mean and variance coefficients. Since calculations are made after lead time reduction, one has to subtract the intended mean and variance reductions from the actual mean and variance values of lead time.

The first column (column Q) in this group is reserved for the safety factor since it is the decision variable that calculates the intended fill rate goal. The corresponding columns and the spreadsheet formulas for each dependent variable are arranged and computed as follows;

Standard deviation of demand during lead time;

$$Formula\ for\ cell\ R10 = SQRT(((H1 - $\textbf{C}$5) * (H10^\wedge2)) + ((G10^\wedge2) * (H2 - $\textbf{C}$6))) \quad (3.17)$$

EOQ;

$$Formula\ for\ cell\ S10 = SQRT(2 * C1 * 365 * G10/(E10 * C2)) \quad (3.18)$$

Safety stock;

$$Formula\ for\ cell\ T10 = R10 * Q10 \quad (3.19)$$

ROP;

$$Formula\ for\ cell\ U10 = G10 * (H1 - $\textbf{C}$5) + T10 \quad (3.20)$$

Fill rate;

$$Cell\ V10 = 1 - ((NORMDIST(Q10,0,1,0) - Q10 * (1 - NORMDIST(Q10,0,1,1))) * R10/S10) \quad (3.21)$$

Two groups of columns discussed above represent all the calculations such as ROP and safety stock except the cost functions. The last group of columns is reserved for this purpose. Since the main purpose of the model is to estimate the impact of reduced distribution time on inventory savings, it is not required to reserve any column for the calculated cost, but it is required to reserve columns for the calculated savings. These columns are equal to the differences between the costs before and after lead time reduction.

The first column (column X) in this group is reserved for the ordering cost savings. Since the coefficients of ordering cost function is independent from the lead time parameters, the estimated ordering savings should be zero. This is mostly due to using

EOQ for the quantity size. Nevertheless, this cost function is reserved in the model to simplify the necessary future modifications. The algebraic expression for the ordering cost savings is given by the relation

$$S_r = C_{r1} - C_{r2} = \left(A\frac{D}{EOQ}\right) - \left(A\frac{D}{EOQ}\right) = 0 \tag{3.22}$$

Where S_r is the estimated ordering cost savings, C_{r1} is the estimated order cost before lead time reduction and C_{r2} is the estimated order cost after lead time reduction. The corresponding spreadsheet formula is computed in the cell "X10" as follows;

$Formula\ for\ cell\ X10 = (\$C\$1 * 365 * G10/L10) - (\$C\$1 * 365 * G10/S10)$ (3.23)

Next cost function is the carrying cost. This cost is the sum of cycle and safety stock cost functions. The next column (column Y) is created to calculate the carrying cost savings caused by lead time reduction. The main impact of the lead time reduction is especially on this cost function since it contains the safety stock function. The algebraic expression for the carrying cost savings is given by the relation

$$S_c = C_{c1} - C_{c2} = \left(\frac{Q}{2} + SS_1\right)vr - \left(\frac{Q}{2} + SS_2\right)vr \tag{3.24}$$

Where S_c is the estimated carrying cost savings, C_{c1} is the estimated carrying cost before lead time reduction and C_{c2} is the estimated carrying cost after lead time reduction. The corresponding spreadsheet formula is computed in the cell "Y10" as follows;

$Formula\ for\ cell\ Y10 = (0.5 * L10 + M10 - 0.5 * S10 - T10) * E10 * \$C\$2$ (3.25)

Expected stock-out cost is the last cost function in the proposed model. Since complete backordering (no lost sales) is assumed, this cost function is referred as

"backordering cost". The next column (column Z) is reserved to calculate the backordering cost. Backordering cost savings is gained when there is no need for the safety stock. If there is no need for the safety stock, lead time reduction will automatically increase the fill rate, so the backordering cost will drop after lead time reduction. The algebraic expression for the backordering cost savings is given by the relation

$$S_s = C_{s1} - C_{s2} = \sigma_{dLT1} G_u(k_1) \left(\frac{D}{Q} B_2 v\right) - \sigma_{dLT2} G_u(k_2) \left(\frac{D}{Q} B_2 v\right) \tag{3.26}$$

Where S_s is the estimated stock-out cost savings, C_{s1} is the estimated stock-out cost before lead time reduction and C_{s2} is the estimated stock-out cost after lead time reduction. The corresponding spreadsheet formula is computed in the cell "Z10" as follows;

$Cell\ Z10 = ((K10/L10) * (NORMDIST(J10,0,1,0) - J10 * (1 - NORMDIST(J10,0,1,1))) -$
$(R10/S10) * (NORMDIST(Q10,0,1,0) - Q10 * (1 - NORMDIST(Q10,0,1,1)))) * 365 *$
$G10 * \$C\$4 * E10$ \hfill (3.27)

The last column (column AA) of this group is reserved to calculate the total savings for an item caused by the lead time reduction. This function is simply the sum of ordering, carrying and backordering cost savings. The algebraic expression for the expected total saving is given by the relation

$$ETS = S_r + S_c + S_s \tag{3.28}$$

where ETS is the expected total saving. The corresponding spreadsheet formula is computed in the cell "AA10" as follows;

$$Formula\ for\ cell\ AA10 = SUM(X10{:}Z10) \hspace{2cm} (3.29)$$

Although the function mentioned above is enough to draw a good picture of cost savings caused by lead time reduction, one can cumulatively sum the total savings of the items in order to analyze the impact of each item on inventory savings. The last column (column AC) is reserved to calculate cumulative savings. The corresponding spreadsheet formula is computed in the cell "AC10" as follows;

$$Formula\ for\ cell\ = SUM(\$AA\$10{:}AA10) \hspace{2cm} (3.30)$$

If there was only one item, one could have set the safety factor as the decision variable and the fill rate as the objective function in Excel Solver. As a constraint, this fill rate should be equal to fill rate goal. When this problem is solved, one would get the optimal safety factor value that would give the intended fill rate goal.

Moreover, the same process should have been repeated to calculate the optimal safety factor after lead time reduction by changing the Excel Solver variable cells manually. However, there are thousands of items rather than only one item. So, this manual approach would become quite difficult and time consuming even if Excel Solver used instead of the tables in appendices of books.

Automating the Process by Using VBA

Fortunately, in Microsoft Excel this process can be automated by using INDEX function, setting the INDEX-functioned cell as the objective function in Excel Solver, and finally writing a simple macro in Excel's Visual Basic Editor in order to carry out this process for all items with a click button (Ragsdale, 2008, pp. 103-113).

First of all, all of the cells created for the first item are copied and pasted (or drag down) through the number of items in the stock, say 200. Since one needs to solve a separate optimization problem for each of 200 items, before and after lead time reduction, it will be more convenient to deal with the decision variable, objective function and the input constraint in a different manner.

To do that, cell AG1 is reserved for the safety factor index, cell AG2 for the fill rate index, cell AG3 to indicate the item number currently under investigation, and cell AG4 to indicate the condition (before or after lead time reduction) of the item currently under investigation. Finally fill rate index columns before and after lead time reduction (column AE and column AF starting from cell AE10 and AF10 respectively) are created in order to use INDEX function without hurting created model. The corresponding spreadsheet formula of these two fill rate index columns are computed in the cells "AE10" and "AF10" as follows;

$Formula_{for\ cell\ AE}10\ =$

$1 - ((NORMDIST(\$AG\$1,0,1,0) - \$AG\$1 * (1 - NORMDIST(\$AG\$1,0,1,1))) * K10/L10$ \quad (3.31)

$Formula\ for\ cell\ AF10 =$

$1 - ((NORMDIST(\$AG\$1,0,1,0) - \$AG\$1 * (1 - NORMDIST(\$AG\$1,0,1,1))) * R10/S10$ \quad (3.32)

Note that these fill rate index formulas differs from model fill rate formulas in terms of safety factor function. New safety factor index cell, AG1, does not have any formula since it is going to be the general decision variable.

The general objective function of the model, fill rate index cell, AG2, contains a formula that returns the intended fill rate goal for the item under investigation. The spreadsheet formula of the fill rate index is computed in the cell "AG2" as follows;

$$Formula\ for\ cell\ AG2 = INDEX(OFFSET(\$AE\$10,,,\$C\$7,2), AG3, AG4) \qquad (3.33)$$

In general, the function INDEX (range, row number, column number) returns the value in the specified row number and column number of a given range (Ragsdale, 2008, p. 106). OFFSET function is used in order to make the range dynamic.

When both "cell AG3" (unit) and "cell AG4" (column) contain the number 1, the formula above returns the first row and the first column of the specified range. That is, when both cells contain number 1, the index returns the fill rate value of the first item <u>before lead time reduction</u>. When "cell AG3" (unit) still contains number 1 but "cell AG4" (column) contains number 2, the index returns the fill rate value of the first item <u>after lead time reduction</u>. Using of INDEX function greatly simplifies the process of solving the optimal safety factors that give the fill rate goal for all items before and after lead time reduction.

In this model the objective is to reach to the intended fill rate goal for each item before and after lead time reduction by finding the optimal safety factor. Thus, the objective cell, decision variable cell and constraints are specified as in Figure 3.
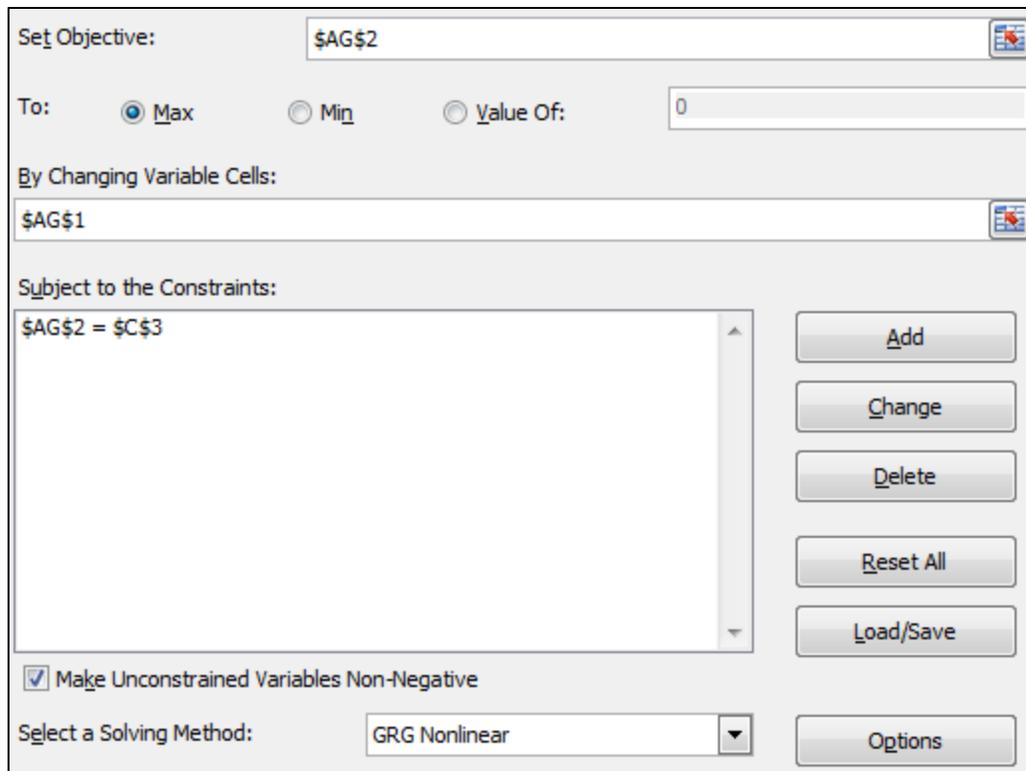
Figure 3. Solver Parameters for the Proposed Model

Although fill rate index function is set as the objective cell, this function should be equal to intended fill rate goal. That is why, it is not important to minimize or maximize it, but it is important to add a constraint to equalize it to the fill rate goal. Also safety factor index is set as the decision variable and make all variables nonzero. Moreover, GRG Nonlinear solving method is selected since there are nonlinear formulas in the model.

