Multi-Echelon Inventory Modeling and Supply Redesign

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Abstract

Many businesses struggle to optimize the flow of inventory and finished goods through existing plants and facilities. The integration of inventory costs, organizational processes, and changing business dynamics make it difficult to determine the optimal flow. This thesis examines the flow of raw materials and finished goods through the supply chain of a multi-national oilfield services company. We study a centralized inventory approach, assessed through heuristics, against the existing decentralized approach. Sensitivity analysis with regard to service level, and mode of transport strengthened the analysis. We show that demand aggregation and lead time are important factors in determining the upper echelon for a company’s internal distribution model. Potential safety stock reduction is 2%, which is mainly due to the improved coordination for materials flowing to the final echelon in the supply chain. However, pipeline inventory increases by 12% as a result of longer lead times.

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1.0 Introduction

This thesis examines the performance of multi-echelon inventory systems. The study reveals that demand aggregation and lead time are important factors in determining the upper echelon for a company’s internal distribution model. The sponsor company is an oilfield services company, but the results of the thesis are relevant for any firm that operates globally and has different points of consumption. The sponsor company has facilities, some built organically and others acquired during decades of operations, across the globe that either hold or consume parts. The best flow of materials through these locations is not clear because the sponsor company is in a period of strategic business adjustment. The company is evaluating its manufacturing footprint and logistic activities. The sponsor company seeks to understand if a consolidation of the logistics activities under the distribution organization would result in improved coordination and financial synergies. In order to determine if the current flow of materials is reasonable and cost effective, we analyzed a proposed alternative. Companies in a variety of industries can use the results of the thesis to reduce inventory holding costs and free working capital through reduction in inventory.

The oilfield services industry is a diverse industry marked by expansive product offerings (Clark, 2016). Oilfield service companies provide testing, analysis, maintenance, repair, and other services that enable drilling operations. According to the sponsoring oilfield service company’s annual report, these services require advanced technologies and quick turnaround times (Annual Report). This thesis project examines the supply chain of an international oil field services company. In particular, this oil field services company provides industry-leading technology to oil drillers across the globe (Annual Report). The oilfield services company professes a technology-driven value proposition and uses their manufacturing facilities as the entry point to their supply chain (Annual Report). Our thesis assesses this model in comparison to a proposed alternative. The alternative system centralizes the flow of goods throughout the company via three international distribution centers. In order to analyze the impact of each method, we examine both absolute and relative metrics. Inventory levels, to include safety, cycle, and pipeline stocks, reveal the quantity
differentials in inventory. Additionally, we explore inventory costs, to include holding and ordering costs. Inventory turns and the new unit inventory cost help provide more strategic insights.

1.1 Oilfield Services Business Model

The oilfield services industry is fundamentally an engineering based business (Annual Report). Firms develop intricate equipment capable of withstanding extreme pressure and temperature ranges (Annual Report). Managers at the company cited intermittent demand, nuanced assembly processes that vary by product, and disparate requirements inherent in extreme operational environments, as limiting factors for manufacturing automation. Yet, while technology and manufacturing are prerequisites for success in the industry, the ability to be present and prepared with minimal lead time across a global footprint is important (Annual Report). Managers at the company cite high stock-out costs as supporting the need for a responsive supply chain. Oilfield service companies have to be ready to perform testing, diagnostics, and other services in austere environments when the client needs the service (Clark, 2016). According to managers at the company, down-time on a rig can lead to millions in lost revenue for the oilfield service company’s clients.

Ultimately, most oilfield service companies do not sell technology or equipment to their clients (“OFS-Value-Creation-Report-Summary.pdf,” n.d.). They are paid to perform a service. Any part, even a lowly bolt, could impede an essential piece of equipment and lead to lost revenue (Doshi, Corrigan, John, Maxson, Shawn, & del Maestro, 2015). Supply chain managers have to intricately manage the need for high service levels, a long trail of stock keeping units (potentially in excess of 30,000), infrequent demand patterns, and the costs of holding inventory (“Beyond Cost Cutting,” 2015). Managers at the company state that SKU rationalization is difficult due to the nature of the oilfield services industry. The wellbore is an austere setting for equipment to function (Dahlberg, 1995). Each oil reservoir has distinctive features that have to be factored into the design of products. Company managers discuss these operational realities is the reason for the large number of SKUs that must be managed.
According to the company’s annual report, demand drivers for oilfield service firms include exploration and production (Annual Report). Yet, the ongoing weakness in crude oil prices has served as a headwind to the industry (“Oilfield Services Industry: Unlocking The Full Potential,” 2014). Oil prices began 2016 around $26 per barrel, reflecting the continuation of the downturn (“Spot Prices for Crude Oil and Petroleum Products,” 2017). Additionally, the oil rig count, sometimes viewed as a proxy for the health of the industry, declined 46% in 2016 compared to 2015 (“Quarterly Perspectives on Oilfield Services and Equipment,” 2015)(“International Rig Count | BakerHughes.com,” 2017). In conversations with company managers, the oilfield services company reports a strong interest in effective supply chain management to balance costs and service in the face of irregular demand. Supply chain management and inventory performance could be the keys to ongoing profitability.

1.2 Organizational Design

The company has several distinct business units. Note that the names of the business units have been changed to protect the anonymity of the sponsoring oilfield services company. An exploration business unit includes the technologies and services needed to discover and define hydrocarbon assets. A drilling business unit contains technologies and services needed to drill and position oil and gas wells. Engineering functions are folded into the business unit along with customer facing services. The production group business unit includes technologies and services needed to sustain oil and gas production for the lifetime of a well. Lastly, the flow equipment unit manufactures technologies to control pressure and flow for drilling rigs, as well as oil and gas wells. The company acknowledges revenue based on the placement of purchase orders and contracts. Service based revenue is recognized when the service is performed (Annual Report).

Manufacturing centers are included in some of these business units. Yet these manufacturing centers do not deliver directly to outside customers. Often, the equipment is not purchased by an outside customer but instead used by the oilfield services company to perform a contracted service. Throughout the thesis, manufacturing centers are identified as engineering and
manufacturing services (EMS). EMS locations could represent different business units for the parent organization, but have an equivalent material flow through the company. Distribution centers are abbreviated as DSC and serve Field locations worldwide. 3 DSC's exist globally for the company. Field locations reflect operating locations where the company conducts services for customers.

1.3 Current Supply Chain Design

The sponsor company currently has decentralized supply chain flow. Raw materials, components, and parts are sourced and procured by EMS. More than twenty EMS locations consolidate inventory. Inventory exists in two buckets: dependent and independent demand. Dependent demand refers to materials used in an assembly or manufacturing process at an EMS location. Independent demand reflects downstream demand from a field location or distribution center (DSC) that is filtered through EMS. Figure 1 depicts the flow for an independent demand part. More than one EMS location could stock the part just as more than one DSC could stock the part.

![Figure 1- Oilfield Services Company Material Flow Chart](image-url)
The majority of parts that flow to a distribution center and ultimately to a field location come from an EMS facility. Only a minority of inventory flow from a supplier directly to a distribution center. Some material does, however, flow directly from the EMS locations to field sites.

EMS locations attach a 31% percent markup to independent and dependent demand. In other words, if part X costs the company $100 from a supplier, EMS will charge the distribution center $131 for that item. The same is true for dependent demand. EMS will attach a 31% markup to the all the subcomponents that go into an assembled or manufactured item that will flow through the supply chain. The markup that is attached to material reflects the organizational costs that occur at that level. These organizational costs include the inventory holding costs, sourcing costs, engineering overhead, assembly, and supplier management. However, as these EMS centers are contained within business units, they can sometimes be profit centers. These manufacturing centers have a profit margin that reflects the value they create or a tax defined benefit. Consequently, the cost of holding inventory is higher at the distribution center and field sites. The cost is not higher due to inefficiency or other inherent costs. Rather, the cost of an item at the distribution centers is 31% greater than the cost of the item to EMS.

The cost structure of an item as it flows through the supply chain illustrates the company’s business rules. Distribution centers, which are considered cost centers, seek to minimize inventory carrying costs while maintaining service levels. However, the inventory cost of distribution centers is inflated because it contains a markup from EMS, even for independent demand items.

1.4 Current Demand Profile

The sponsor has several Enterprise Resource Planning and tracking systems used throughout the company to coordinate and track material flow and the demand. Aggregate demand data is presented at the monthly level because not all collection systems capture demand at a more granular level for processing and screening. Figure 2 demonstrates the volatility of demand at the regional level during 2016. Demand patterns show extreme volatility over the course of a year at the aggregate level. Volatility is a supply chain challenge for any company (Seitz & Yanosek, 2014).
The cost of a stock out event is extremely high and demand is highly variable. The rig count and the price of oil are drivers of this systematic uncertainty ("International Rig Count | BakerHughes.com," 2017).