When the created model is solved, Excel solver finds the optimal safety factor for the first item before lead time reduction. To continue to solve the model for other items and also for after lead time reduction, one should change the values in cells AG3 (Unit) and AG4 (column) and use Excel Solver to re-optimize the spreadsheet model for each

item before and after lead time reduction. As stated before, it is a cumbersome approach since there are usually thousands of items.

To deal with this problem, one needs to write a simple macro that will find the optimal safety factor for each item before and after lead time reduction. To do this, firstly the "Developer Tab" is needed to be turned on in the ribbon by using Excel Options menu. Then, inside the developer tab, a "Command Button" should be generated by clicking "Insert" icon and then choosing the "Command Button" from "Active X Controls". Then it should be dragged onto the spreadsheet to draw a command button (Walkenbach, 2010, p. 120). Finally, one needs to change the name and some properties of the command button by choosing "Properties" icon. The properties window contains several properties that can be used to customize the appearance and the behavior of the command button (Ragsdale, 2008, p. 107). In the proposed model, the change made in the command button's property values as follows,

Property	New Value
(Name)	Savings
Caption	Calculate Savings
TakeFocusOnClick	FALSE

To bring up the code window, one needs to double click on the command button or hit ALT+F11 key. Here is the Excel's Visual Basic Editor that the macro code is inserted. The macro code written for the proposed model is shown in Figure 4.

Figure 4. VBA Code for the Command Button's Click Event

When the model is completes, the statements above will be executed whenever the "Calculate Savings" button is clicked. The logic behind this programming code is simple. The first part of the code is to clear the previous work that is why, this part is neglected. The macro statements of interest and their purposes are as follows.

FinalRow = Cells(Rows.Count, 2).End(xlUp).Row: Goes to the final row of column 2 and then finds the final row of the data. So, the model counts the number of items automatically (VBA4Excel, 2012).

For-Next Loop of Column: Repeats the process before and after lead time reduction for an item.

For-Next Loop of Unit: Repeats the process until the last item. There are "Final Row-9" items since items start from the 10th row.

Range("AG4") = Column: Places the current value of "Column" (the number 1 and 2 for before and after lead time reduction respectively) into cell "AG4" on the spreadsheet model.

Range("AG3") = unit: Places the current value of "unit" (the number 1,2….until Final Row-9) into cell AG4 on the spreadsheet model.

SolverSolve UserFinish:=True: Tells Excel Solver to solve the problem for the current values without displaying the usual Solver Results dialog box (Ragsdale, 2008, p. 109).

If Column = 1 Then Range("J" & 9 + unit) = Range("AG1"): Takes the optimal safety factor value in cell AG1 and places it in row "9 + unit" in column J when Column equals 1 (before lead time reduction).

If Column = 2 Then Range("Q" & 9 + unit) = Range("AG1"): Takes the optimal safety factor value in cell AG1 and places it in row "9 + unit" in column Q when Column equals 2 (after lead time reduction).

Excel Solver function of a VBA program is disabled when it is the first time to use Solver in a macro program. To enable it one firstly needs to click Tools in the code window, then click References and then check the box for Solver (Ragsdale, 2008, p. 109).

Since the macro code is also built, one finally clicks the "Design Mode" icon on the Developer tab to finish constructing the code.

Finally, when "Calculate Savings" button is clicked, the spreadsheet model starts to calculate the optimal safety factor values that give the specified fill rate goal firstly for all items before lead time reduction, and then it repeats the same process after lead time reduction starting from the first item. Here is the logic of the model:

When the lead time is reduced, the first impact happens on standard deviation of demand during lead time. Second impact is on safety factor. Since the standard deviation of demand during lead time decreases, a smaller safety factor will be needed to reach to the same fill rate goal. The overall impact comes from these two variables. Safety stock is a product of standard deviation of demand during lead time and the safety factor. Since both of them decrease, the safety stock decreases more. This process results in getting carrying cost savings.

Stock availability of some items can be already over the fill rate goal, that is, there is no need to keep safety stock for those items. The proposed model will calculate zero safety factors for these items. At this point, when the lead time is reduced, the model cannot reduce the safety factor, since it is already zero. So, it calculates the new fill rate which is greater than the specified fill rate goal. For those items one gets no carrying cost savings but backordering cost savings.

The black cells are the cells that VBA run over. Thus, they mean nothing to the end user. The spreadsheet model runs the process over these cells and places them into the grey-white cells that calculate the estimated savings.

Finally, Cell I4 is the cell that shows the overall annual estimated saving of the lead time reduction. This cell is the reason why the proposed model is created. It sums up

each total saving per item and gives the total annual estimated saving. The algebraic expression for the total annual estimated saving is given by the relation

$$OAES = \sum_{x=1}^{n} ETS_n \qquad (3.34)$$

The corresponding spreadsheet formula is computed in cell I4 as follows;

$$Formula\ for\ merged\ cell\ \text{I4} = SUM(AA10:AA1048576) \qquad (3.35)$$

IV.   Application, Results and Analysis

In this chapter, the application of the proposed model, the results and their analysis are presented. The proposed model is applied to DOD supply chain. USTRANSCOM, as Distribution Process Owner (DPO) for DOD is responsible for coordinating /synchronizing the DOD distribution system, and developing/implementing distribution process improvements that enhance the DOD supply chain. To that end, there is interest in the "payoff" of distribution process improvements that reduces lead time for ordering/shipping materiel. Specifically, there is interest in estimating the benefits to inventory investment at forward and strategic storage sites as an outcome of reduced distribution lead time through process improvements.

Background

Class IX items are the parts and assemblies required to maintain the trucks, radios, helicopters, missiles, armaments, and other weapon systems that the U.S. Army Material Command manages (LaFalce, 2009). Class IX items are of interest to most logisticians because in Operation Iraqi Freedom, Class IX (repair parts) supply system seems to have been almost completely ineffective within the theater of operations. Accounts describe minimal or no Class IX ever reaching forward units, vehicles abandoned or forced to fight with degraded capabilities for lack of spare parts, vehicles cannibalized to keep other vehicles in the fight, and units forced to send their own assets far to rear in an effort to obtain needed parts. According to Major Stuart's study, the 3rd Infantry Division's (ID) 1st Brigade Combat Team (BCT) reported having to abandon nearly five percent of BCT and attached equipment (Stuart, 2004, p. 5).

The second segment of the strategic distribution pipeline after DLA consists of the Defense Transportation System, managed by the U.S. Transportation Command. USTRANSCOM is a unified command that serves as the DOD's single manager for transportation. It controls three service component commands: the Military Surface Deployment and Distribution Command, the Air Force's Air Mobility Command, and the Navy's Military Sealift Command. In addition to the physical transportation of assets, USTRANSCOM is also responsible for tracking the in-transit status of assets within its segment of the pipeline (Stuart, 2004, p. 20).

In this process the customer is the supply support activities (SSAs). A part request can be filled from several sources. Unit-level fill occurs when the part required by the maintenance technician is issued from inventory held and maintained by the parts clerk at unit-level inventory. SSA fill occurs when the part required by the maintenance technician is issued from inventory held at the supporting SSA. In this case, the unit parts clerk passes the request to the SSA. If the SSA is unable to issue the requested item from on-hand assets, the SSA passes a requisition for the desired part further up to supply chain (Girardini, et al., 2004, p. 6). The requisition process defined in the proposed model starts at this point. When the parts become available from one of the supply sources, the part is delivered to the supporting SSA. When SSA receives the desired parts, requisition lead time ends. Figure 5 summarizes this process.
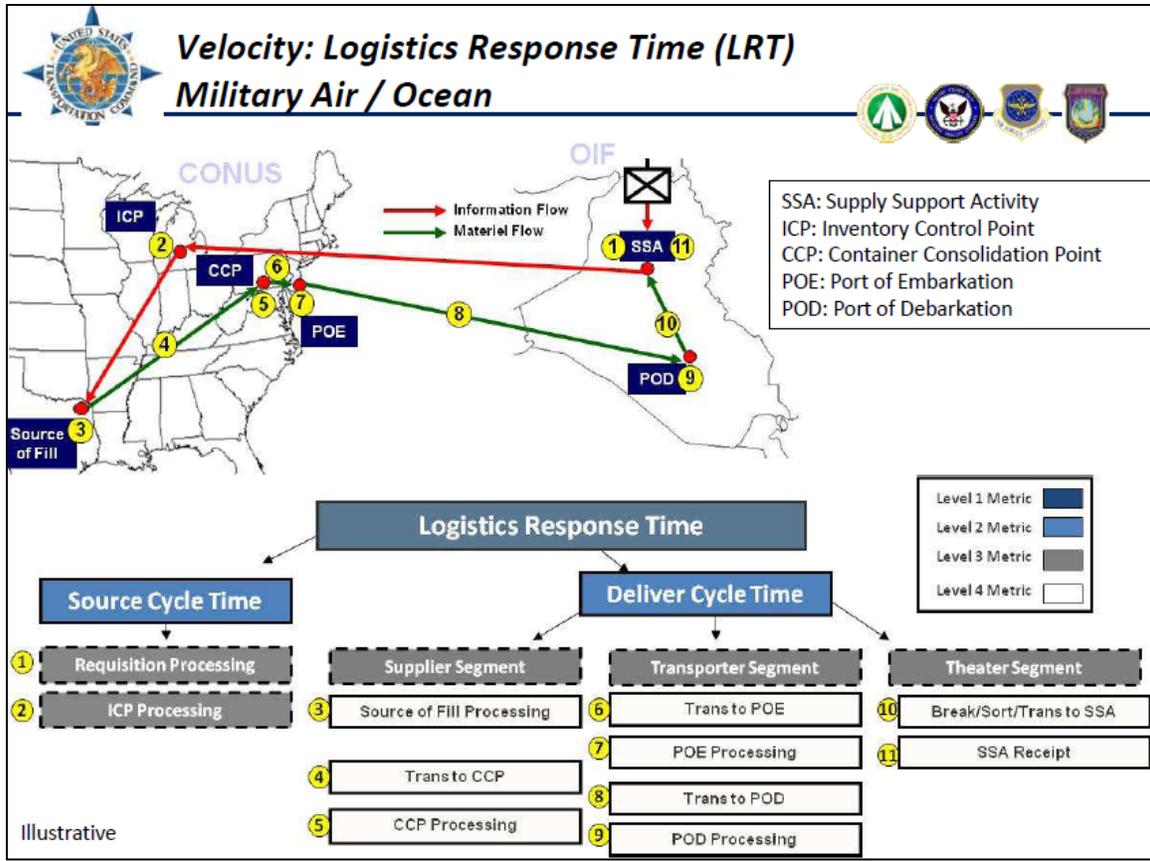
Figure 5. Summary of Requisition Lead Time (USTRANSCOM, 2011)

SSA is chosen as the customer to see the effects of lead time reduction because if an SSA fill is not possible, the requirement must be passed on to one of the other supply sources, which can lead to lengthy delays. The corresponding requisition lead time is the longest one; hence the savings caused by the lead time reduction can be seen much more easily.

The Army uses a Dollar Cost Banding (DCB) algorithm to calculate the breadth and depth of the stock. DCB uses a modified economic order quantity (EOQ) formula to set the order quantity. The modifications to the classical EOQ formula address practical issues about shortage constraint for high-demand items and the minimum warehouse location size that must be allocated for low-demand items (Girardini, et al., 2004, p. 22).