![Material Flow Last 12 Months](image)

**Figure 2 - 12 Month Material Flow**

This volatility is observed at more granular level as well. Figure 3 demonstrates demand patterns at the part level. Figure 3 does not depict all SKUs carried by the company. It has been refined to track SKUs with demand in the past twelve months. Figure 3 depicts demand by part by arc. In other words, the Part X demanded by EMS A is viewed separately from Part X demanded by EMS B. 48% of parts demanded by EMS locations only were requested once during a twelve-month demand period. This pattern suggests highly sporadic demand. Only 5% of parts had EMS demand for greater than 9 months.
Field sites follow an even more dramatic demand profile than the EMS locations, as evidenced by Figure 4. Only 3% of parts by location have demand in more than nine months. Note that demand does equal consumption. Field locations may consume these parts every month even if they only demand replenishment once a year. The systems do not track consumption data. Rather, the systems track when field locations place an order to a distribution center or EMS location for part replenishment.
These demand patterns create serious challenges for inventory management. High stock out costs and substantial lead times support the need for safety stock to ensure service levels and revenue generation. Infrequent demand, long assembly processes, and forecasting challenges complicate inventory management. As a result, the sponsor company has to be careful to avoid inventory increases. Inventory increases, as discussed in Section 2.0 Literature Review, pose risks that can erode profitability.

### 1.5 Lead Time Characteristics

Lead time characteristics across the sponsor company vary significantly by region. Tax implications and other factors require the company to ship to certain countries from certain distribution centers. A key driver to long lead times across regions is the time spent clearing customs as the company frequently ships across international boundaries. Even air deliveries have lead times averaging 7 or more days. Table 1 demonstrates the longer than expected lead times even for air shipments.

**Table 1 - Distribution Centers to EMS Lead Time**

<table>
<thead>
<tr>
<th>DSC - EMS</th>
<th>Average of Total Lead Time (Dual Mode of Travel)</th>
<th>Average of Total Lead Time (Air Only)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Middle East to APAC</td>
<td>24</td>
<td>16</td>
</tr>
<tr>
<td>USA to LAM</td>
<td>11</td>
<td>7</td>
</tr>
<tr>
<td>USA to NAM</td>
<td>7</td>
<td>7</td>
</tr>
<tr>
<td>Europe to Europe</td>
<td>8</td>
<td>7</td>
</tr>
<tr>
<td>Europe to LAM</td>
<td>18</td>
<td>12</td>
</tr>
<tr>
<td><strong>Grand Total</strong></td>
<td><strong>13</strong></td>
<td><strong>10</strong></td>
</tr>
</tbody>
</table>

Table 2 reveals the long lead time to supply field sites. Oilfield service companies serve remote customers across the globe. Shipment to these locations is a long process, even when using air freight. Air freight can sometimes serve as a bridging function in a firm’s supply chain (Silver, Silver, Pyke, & Peterson, 1998a). Some companies can use air transport to reduce lead times to counterbalance a poor forecast. The average air lead time is 13 days or greater. Customs clearance remains a time consuming element of international shipping.
Table 2 - Distribution Centers to Field Sites Lead Time

<table>
<thead>
<tr>
<th></th>
<th>Average of Total Lead Time (Dual Mode of Travel)</th>
<th>Average of Total Lead Time (Air Only)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Middle East to Middle East</td>
<td>21</td>
<td>17</td>
</tr>
<tr>
<td>Middle East to RCA</td>
<td>49</td>
<td>40</td>
</tr>
<tr>
<td>USA to LAM</td>
<td>35</td>
<td>28</td>
</tr>
<tr>
<td>USA to NAM</td>
<td>13</td>
<td>13</td>
</tr>
<tr>
<td>Europe to EAF</td>
<td>33</td>
<td>29</td>
</tr>
<tr>
<td>Europe to LAM</td>
<td>31</td>
<td>26</td>
</tr>
<tr>
<td>Europe to RCA</td>
<td>18</td>
<td>17</td>
</tr>
<tr>
<td><strong>Grand Total</strong></td>
<td><strong>28</strong></td>
<td><strong>24</strong></td>
</tr>
</tbody>
</table>

1.6 Proposed Multi-Echelon Inventory Model

In light of the industry dynamics and organizational requirements, the sponsor company seeks to assess a centralized two-echelon inventory model. Our hypothesis is that a centralized inventory model can pool uncertainty and enable a reduction in inventory without impeding service levels. Figure 5, seen below, depicts the proposed supply chain.