Thus, in the proposed model classical EOQ formula is used to calculate the order quantities. One of the shortcomings of Dollar Cost Banding study is about actual demand calculation. In DCB algorithm study, it is written that actual demands from two-year review period are used to create a demand profile for each item. However, a record of how many requisitions for an item is received and when the requisitions came in during the two year period is the source for actual demand (Girardini, et al., 2004, p. 23).

This record doesn't provide the accurate daily demand average and variation that is needed to calculate the safety stocks since it is only about the requisition process. Actual demands in a period, often reflects timing differentials related to when the demands are used rather than when the requisitions are ordered. If one uses requisition data instead of demand data, reported daily demand for an SSA in a period may be high because of the order quantities are either ordered or received during this period, but are not used until a subsequent period. Conversely, demands may be low in a period when the parts in the inventory are used but not replenished.

So, if there is no replenishment, does it mean the daily demand rate for that period is zero? These timing differences create a discrepancy between actual requisition levels and actual levels demands used during the period. It would be easy to do such a calculation but it would be wrong. Kaplan calls it spending fluctuations (Kaplan & Cooper, 1998, p. 279). It is one of the reasons that the actual demand rates driven from requisition data are inappropriate to calculate the safety stocks. To find the accurate average daily demand and standard deviation, the demand data is needed, not requisition data.

In such a case, the demand buckets are very important. The use of daily or weekly demand time buckets, as opposed to monthly or quarterly, does provide the necessary insight to calculate the demand variation more precisely. In other words, smaller buckets are required to calculate the standard deviation of the daily demand accurately. Also, the historical demand horizon often should be as much as 12 to 36 months to calculate more precise daily demand average and standard deviation (Hamel, 2011).

Problem Statement

Under DOD supply chain, USTRANSCOM is a unified command that serves as the DOD's single manager for transportation. The forward and strategic SSAs are the end users in this study. The purpose is to estimate the impact of reduced distribution lead time on inventory investment savings and to answer the question of "what is a day taken out of the pipeline worth?" by using the proposed model. The proposed model calculates safety stock levels of the class IX materiel using the historical data. After reducing the lead time by one day, it calculates the new safety stock levels. There will be a difference between those levels. These levels are needed to calculate the relevant inventory costs. In the calculation of expected total relevant cost of inventory, there are three different costs. These are ordering and setup cost, carrying cost and stock-out cost. Since only the lead time is changed, the difference will be on inventory cost and stock-out cost. Complete backordering is assumed when an item is temporarily out of stock. It means that any demand, when out of stock, is backordered and filled as soon as adequate-sized replenishment arrives and customer does not go elsewhere to satisfy the need. So, the main concern is on carrying cost and stock-out cost.

Data Collection

To do this, the primary data is needed. The questions asked to Army and USTRANSCOM in order to get the relevant data and run the model are as follows;

1. What is the service level standard in the Army?

2. What is the daily usage (demand) of each item in each SSA in the last two years? (If daily demand data is not available, weekly demand data is needed.)

3. How many days did the lead time take to complete each requisition for each SSA in the last two years? (Days in the interval between the submission of a replenishment requisition and receiving the materiel.)

4. What is the unit price for each item?

As a respond, a data file that consists of the requisitions of a 1-year period from 3 different SSAs is received. This data provides the lead times of each requisition process (number 3) and the unit prices for all items that are requested. Besides, service level standard is said to be 85% although it is not specified which service level is used by USTRANSCOM. Thanks to Dollar Cost Banding study of RAND Corporation, it is determined that the Department of the Army uses fill rate service level method and SSA fill rate goal is 85 percent stock availability given current demand level (Girardini, et al., 2004, p. 38).

However, this data file is just a data that covers requisition information, not daily demand information. Moreover, most of the items are the slow moving items which are ordered only once in the 1-year period. This information is enough to calculate the average daily demand, but it is not enough to calculate the daily demand variability.

Although the actual demand data is asked for again, it is said to continue with the current data that forces to make an additional assumption.

This additional assumption is that the variance of the daily demand of an item is equal to its mean. Since the main purpose of this study is to develop a repeatable model and there is no data to calculate the variance of daily demand (a necessary parameter to calculate the safety stocks), it is decided to make this additional assumption.

Input Analysis

As mentioned above, lead time parameters of related SSAs and the daily demand parameters for each item for each SSA are analyzed in order to get the most accurate parameters.

Lead Time Input Analysis

One of the critical elements of the computation of inventory levels is the time needed to restock an item in the SSA after the inventory position of the item reaches or goes below the ROP, and a replenishment requisition is generated. The time between the date of requisition and date of receipt is often referred to as the replenishment lead time. Total number of requisitions generated in the given data file is 48280 for 1-year requisition period. It is comprised of requisitions from 3 different SSAs. These are SSA1, SSA2 and SSA3. The requisitions are sorted according to their SSAs in order to calculate the lead time mean and standard deviation for each SSA.

The data file gives the date of requisition and the date of receipt. The differences between them are the requisition lead times. However some data are missing in terms of dates. That is why; the rows that have missing information are needed to be deleted and

prepared for analyzing the parameters. As stated before, it is assumed that lead time follows a normal distribution with mean l and variance $\sigma_l{}^2$. Arena Input Analyzer is used to fit a normal distribution for each SSA lead time data in order to get the corresponding graphs.

SSA1 is the biggest army supply support activity according to the data. 65% of all requisitions (31211) are generated from SSA1. After cleaning the raw data, there are 29974 different lead times for SSA1. For the lead time data of SSA1, a mean of 21.4 days and a standard deviation of 6.07 days are the normal distribution parameters.
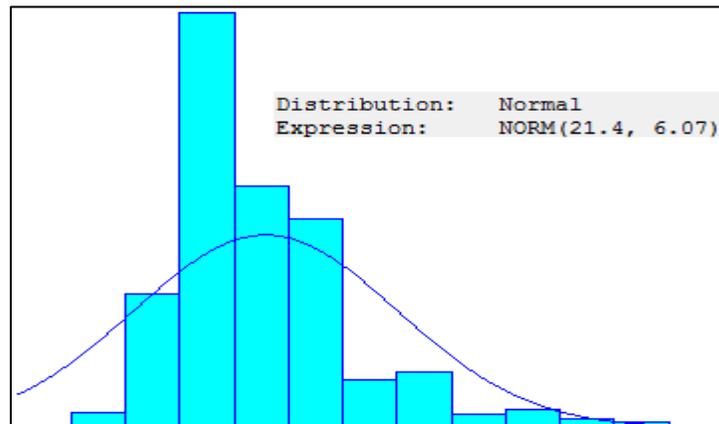
Figure 6. SSA1 Lead Time Data Normal Distribution

11% of all requisitions (5292) are generated from SSA2. After cleaning the raw data, there are 5198 different lead times for SSA2. For the lead time data of SSA2, a mean of 16.6 days and a standard deviation of 7.12 days are the normal distribution parameters.
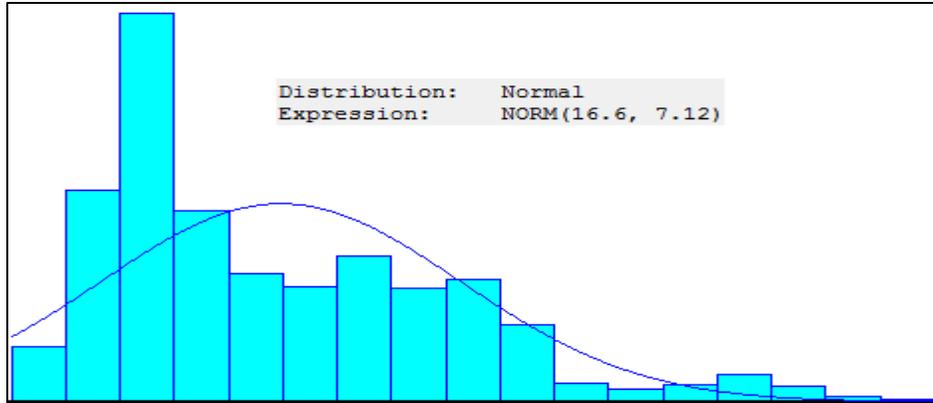
Figure 7. SSA2 Lead Time Data Normal Distribution

24% of all requisitions (11777) are generated from SSA3. After cleaning the raw data, there are 11151 different lead times for SSA3. For the lead time data of SSA3, a mean of 12 days and a standard deviation of 4.7 days are the normal distribution parameters.
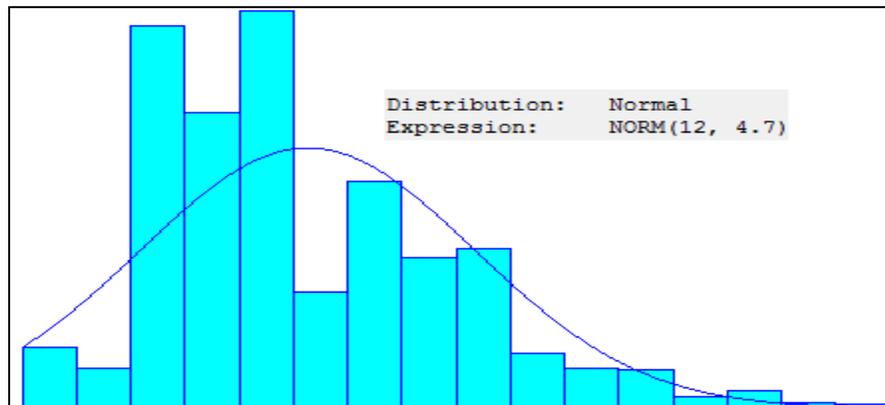
Figure 8. SSA3 Lead Time Data Normal Distribution

Daily Demand Input Analysis

To analyze the daily demand of each item at each SSA, data set firstly needed to be sorted out according to their SSAs, and each SSA requisition data needed to be saved separately. The most of the items are requested only once for 1-year period that makes the daily demand average equal to the quantity requested / 360 days. But also there are

items that are requested for hundreds of units. Also the unit prices of items range from $0.01 to $25,316.74. So, how does one have to decide to the inventory breadth? In other words, where to stop?

The algorithm in the traditional army stocking policy used a "one-size-fits all" approach for determining the inventory breadth. An item not currently stocked would need 9 requests over a year period to be added, while an item already stocked would need 3 demands to be retained. One of the shortcoming of this 9/3 policy was that there was no difference among items according to cost or criticality. Thus, these criteria were applied equally to a ten cent screw and a $500,000 tank engine, despite their different levels of impact (Girardini, et al., 2004, p. 19).

The DCB algorithm that took place of traditional army stocking policy provides a better insight by adjusting the criteria for determining inventory breadth according to the item's criticality, size, density, and dollar value. It provides a bigger picture of demand by using a two year demand history. As unit price goes down, so do the add/retain criteria. Table 5 shows the DCB qualification logic (Girardini, et al., 2004, p. 19).

Table 5. DCB Qualification Logic

Essentiality Code	High-Priority Demand	< $10	< $100	< $1,000	> $1,000
Yes	Yes	2/1	3/1	6/3	9/3
Yes	No	4/2	4/2	6/3	9/3
No	Yes	2/1	3/1	6/3	9/3
No	No	12/3	15/3	30/3	1,000/3

Another way to determine the breadth of inventory is applying ABC classification. The main reason behind applying an ABC classification is that the number

of items is too large to implement an item based inventory control policy. Typically, 20% of the items requested account for 80% of the total annual dollar demand. That is why; all the items requested should not be controlled at the same extent. Silver suggests developing a distribution by annual demand value curve (Silver, Pyke, & Peterson, 1998, p. 33). Also, Teunter, Babai and Syntetos ranks the items based on the value of $bD/_{vrQ}$, where b is the criticality measured by stock-out cost (Teunter, Babai, & Syntetos, 2010).

In this study, ABC classification is decided to be applied to determine the inventory breadth. To do that, the unit price v, and the annual demand D, is needed to be identified for each item requested. To do that, the requisitions firstly needed to be sorted based on their National Item Identification Numbers, or NIIN. Since some of the items are requested more than once, the quantities requested for each item are summed in order to find their annual demand. Although it seems very complicated to sum quantities requested for each item especially when there are thousands of items, it is an easy process to calculate these annual demands in Excel PivotTable. Then, the product "Dv" is calculated for each item, and these Dv values are ranked in descending order, starting with the largest value.

Finally, the corresponding cumulative value of the total annual dollar demand, cumulative percent of the total number of items requested and cumulative percent of total annual dollar demand are calculated. Table 6 shows these values that are calculated for SSA1. As it can be seen from Table 6, first 20 items that have the largest Dv values that

account for 20% of the total dollar value, although they are not even 1% of all items in number.

Table 6. SSA1 Items by Descending Dollar Demand

#	NIIN	Unit Price	D	D/360	Dv	Cumulative Dv	Cumulative % of # of Items	Cumulative % of Total Annual Dollar Demand
1	015764558	$25,316.74	19	0.052778	$481,018.06	$481,018.06	0.01%	3%
2	015773677	$1,349.11	287	0.797222	$387,194.57	$868,212.63	0.02%	5%
3	001621010	$3,389.28	106	0.294444	$359,263.68	$1,227,476.31	0.04%	7%
4	015210941	$794.00	324	0.9	$257,256.00	$1,484,732.31	0.05%	8%
5	015773663	$1,460.57	138	0.383333	$201,558.66	$1,686,290.97	0.06%	9%
6	015638562	$4,737.00	38	0.105556	$180,006.00	$1,866,296.97	0.07%	10%
7	009545657	$14.01	12187	33.85278	$170,739.87	$2,037,036.84	0.08%	11%
8	014787422	$1,815.37	84	0.233333	$152,491.08	$2,189,527.92	0.09%	12%
9	014072627	$2,800.00	53	0.147222	$148,400.00	$2,337,927.92	0.11%	13%
10	014768971	$2,785.95	51	0.141667	$142,083.45	$2,480,011.37	0.12%	14%
11	014851472	$402.44	337	0.936111	$135,622.28	$2,615,633.65	0.13%	15%
12	015801324	$850.00	140	0.388889	$119,000.00	$2,734,633.65	0.14%	15%
13	015773950	$3,747.50	30	0.083333	$112,425.00	$2,847,058.65	0.15%	16%
14	015367270	$3,022.15	37	0.102778	$111,819.55	$2,958,878.20	0.17%	17%
15	015759838	$335.32	322	0.894444	$107,973.04	$3,066,851.24	0.18%	17%
16	015770620	$2,202.51	47	0.130556	$103,517.97	$3,170,369.21	0.19%	18%
17	000577252	$103.01	968	2.688889	$99,713.68	$3,270,082.89	0.20%	18%
18	015695877	$1,628.69	61	0.169444	$99,350.09	$3,369,432.98	0.21%	19%
19	014389450	$240.96	411	1.141667	$99,034.56	$3,468,467.54	0.22%	19%
20	015746258	$3,646.20	26	0.072222	$94,801.20	$3,563,268.74	0.24%	20%

Table 6 is one of the most valuable tools handling the breadth of inventory because it helps user to identify the items that are most and least important. The corresponding values of the cumulative percent of total annual dollar demand and the cumulative percent of the total number of items requested are plotted for SSA1 on Figure 9.
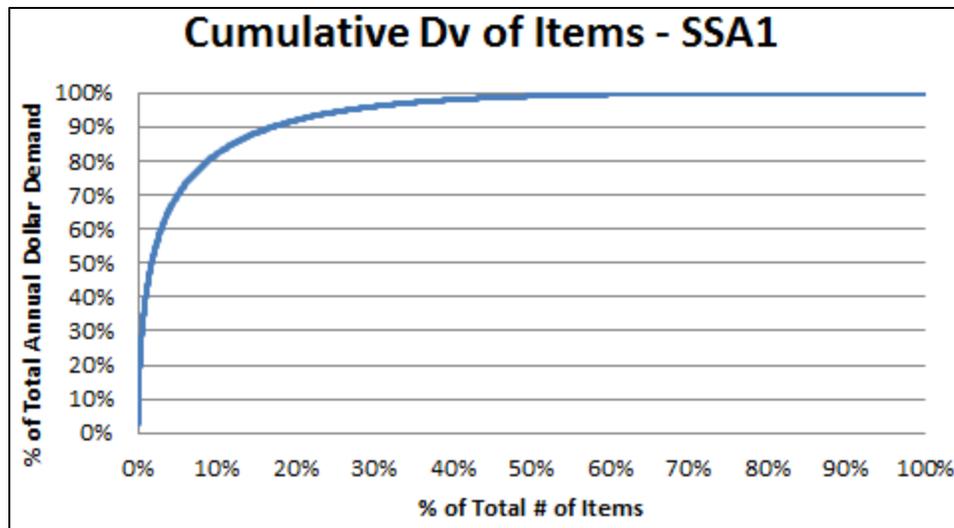
Figure 9. SSA1 Cumulative Dollar Demand of Items

It can be seen from Figure 9 that more than half of the items that are least important don't account even for 2% of the total annual dollar demand. While the 80-20 rule is typical, the precise number of members in each of the A, B, and C categories depends on how spread out the cumulative Dv curve actually is (Silver, Pyke, & Peterson, 1998, p. 35). In this study, the items that have the smallest Dv values that account for the last 2% of the total annual dollar demand is categorized as C items. Since the savings from these items will almost be none, it is decided not to take this category into account. So, the inventory breadth consists of A and B items. For example, the ABC classification summary of the items requested from SSA1 is as follows;

Table 7. SSA1 ABC Classification Summary

	Total Annual Dollar Demand (Dv)	# of Items	Cumulative % of # of Items	Cumulative % of Total Annual Dollar Demand
A items	$13,404,089.65	564	6.7%	75.0%
B items	$4,111,595.25	2885	34.1%	23.0%
C items	$354,395.17	5002	59.2%	2.0%
Total	$17,870,080.07	8451	100.0%	100.0%

As it can be seen from Table 7, C items that encompass 59.2% of the items are not taken into account, because they account only for 2% of the total annual dollar demand.

Next, ABC classification approach is applied to SSA2 to determine the inventory breadth of SSA2 items by taking advantage of Excel PivotTable. The corresponding values of the cumulative percent of total annual dollar demand and the cumulative percent of the total number of items requested are plotted for SSA2 on Figure 10.
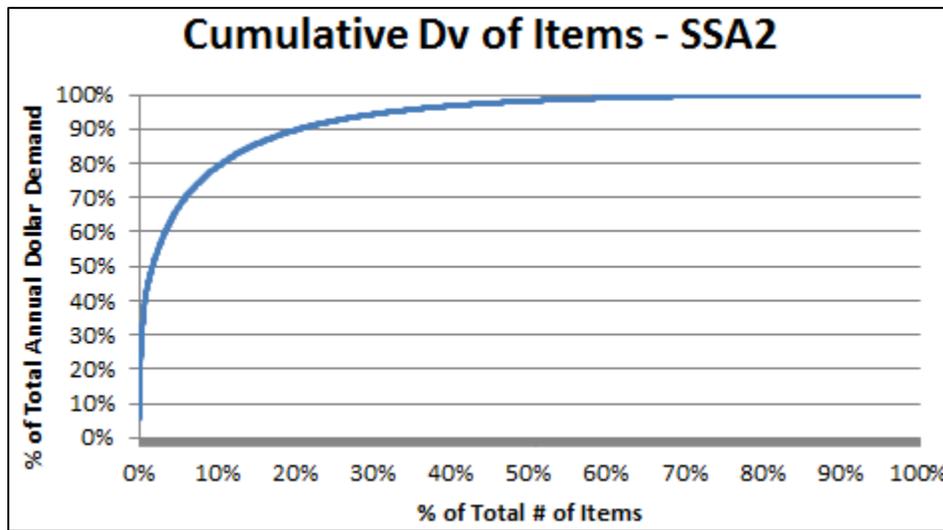
Figure 10. SSA2 Cumulative Dollar Demand of Items

The ABC classification summary of the items requested from SSA2 is as follows;

Table 8. SSA2 ABC Classification Summary

	Total Annual Dollar Demand (Dv)	# of Items	Cumulative % of # of Items	Cumulative % of Total Annual Dollar Demand
A items	$1,226,087.34	234	7.9%	75.0%
B items	$376,091.52	1215	40.9%	23.0%
C items	$32,308.02	1519	51.2%	2.0%
Total	$1,634,486.88	2968	100.0%	100.0%

According to Table 8, 51.2% of the items requested from SSA2 are C items that account only for 2% of the total annual dollar demand. Thus; they are excluded from the model.

Finally, ABC classification approach is applied to SSA3 to determine the inventory breadth of SSA3 items. The corresponding values of the cumulative percent of total annual dollar demand and the cumulative percent of the total number of items requested are plotted for SSA3 on Figure 11.
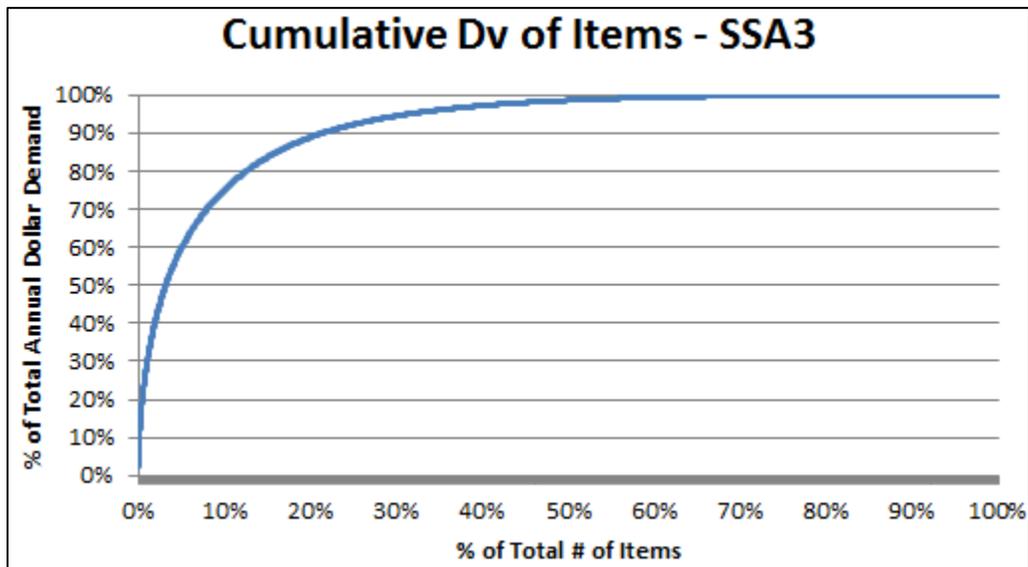
Figure 11. SSA3 Cumulative Dollar Demand of Items

The ABC classification summary of the items requested from SSA3 is as follows;

Table 9. SSA3 ABC Classification Summary

	Total Annual Dollar Demand (Dv)	# of Items	Cumulative % of # of Items	Cumulative % of Total Annual Dollar Demand
A items	$4,743,212.15	589	10.0%	75.0%
B items	$1,455,169.09	2110	35.8%	23.0%
C items	$124,188.24	3195	54.2%	2.0%
Total	$6,322,569.48	5894	100.0%	100.0%

According to Table 9, 54.2% of the items requested from SSA3 are C items that account only for 2% of the total annual dollar demand. Thus; they are excluded from the model.