![Proposed Multi-Echelon System](image)

*Figure 5 - Proposed Multi-Echelon System*

Inventory flows through a multi-echelon supply chain. The supplier ships the majority of items directly to three global distribution centers. Each of these distribution centers would then provide resupply to field and EMS locations worldwide. Parts that require inspection at an EMS location would be considered out of scope.
The centralized inventory management approach contrasts with the current system’s more decentralized organization. Currently, inventory enters the supply chain through more than eighteen EMS locations. Demand patterns at the various EMS centers do lead to some natural consolidation. In other words, certain parts tend to concentrate in certain facilities. However, the number of points to the supply chain lead to inventory being spread out over those locations. The future state, however, would concentrate inventory in three global distribution centers. In order to build a model and recommendation for the sponsor company, we turned to research to identify various methodologies and standards. The literature review enabled us to build a foundation which we could use to assess the future state model.

2.0. Literature Review

Cyclicality in demand and high service requirements create highly complex and dynamic supply chains in the oil & gas industry (Seitz & Yanosek, 2014) (Goni, Izquierdo, Wong, & Rodrigues de Almeida, 2014). Firms within the industry must balance fluctuating production volumes and the need to support growth as oil prices rise (Hamad Al Jedaie, 2014). An international oilfield services company seeks to better understand inventory management at manufacturing and field nodes to maximize company performance (“Cash in The Barrel: Working capital management in the oil and gas industry 2014,” 2014). We define performance as cost minimization constrained by required service levels. In order to understand the challenges and opportunities for the company, we reviewed similar industries and supply chain publications.

2.1 Inventory’s Importance To The Firm

Inventory represents a significant area of opportunity for companies within the oil & gas industry (Hamad Al Jedaie, 2014) (“Cash in The Barrel: Working capital management in the oil and gas industry 2014,” 2014). Sarkar and Sarkar discuss the importance of inventory in a discussion on the impact of working capital within oil & gas companies. Through an in depth analysis of financial figures of merit, Sarkar and Sarkar find that working capital strongly influences profitability index and return on equity (“Impact of Working Capital Management on Corporate
Performance: An Empirical...: BartonPlus,” n.d.). The method employed by Sarkar and Sarkar to evaluate working capital’s importance hinges on regression analysis of financial metrics. Ultimately, the authors find that reducing working capital and increasing liquidity has meaningful impact on overall financial performance (Mauergauz, 2016)(Sarkar, 2013). While Sarkar and Sarkar use metrics from many companies, a similar review could use historical data from the research company. Additionally, Sarkar and Sarkar’s rubric could quantify the financial ramifications of inventory strategy for the target research company.

2.2 Inventory Within The Oil & Gas Industry

The oilfield services industry, like the aerospace industry, requires a significant investment in inventory to maintain service levels (“Beyond Cost Cutting,” 2015) (Hamad Al Jedaie, 2014). Consumption for an oil & gas company occurs at more than one node within the supply chain. Additionally, multiple individuals could be managing inventory independently at different nodes. Mauro’s 2005 study of Honeywell Aerospace described two to three echelons between the company and the consumption point. Accordingly, multiple planning processes existed within the company (Mauro, 2008). Mauro uses an exponential curve to describe the relationship between service level and inventory. As the oilfield services company has high service level requirements, the curve highlights the strategic importance of inventory. The complexity of oilfield services and aerospace hints that the ability of an organization to adapt is essential. Chroust suggests as much in his book Systemic Flexibility and Business Agility.

2.3 Evaluating Inventory Design

Reductions in working capital, inventory units, and total cost can all be used to evaluate inventory performance (Mauergauz, 2016b). Additionally, a qualitative assessment of a policies impact on organizational attributes is also helpful. The policy’s ability to react to demand and meet demand are also important. Mauergauz (2016b) suggests evaluating the industry dynamics for this assessment. The study categorizes four quadrants of industries: mature, stable, new, and growing. The oil & gas industry shares characteristics of each of these categories.
2.4 Single Echelon Inventory

The single echelon inventory model is the building block for more advanced models and strategies for managing inventory levels. The single echelon inventory model seeks to answer two questions. These models say how much inventory firm should order and when they should order that inventory (Mauergauz, 2016a). Mauergauz (2016a) demonstrates how a firm should calculate $Q^*$, the optimal order quantity, and $s$, the reorder point. This $Q^*$ and $s$ system enables a firm to carry the cost minimizing amount of inventory. This study demonstrates the $Q$ and system in conjunction with a fixed review point.