Experiments and Results

All of the experiments of the proposed model is performed on a computer with an Intel® Core™ i5 CPU M450 @2.40 GHz processor with 4 GB RAM using Microsoft® Excel 2010, but features of the proposed model are also supported by Microsoft® Excel 2007.

To analyze the impact of lead time reduction, firstly the primary data needed (yellow cells) to be entered. As stated in chapter 3, these primary data and their corresponding spreadsheet cells are as follows;

						Demand		Lead Time		Lead Time Reduction	
Independent Variables	Order Cost	Carrying Cost %	Fill Rate Goal %	Fractional Charge	Unit Price	Average	Standard Deviation	Average	Standard Deviation	Average	Standard Deviation
Spreadsheet Cells	C1	C2	C3	C4	E10	G10	H10	H1	H2	C5	C6

According to Dollar Cost Banding study, the United States Army uses $13.26 as the ordering cost, and uses 22% as the carrying cost as a percentage of unit price (Girardini, et al., 2004, pp. 97-98). Also, SSA fill rate goal is 85 percent stock availability given current demand level according to the same study. 0.5 is used as the fractional charge per unit short, B_2. This fractional charge is needed to calculate the stock-out cost. In this study, these values are used as the primary independent variables, but user can change any of these values in order to make different sensitivity analyses. For example, by increasing the fill rate, the user can observe the increase in safety stock or if the user

calculates the fractional charge per unit short, B_2 more accurately, he can plug it into the model. Moreover, if user wants to see only carrying cost savings, B_2 can be set to zero.

Note that, nothing is entered in "cell C7", since the model calculates the number of items automatically. The corresponding spreadsheet formula is computed in the cell "C7" as follows;

$$Formula \ for \ cell \ C7 = MATCH(9.99999999999999E + 307, E:E) - 9 \qquad (4.1)$$

The analyzed lead time mean and standard deviation are plugged into the model for each SSA experiment. Next, NIIN, unit price, daily demand mean and standard deviation information of the items requested for each SSA are entered according to their "Dv" values in a descending order. The purpose of this descending order is to see the impact of ABC classified items on the savings. So, user will be able to see another Pareto diagram that shows the cumulative percentage of total annual dollar savings of the ABC classified items.

Next, the intended days of reduction in terms of mean and standard deviation (red cells) are entered. In this case, the impact of one day (mean) reduction is calculated. Then the model is rerun for each SSA by reducing only the standard deviation of the lead time by one day. Finally the model is rerun by reducing both the mean and the standard deviation together by one day for each SSA.

SSA1

For SSA1, there are 3449 items in the model. After entering the primary data, "*Calculate Savings*" button is clicked in order to see 1-day lead time reduction savings.

For 3449 items, it takes about 60 minutes for the model to solve the optimization problem for each item before and after lead time reduction. In other words, Excel Solver works $3449 \times 2 = 6898$ times in order to find the optimal safety factor value that gives 85% fill rate goal for each item before and after lead time reduction. Time can be more or less based on different computer systems.

The estimated annual savings caused by 1-day lead time reduction <u>in mean</u> is **$8,249.93** for SSA1. Carrying cost accounts for $4,792.11 and stock-out cost accounts for $3,457.82 of this saving while there is no ordering cost savings. If the fractional charge per unit short, B_2, is updated the stock-out cost changes accordingly.

The estimated annual savings caused by 1-day lead time reduction <u>in standard deviation</u> is **$14,705.71** for SSA1. Finally, the estimated annual savings caused by 1-day lead time reduction <u>in both mean and standard deviation together</u> is **$23,246.05** for SSA1. The model results also show that safety factor, k increases as Dv increases; that is, larger safety factors are given to the faster-moving or more critical items.

Firstly, from Figure 12, it can be easily seen that more important items have more impact on inventory savings than less important items, because the pace of increase on savings is decreasing by adding less important items into calculation. If C items had been taken into account, the model would run at least 60 more minutes (C items account for approximately 50% of the items) but there wouldn't be any significant increase on savings.
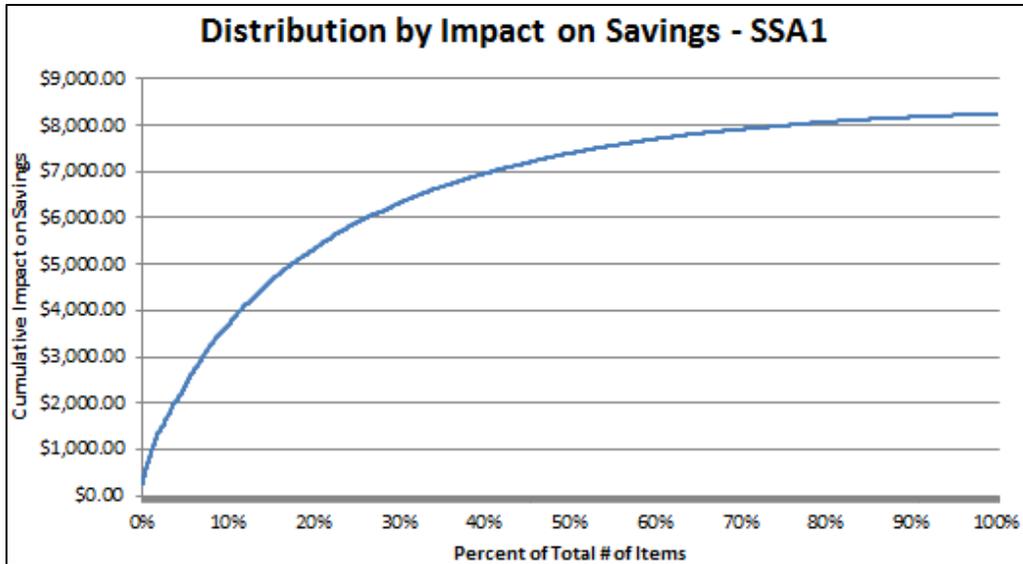
Figure 12. SSA1 Cumulative Distribution by Impact on Savings

Secondly, the savings caused by 1-day mean reduction, 1-day standard deviation reduction and 1-day reduction in both mean and standard deviation together are compared. The purpose is to see which one of these processes is more effective for SSA1 inventory investment.
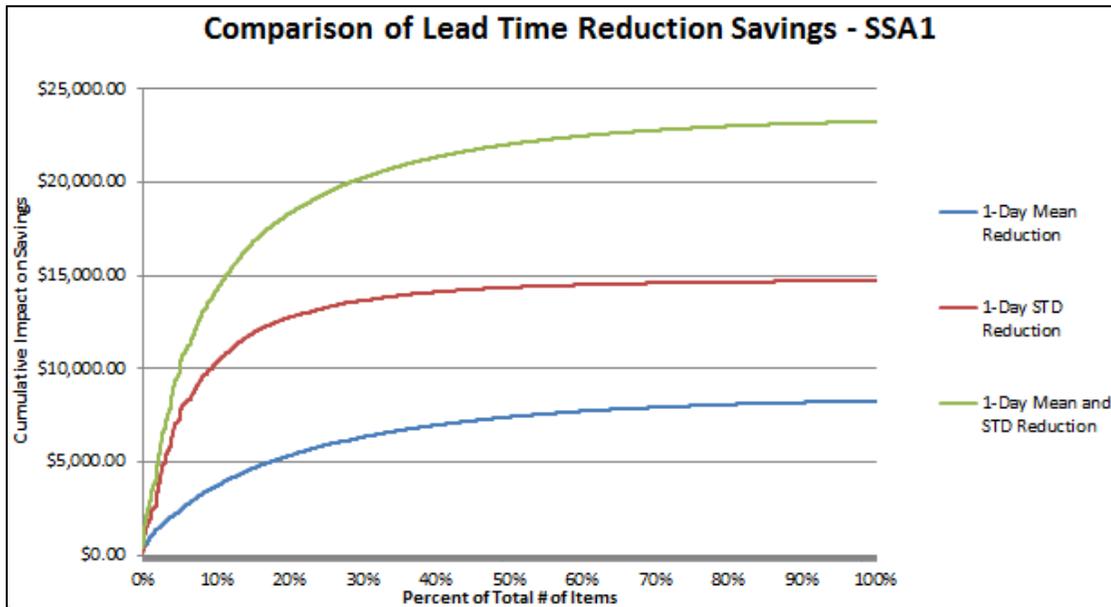

Figure 13. Comparison of Lead Time Reduction Savings in SSA1

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Figure 13 shows cumulative impact of lead time reductions on savings for SSA1. According to the graph, it seems that reducing variability of SSA1 lead time tends to have a greater impact than reducing lead time itself. This is true especially for more important items that have larger annual dollar demand (Dv). For less important items, there seems no significant difference between reducing lead time variability and reducing lead time itself. Moreover, it can be even say that for less important items reducing lead time gives slightly more savings than reducing variability of SSA1 lead time.

SSA2

For SSA2, there are 1449 items in the model. After entering the primary data, "*Calculate Savings*" button is clicked in order to see 1-day lead time reduction savings. For 1449 items, it takes about 30 minutes for the model to solve the optimization problem for each item before and after lead time reduction. Time can be more or less based on different computer systems.

The estimated annual savings caused by 1-day lead time reduction <u>in mean</u> is **$1,248.26** for SSA2. Carrying cost accounts for $554.09 and stock-out cost accounts for $694.17 of this saving while there is no ordering cost saving.

The estimated annual savings caused by 1-day lead time reduction <u>in standard deviation</u> is **$1,371.51** for SSA2. Finally, the estimated annual savings caused by 1-day lead time reduction <u>in both mean and standard deviation together</u> is **$2,641.78** for SSA2.

Firstly, from Figure 14, it can be easily seen that more important items have more impact on inventory savings than less important items, because the pace of increase on savings is decreasing by adding less important items into calculation.
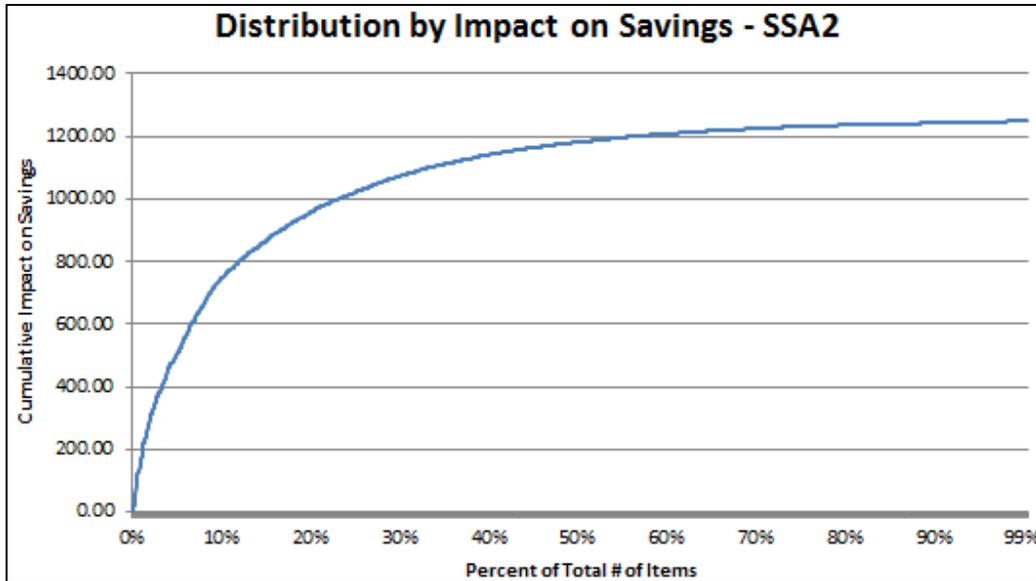
Figure 14. SSA2 Cumulative Distribution by Impact on Savings

Secondly, the savings caused by 1-day mean reduction, 1-day standard deviation reduction and 1-day reduction in both mean and standard deviation together are compared. The purpose is again to see which one of these processes is more effective for SSA2 inventory investment.
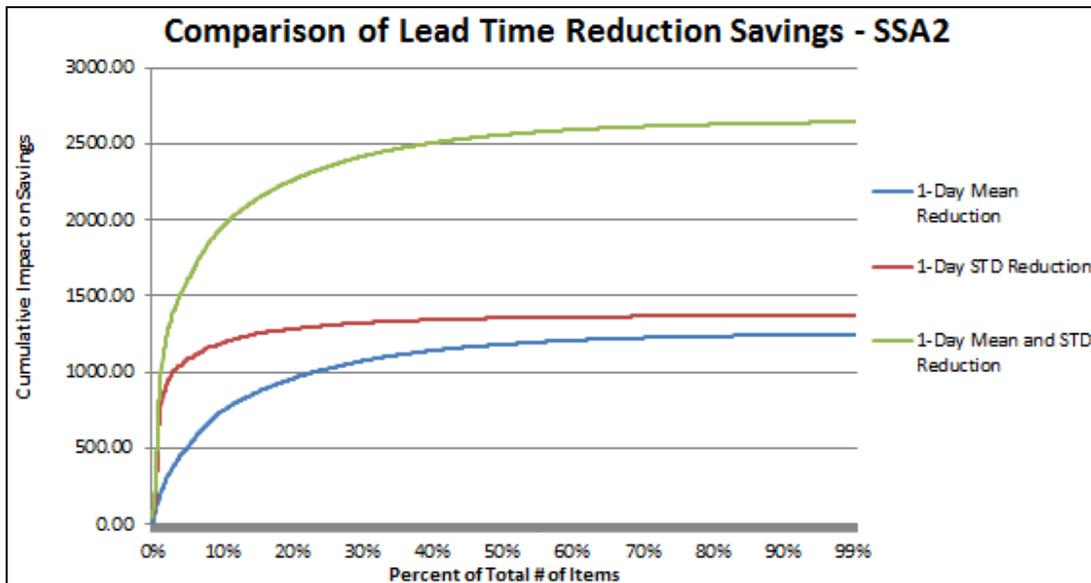

Figure 15. Comparison of Lead Time Reduction Savings in SSA2

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Figure 15 shows cumulative impact of lead time reductions on savings for SSA2. According to the graph, it seems, as in the SSA1 analysis, that reducing variability of SSA2 lead time tends to have a slightly greater impact than reducing lead time itself. For less important items, reducing lead time gives slightly more savings than reducing variability of SSA2 lead time.

SSA3

For SSA3, there are 2699 items in the model. After entering the primary data, "*Calculate Savings*" button is clicked in order to see 1-day lead time reduction savings. For 2699 items, it takes about 45 minutes for the model to solve the optimization problem for each item before and after lead time reduction. Time can be more or less based on different computer systems.

The estimated annual savings caused by 1-day lead time reduction <u>in mean</u> is **$7,118.79** for SSA3. Carrying cost accounts for $3,375.07 and stock-out cost accounts for $3,743.72 of this saving while there is no ordering cost saving.

The estimated annual savings caused by 1-day lead time reduction <u>in standard deviation</u> is **$3,056.21** for SSA3. Finally, the estimated annual savings caused by 1-day lead time reduction <u>in both mean and standard deviation together</u> is **$10,557.88** for SSA3.

Firstly, it can be easily seen from Figure 16 that more important items have more impact on inventory savings than less important items and this is the reason why C items are excluded from the model.
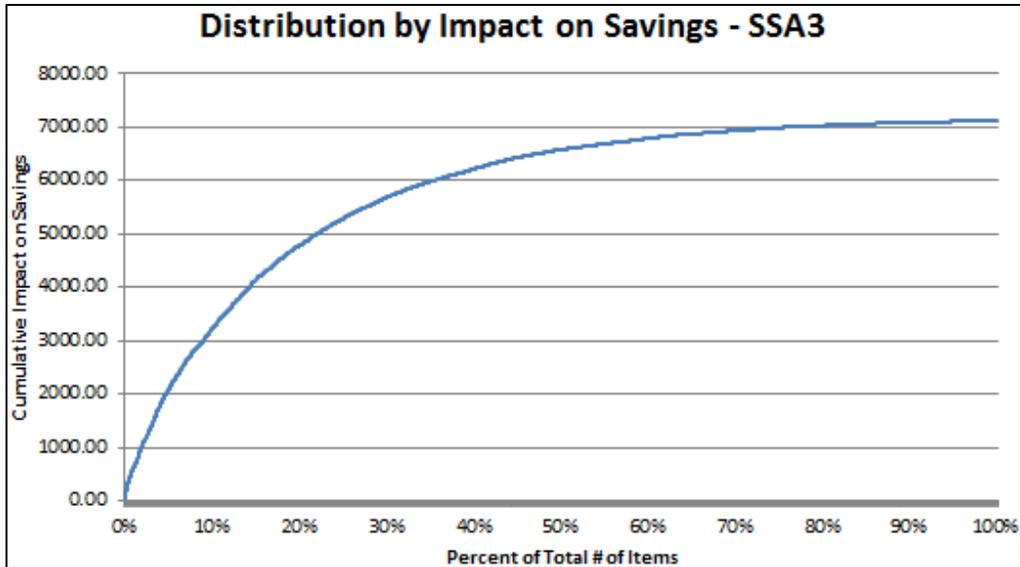
Figure 16. SSA3 Cumulative Distribution by Impact on Savings

Secondly, the savings caused by 1-day mean reduction, 1-day standard deviation reduction and 1-day reduction in both mean and standard deviation together are compared. The purpose is again to see which one of these processes is more effective for SSA3 inventory investment.
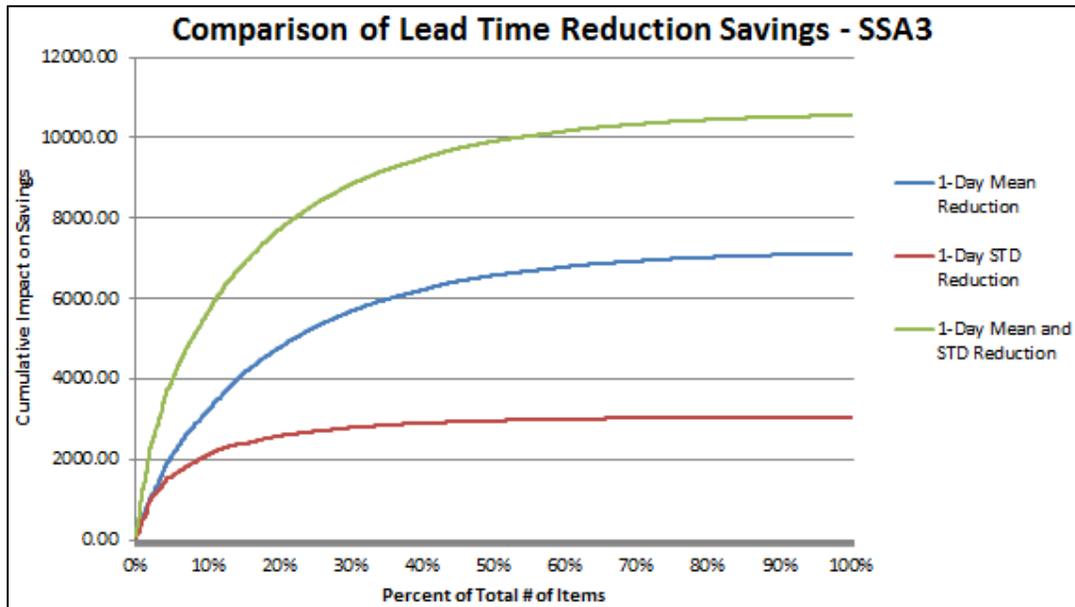
Figure 17. Comparison of Lead Time Reduction Savings in SSA3

Figure 17 shows cumulative impact of lead time reductions on savings for SSA3. This time the results are different than the results of SSA1 and SSA2. For SSA3, reducing lead time mean tends to have a greater impact than reducing variability. Moreover, this greater impact continues until the last item.

Sensitivity Analysis

Sensitivity analysis can provide a better picture of how the result will change if different days of reductions in mean and standard deviation are applied to the model. Since all relevant factors are not known with certainty, to run many "what-if" scenarios provides a better insight into the benefits of lead time reduction. By using the proposed model, user can run many "what-if" scenarios and come up with different results.

For SSA1, the model is run for 15 times; from 1-day to 5-day reduction for mean, standard deviation and both.
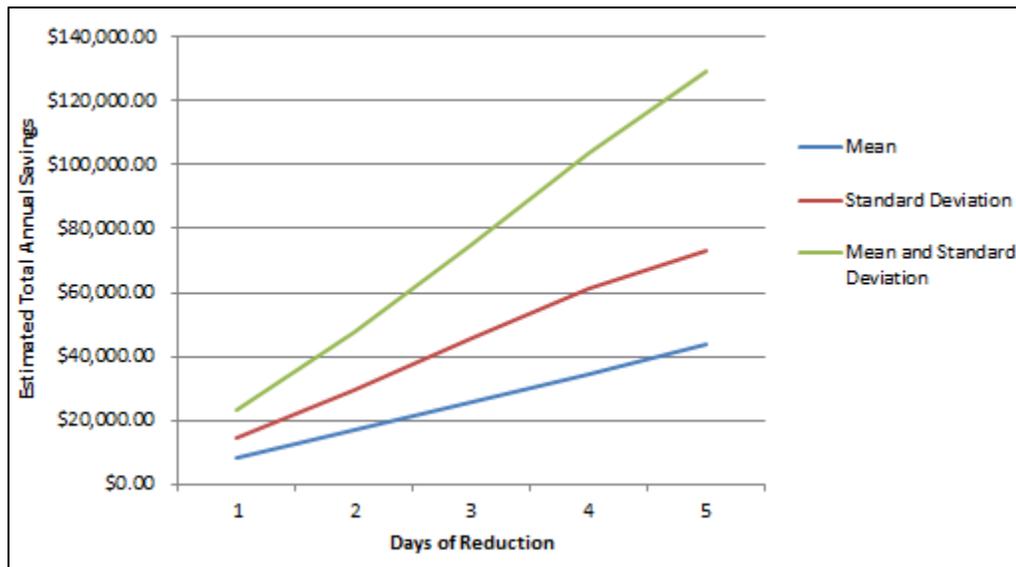
Figure 18. Savings by Days of Reduction in SSA1

Figure 18 summarizes the results of estimated savings for SSA1 inventory investment. It seems that continuous lead time variability reduction has a greater impact than the reduction of lead time mean. However, trying to reduce both gives the best bang for the buck.