Safety stock is used to accommodate fluctuations in demand over time. The amount of safety stock can be derived several ways. Safety stock can set to a given service level, fill rate, cost of stock out event, or cost per item short (Mauergauz, 2016a). Each firm must analyze what is the correct method and approach to establishing safety stock. In the chart above, safety stock is denoted by $Z_c$. The amount of stock at the end of a period is given as $Z_{min} = S - TD$. Meanwhile, the order quantity is given as $Q = S - Z_{min} = TD$. The reorder point $s$ is given as $S = Z_{min} + DL = S - D(T - L)$.

In these foundational equations, $T$ equals $Q^*$ divided by average demand. $D$ represents demand. This is a very common approach to defining inventory in a fixed reorder cycle model. The key decision points in this model concerns consumption and forecasts. Mauergauz finds that considerable adjustments in order quantity and mean stock value accompany small demand fluctuations." (Mauergauz, 2016a). Detailed understanding of demand and forecasts are needed to make an accurate inventory model.

2.5 Multi-echelon Supply Chain

Large companies often go hand-in-hand with expansive supply chains. Typically, multinational organizations operate supply chains with multiple stocking points and echelons. In a multi-echelon system, materials flow through each echelon in the network to reach a consumption point. For example, a multinational firm supplies finished goods from a factory to a regional
distribution center. The regional distribution center transports those goods to local warehouses. Lastly, local warehouses deliver to customers or retail stores. In practice, companies often own, or manage, multiple echelons in the supply chain.

Globalization has elevated interest in supply chain management (Silver et al., 1998a). Inventory optimization in a multi-echelon supply chain enables companies to enhance efficiency at the operational level (Silver, Silver, Pyke, & Peterson, 1998b). Strategically, inventory optimization helps companies improve financial metrics. Inventory reductions can drive improvements in a firm's return on assets, a critical indicator for investors (Higgins, 2012).

Information technology is an essential part of advanced supply chain management strategies (Ganesan, 2015) (Hamad Al Jedaie, 2014). Demand data and inventory levels at the part level can be tracked electronically. Individual echelons are connected via Electronic Data Interchange (EDI), Radio Frequency Identification (RFID), satellite communications, etc. These technologies have quickly scaled and evolved to improve inventory management. With information systems as a foundation, companies can collaborate across the world. Visibility of end-to-end materials flow and improved communication characterize the modern supply chain (Ganesan, 2015).

2.6 Echelon Inventory

Multi-echelon systems introduce the concept of echelon inventory. For instance, we can explore a three-stage multi-echelon system, where the echelons are named i, j, and k. Echelon inventory of echelon j includes inventory at echelon j and the inventory downstream. In this case, echelon inventory for echelon j would include inventory for echelon j and k. Echelon inventory includes units that are at or have passed through j, but have not been committed to outside customers. Echelon inventory enables the downstream inventory to be considered for the replenishment of j (Silver et al., 1998b).

However, echelon inventory also means the same part will appear in more than one echelon. In reaction to this, only the value-add at echelon j is considered for the valuation of the
inventory at \(j\). The inventory holding cost at echelon \(j\) thus only considers holding the incremental value of the inventory (Silver et al., 1998b).

### 2.7 Theoretical models

A. J. Clark and H. Scarf led early studies of multi-echelon inventory systems in 1960s. Since then, numerous models have been developed for multi-echelon inventory optimization. The following section focuses on models that are close approximations to the firm’s current and future supply networks (Axsäter, 2015).

#### 2.8.1 Clark-Scarf Model in a Distribution System

In 1960s, Clark and Scarf had developed the first echelon-inventory model for a multi-echelon system. The model and its extensions have been among the most popular models in practice. Clark-Scarf model works well under real and complex scenarios where demand is probabilistic. It therefore helps to determine the optimal safety stock at each echelon (Axsäter, 2015).