For SSA2, the model is run for 15 times; from 1-day to 5-day reduction for mean, standard deviation and both.
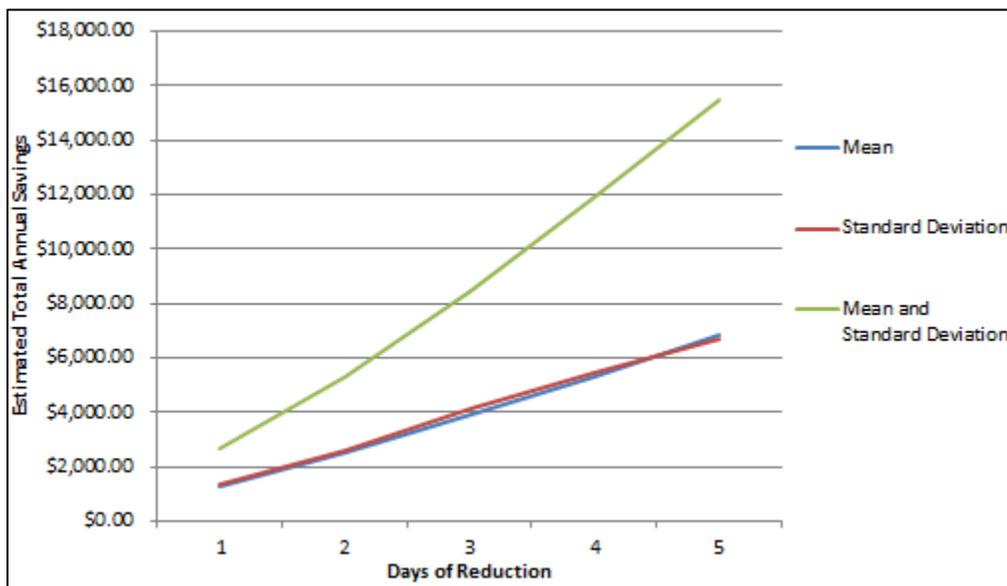
Figure 19. Savings by Days of Reduction in SSA2

Figure 19 summarizes the results of estimated savings for SSA2 inventory investment. It seems that there is not any significant difference between reducing lead time mean and standard deviation in terms of savings.

For SSA3, the model is run for 12 times; from 1-day to 4-day reduction for mean, standard deviation and both, since the standard deviation of SSA3 lead time is less than 5 days.
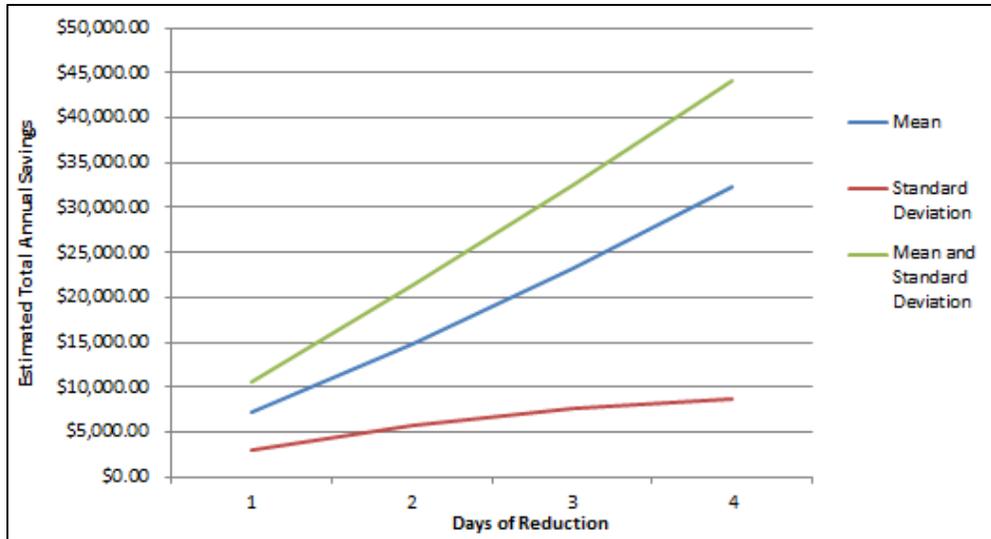
Figure 20. Savings by Days of Reduction in SSA3

Figure 20 summarizes the results of estimated savings for SSA3 inventory investment. It is obvious that reducing mean is more effective than reducing variability.

Finally, the SSAs are compared in order to prioritize the investment opportunities. Figure 21 shows the comparison of the lead time <u>mean</u> reduction impacts on inventory savings of SSAs.
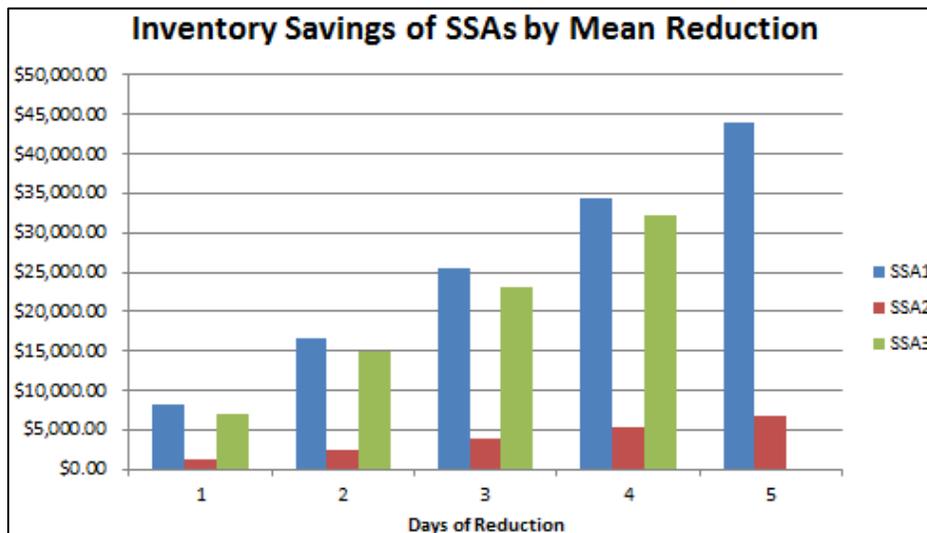
Figure 21. Comparison of SSAs by Mean Reduction

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According to the lead time reduction (mean) results of the proposed model, inventory savings of SSA1 and SSA3 are very close to each other. That is why; the decision maker firstly needs try to reduce SSA1 and SSA3 lead time means rather than the one of SSA2.

Figure 22 compares the lead time <u>variability</u> reduction impacts on inventory savings of SSAs.
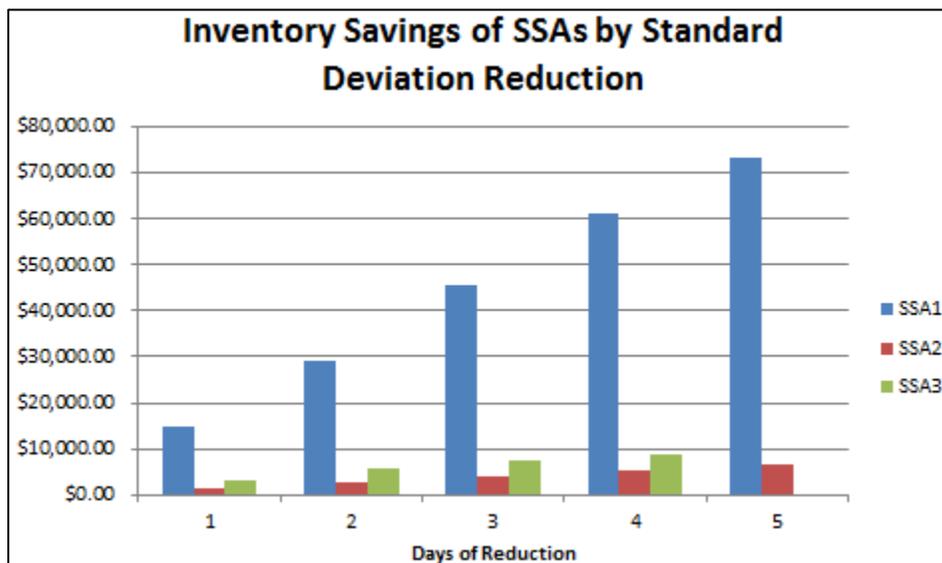
Figure 22. Comparison of SSAs by Variability Reduction

According to the lead time reduction (standard deviation) results of the proposed model, it is very obvious that reducing lead time variability of SSA1 is far more advantageous than the others. Thus, the decision maker needs to prioritize the reduction process of SSA1 lead time variability, since it is also more advantageous than reducing SSA1 and SSA3 lead time means.

V. Conclusions and Recommendations

Conclusions

"The mean is mean but the variability is meaner."

When "Calculate Savings" button is clicked, the spreadsheet model starts to calculate the optimal safety factor values that give the specified fill rate goal firstly for all items before lead time reduction, and then it repeats the same process after lead time reduction, starting again from the first item. Here is the logic of the model:

When the lead time is reduced, the first impact happens on standard deviation of demand during lead time, and then on safety factor. Since the standard deviation of demand during lead time decreases, a smaller safety factor is needed to reach to the same fill rate goal. The overall impact comes from these two variables. Safety stock is the product of standard deviation of demand during lead time and safety factor. Since both of them decrease, safety stock decreases more. This process results in getting carrying cost savings.

Stock availability of some items can be already over the fill rate goal, that is, there is no need to keep safety stock for those items that leads to zero safety factor. These are especially slow-moving or cheaper items. At this point, when the lead time is reduced, the model cannot reduce the safety factor, since it is already zero. But it reduces standard deviation of demand during lead time. So, it leads to a new fill rate which is greater than the specified fill rate goal. For those items there are no carrying cost savings but backordering cost savings.

Most of the items in an inventory are slow-moving items requested only once or twice a year. Furthermore, some of these items are less important items in terms of their dollar value. To make a trade-off between time and accuracy, ABC classification approach is preferred in order to determine the inventory breadth. The items that have the smallest Dv values that account for the last 2% of the total annual dollar demand are categorized as C items. Since the savings from these items will almost be none, this category is excluded from the model and this approach is proved in results section. So, the inventory breadth consists of A and B items that account for 98% of total annual dollar demand, but they cover less than 50% of the items. The model results also show that safety factor, k increases as Dv increases; that is, larger safety factors are given to the faster-moving or more important items.

The proposed model is created in order to develop a repeatable process to estimate the impact of reduced distribution time on inventory investment savings at forward and strategic locations to motivate decision makers to support enterprise-wide distribution process improvement. Although most of the research papers take cycle service level into account to estimate the safety stock, cycle service level does not mean a lot in real world situations. In real world examples, firms mostly use fill rate goals as service levels to set safety stock levels. Although it is cumbersome to calculate safety stock levels based on fill rate goals, Excel Solver and VBA features of spreadsheets make it easier to model this process. The proposed spreadsheet model contains all the functions needed to calculate the expected inventory investment savings caused by lead time reduction such as related inventory cost functions, safety stock and reorder point calculations.

Also, it is different than the previous research in that, the spreadsheet model does not include the expression for the cost of lead time reduction in the objective function. Rather, it calculates the savings by reducing the mean and the standard deviation of the normally distributed lead time and then leads decision makers to see whether the savings can pay for the cost of reduction. Since the proposed spreadsheet model is a repeatable and a visual process that estimates the impact of reduced distribution time on inventory investment savings, it seems to be the right model for the research objective.

When the spreadsheet model is finalized, results of some single item examples from inventory control books and articles are compared with the results of proposed model in order to verify the proposed model. Expectedly, the same results are found. Almost all of the researchers solve the fill rate based-safety stock problems manually. Since a mathematical formulation is not possible between safety factors and fill rate goals, some conversion tables like "Table of Loss Integral Standardized Normal Distribution (Bowersox, Closs, & Helferich, 1986, p. 214)" or "Table of Some Functions of the Unit Normal Distribution (Silver, Pyke, & Peterson, 1998, pp. 724-734)" are used. In the proposed model, Excel Solver is used instead of those tables to find the related safety factors and VBA is used to make the model continuous. The proposed model not only finds the same values but also gives more precise values and makes it a lot faster. So, it is verified that the proposed spreadsheet model addresses the question of "what is a day taken out of pipeline worth in inventory" and beyond. That is why; the spreadsheet model seems to be built right.

Also the end-users are encouraged to save a copy of the proposed model and not to change the structure and the formulas if they don't have enough knowledge on the spreadsheet model's domain in terms of its purpose, assumptions, mathematical formulations and outcomes. End-users who have the domain knowledge can easily change and upgrade the model for future purposes. Also it is useful to protect the formulated cells in order to prevent the possible accidental overwriting.

The normal approximation suggests that reducing lead time variability has greater impact than reducing lead time mean. But this is not always the case as in the analysis of this study, especially when lead time variability is small. That is why, it is suggested for user to run the model for each case and interpret the results accordingly. From the results, it seems that reducing variability tends to have a greater impact for more important items that have larger annual dollar demand (Dv). For less important items, there seems no significant difference between reducing lead time variability and reducing lead time itself. Moreover, it can be even said that for less important items reducing lead time gives slightly more and consistent savings than reducing variability.

The proposed model also enables users to prioritize the investment opportunities by comparing different inventories with many "what-if" scenarios. In the case of this study, it is found out that reducing lead time variability of SSA1 seems to be more advantageous than the other choices. After that SSA1 and SSA3 lead time means seem to be tenable to reduce.

This model is a repeatable spreadsheet model. Since it has hundreds of formulations, and the codes are written for specific rows and cells, it is sensitive to

accidental changes, and additions (Cunha & Mutarelli, 2007). This is especially a serious problem for macro coding, since the cell numbers are entered into the macro code. Thus, user should update the code window if he updates the spreadsheet model. But it is not necessary to update the spreadsheet, since it automatically updates formulations when additional row or columns are entered.

This research is significant because it aims at managerial prescriptions on how to reduce safety stocks and ultimately inventory cost by reducing lead time mean or variability without hurting the fill rate service levels provided to customers.

Also, another contribution in this study is that a means of automatically calculating the inventory control parameters such as safety stock and reorder point, and estimated savings caused by lead time mean or variability reduction is provided to the users. So, decision makers can do a trade-off analysis whether reducing lead time would override the lead time crashing cost.

While this analysis draws from the military environment, the lessons learned can be applied to any company trying to reduce the cost of inventory by using lean philosophy because the roots of this model is driven from the applications of the commercial world.

Further Research

Future research may be conducted to consider other demand and lead time distributions. Also, the proposed model can be modified by using different stock-out cost structures. Since most of the firms use EOQ as their lot size, it is also used in the proposed model. If optimal order sizes are calculated based on different cost structures,

they can be plugged into the model instead of EOQ. This will also result in ordering cost savings that is already in the model. If safety factor is calculated based on other objectives such as cost minimization or other service levels, the model should be modified accordingly. Another extension of this model may be conducted by considering the inventory model with a mixture of lost sales and backorders. Also, it would be of interest to add a crashing cost factor into the model in the future research on this problem.

Appendix A. A Screenshot of The Proposed Spreadsheet Model

Order Cost	$13.26	Lead Time	21.41																Safety Factor Index		0
Carrying Cost %	22%	STD of Lead Time	6.068																Fill Rate Index		98%
Fill Rate Goal %	85%																		Unit		3449
Fractional Charge per Unit Short (B₂)	0.5	Calculate Savings		$8,249.93				100%	COMPLETED										Column		2
Reduced # of Days	1																				
STD Reduction	0																				
# of Items	3449		DAILY DEMAND			BEFORE LEAD TIME CRASH					AFTER LEAD TIME CRASH						SAVINGS				

#	NIIN	UNIT PRICE	AVERAGE	STD.DEV.	SAFETY FACTOR	STD.DEV of LEADTIME DEMAND	EOQ	SS	ROP	FILL RATE	SAFETY FACTOR	STD.DEV of LEADTIME DEMAND	EOQ	SS	ROP	FILL RATE	ORDERING COST SAVING	CARRYING COST SAVING	STOCKOUT COST SAVING	TOTAL SAVING PER ITEM	Cumulative Savings	FILL RATE INDEX	
1	015764558	$25,316.74	0.05	0.23	1.35	1.1	0.3	1.5	2.6	85.0%	1.34	1.1	0.3	1.5	2.5	85.0%	$0.00	$241.92	$0.04	$241.96	$241.96	-46.25%	-43.08%
2	015773677	$1,349.11	0.8	0.89	0.80	6.4	5.1	5.1	22.2	85.0%	0.79	6.3	5.1	5.0	21.3	85.0%	$0.00	$25.51	$0.00	$25.51	$267.47	50.23%	50.72%
3	001621010	$3,389.28	0.29	0.54	0.93	3.1	2.0	2.9	9.2	85.0%	0.92	3.0	2.0	2.8	8.8	85.0%	$0.00	$52.61	$0.00	$52.61	$320.08	37.12%	38.10%
4	015210941	$794.00	0.9	0.95	0.67	7.0	7.1	4.7	23.9	85.0%	0.66	6.9	7.1	4.6	23.0	85.0%	$0.00	$14.23	$0.02	$14.25	$334.33	60.42%	60.78%
5	015773663	$1,460.57	0.38	0.62	0.72	3.7	3.4	2.7	10.9	85.0%	0.71	3.6	3.4	2.6	10.4	85.0%	$0.00	$21.89	$0.00	$21.89	$356.22	56.68%	57.29%
6	015638562	$4,737.00	0.11	0.32	0.95	1.6	1.0	1.6	3.8	85.0%	0.94	1.6	1.0	1.5	3.7	85.0%	$0.00	$50.45	$0.00	$50.45	$406.67	34.16%	35.48%
7	009545657	$14.01	33.9	5.82	0.38	207.2	326.1	79.5	804.4	85.0%	0.38	207.1	326.1	79.4	770.4	85.0%	$0.00	$0.27	-$0.04	$0.23	$406.90	74.65%	74.66%
8	014787422	$1,815.37	0.23	0.48	0.73	2.6	2.4	1.9	6.9	85.0%	0.72	2.6	2.4	1.9	6.6	85.0%	$0.00	$23.31	-$0.01	$23.30	$430.20	55.61%	56.36%
9	014072627	$2,800.00	0.15	0.38	0.83	2.0	1.5	1.6	4.8	85.0%	0.82	2.0	1.5	1.6	4.6	85.0%	$0.00	$31.86	$0.00	$31.86	$462.06	47.87%	48.85%
10	014768971	$2,785.95	0.14	0.38	0.82	1.9	1.5	1.6	4.6	85.0%	0.81	1.9	1.5	1.5	4.4	85.0%	$0.00	$31.16	$0.00	$31.16	$493.22	48.20%	49.18%
11	014851472	$402.44	0.94	0.97	0.46	7.2	10.1	3.3	23.4	85.0%	0.46	7.2	10.1	3.3	22.4	85.0%	$0.00	$6.40	$0.00	$6.40	$499.62	71.48%	71.74%
12	015801324	$850.00	0.39	0.62	0.56	3.7	4.5	2.1	10.4	85.0%	0.55	3.7	4.5	2.0	10.0	85.0%	$0.00	$11.60	-$0.02	$11.58	$511.20	66.85%	67.32%
13	015773950	$3,747.50	0.08	0.29	0.88	1.4	1.0	1.3	3.0	85.0%	0.87	1.4	1.0	1.2	2.9	85.0%	$0.00	$34.67	$0.00	$34.67	$545.86	42.39%	43.58%
14	015367270	$3,022.15	0.1	0.32	0.83	1.6	1.2	1.3	3.5	85.0%	0.82	1.6	1.2	1.3	3.4	85.0%	$0.00	$29.73	$0.00	$29.73	$575.59	47.52%	48.57%
15	015759838	$335.32	0.89	0.95	0.39	7.0	10.8	2.7	21.9	85.0%	0.39	6.9	10.8	2.7	20.9	85.0%	$0.00	$5.04	$0.00	$5.05	$580.63	74.33%	74.56%
16	015770620	$2,202.51	0.13	0.36	0.75	1.9	1.6	1.4	4.2	85.0%	0.74	1.8	1.6	1.3	4.0	85.0%	$0.00	$22.88	$0.00	$22.87	$603.51	54.30%	55.18%
17	000577252	$103.01	2.69	1.64	0.26	18.0	33.9	4.7	62.2	85.0%	0.26	17.9	33.9	4.6	59.5	85.0%	$0.00	$1.64	$0.06	$1.70	$605.21	78.82%	78.91%
18	015695877	$1,628.69	0.17	0.41	0.68	2.2	2.1	1.5	5.1	85.0%	0.67	2.1	2.1	1.4	4.9	85.0%	$0.00	$17.97	-$0.01	$17.96	$623.17	59.64%	60.38%
19	014389450	$240.96	1.14	1.07	0.33	8.5	14.4	2.8	27.3	85.0%	0.33	8.4	14.4	2.8	26.1	85.0%	$0.00	$3.64	$0.00	$3.64	$626.80	76.48%	76.67%
20	015746258	$3,646.20	0.07	0.27	0.87	1.3	0.9	1.1	2.7	85.0%	0.86	1.3	0.9	1.1	2.6	85.0%	$0.00	$31.46	$0.01	$31.47	$658.27	43.66%	44.84%

Appendix B. VBA Code

```
Private Sub Savings_Click()

    'This part of the code is to clear the previous work
    Range("J10").Select
    Range(Selection, Selection.End(xlDown)).Select
    Range(Selection, Selection.End(xlDown)).Select
    Selection.ClearContents
    Range("Q10").Select
    Range(Selection, Selection.End(xlDown)).Select
    Range(Selection, Selection.End(xlDown)).Select
    Selection.ClearContents
    Range("X4").Select
    'The first part ends here

FinalRow = Cells(Rows.Count, 2).End(xlUp).Row

    For Column = 1 To 2 'Safety Factor Columns Before and After Lead Time Reduction
        Range("AG4") = Column

        For unit = 1 To FinalRow - 9 'The Number of Items
            Range("AG3") = unit
            SolverSolve UserFinish:=True
            If Column = 1 Then
                Range("J" & 9 + unit) = Range("AG1")
            End If
            If Column = 2 Then
                Range("Q" & 9 + unit) = Range("AG1")
            End If
        Next unit

    Next Column
End Sub
```

A SPREADSHEET MODEL THAT ESTIMATES THE IMPACT OF REDUCED DISTRIBUTION TIME ON INVENTORY INVESTMENT SAVINGS: WHAT IS A DAY TAKEN OUT OF THE PIPELINE WORTH IN INVENTORY?

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Vita

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14. ABSTRACT
　　In most of the literature dealing with inventory problems, either with a deterministic or probabilistic model, lead time is viewed as a prescribed constant or a stochastic variable, which therefore, is not subject to control. But, in many practical situations, lead time can be reduced by an extra crashing cost; in other words it is controllable.
　　This study proposes a repeatable spreadsheet optimization model that estimates the impact of reduced replenishment lead time on inventory investment savings at forward and strategic locations to motivate decision makers to support enterprise-wide distribution process improvement. The contribution of this study is that a means of automatically calculating the inventory control parameters such as safety stocks and reorder points, and estimated savings caused by lead time mean or variability reduction is provided to the user. So, a trade-off analysis can be done as to whether reducing lead time would override the lead time crashing cost.
　　First, the model finds the optimal safety factor of an item based on a fill rate goal using Excel Solver. Then, Excel's VBA automates the process of finding safety factors for other items before and after lead time reduction. Finally, the model is applied to three different supply support activities to show the superior features of the model that also allow the user to change and upgrade it for future research.

15. SUBJECT TERMS
　　Impact of lead time reduction; Safety Stock; Fill rate; Safety stock based on fill rate; lead time; Daily demand during lead time; Inventory cost; Carrying Cost; Backordering Cost; Spreadsheet modeling; Optimization model; VBA

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