The Clark-Scarf model produces exact solutions for simple serial systems. When it comes to distribution systems, as is the case of the sponsor company, the solution is no longer exact. An approximation is drawn based on a so-called "balance" assumption. This assumption allows upstream echelons to make negative allocations to its immediate downstream neighbors. Thus, the total inventory among the downstream echelons can be optimally distributed (Axsäter, 2015).

![Figure 6 - 2-Stage Serial System (left) Vs. 2-Stage Distribution System (right)](image-url)
Eppen and Schrage extend the original model with identical retailers and central warehouse carrying zero inventory. Federgruen and Zipkin developed the model further to allow retailers with non-identical retailers and central warehouse carrying inventories by Federgruen and Zipkin.

2.8.2 Illustration of a 2-Stage Multi-Echelon System

Axssäter demonstrated a 2-stage Clark-Scarf model (Axssäter, 2015). Demand at the retailers is assumed to be independent and normally distributed. However, the sponsor company’s does not reflect a normal distribution for all parts. In Axssäter’s model, retailers replenish from warehouse, while the warehouse replenishes from outside supplier with infinite stock. All echelon points adopt periodic review and echelon stock order-up-to-S policy.

Notations are listed below. Installation 0 is the warehouse, and 1,2…N are the retailers.

\begin{align*}
L_0 & : \text{Lead time (integrals of periods) for replenishment at warehouse} \\
L_j & : \text{Lead time (integrals of periods) for replenishment at retailer } j \\
D_j(n) & : \text{Probabilistic demand at retailer } j \text{ over } n \text{ period} \\
\mu_j & : \text{mean demand per period at retailer } j \\
\sigma_j & : \text{standard deviation of demand per period at retailer } j \\
\mu_0 & : \text{mean demand over lead time to replenish warehouse} \\
\sigma_0 & : \text{standard deviation of demand over lead time to replenish warehouse} \\
\mu_j' & : \text{mean demand over lead time plus 1 period to replenish retailer } j \\
\sigma_j' & : \text{standard deviation of demand over lead time plus 1 period to replenish retailer } j \\
e_j & : \text{echelon holding cost per unit per period at installation } j \\
h_j & : \text{holding cost per unit per period at installation } j \text{ (} h_0 = e_0, \ h_j = e_0 + e_j \text{ for } j>0 \text{)} \\
b_j & : \text{shortage cost per unit per period at retailer } j \\
S_j^e & : \text{order-up-to echelon stock at installation } j \\
y_j & : \text{realized echelon inventory position at retailer } j \text{ in period } t+L_0 \text{ just before the period demand} \\
x^+ & : \text{max}(0,x) \text{ for any expression } x \\
x^- & : \text{min}(0,-x) \text{ for any expression } x
\end{align*}

Consider an arbitrary period \(t\), lead time \(L_0\). Echelon stock at the warehouse at \(t+L_0\) just before the period demand, is \(S_j^e - D_0(L_0)\) where \(D_0(L_0)\) is both demand at the warehouse and for the total system. The total relevant cost at retailer \(j\) after transformation:

\[
\tilde{C}_j(y_j) = e_jy_j - h_jy_j^+ + (h_j + b_j)E(y_j - D_j(L_j + 1))^-
\]
With the "balance" assumption, the optimal solution order-up-to level-\(S^e_j\) at retailer \(j\) is found from the following equation. Note that \(\mu_j\) is mean demand and \(\sigma_j\) is the standard deviation of demand.

\[
\phi\left(S^e_j - \mu_j^* / \sigma_j^*ight) = \frac{e_0 + b_j - \lambda}{h_j + b_j}
\]

The optimal order-up-to level-\(S^e_0\) at warehouse is found from the following equation.

\[
\hat{C}_0(S^e_0) = h_0(S^e_0 - \mu_0^*) + \hat{C}_r(S^e_j) + \int_{S^e_j}^{\infty} \left[\hat{C}_r(S^e_j - u) - \hat{C}_r(S^e_j)\right] \frac{1}{\sigma^*_0} \phi\left(\frac{u - \mu^*_0}{\sigma^*_0}\right) du.
\]

### 2.8.3 Illustration of a N-Stage Multi-Echelon System

Figure 7 demonstrates a general N-Stage distribution model (van der Heijden, Diks, & de Kok, 1997). The model considers an N-echelon system which allows inventory holding at any stock point. The system is divergent. The demand at the end echelons are independent and normally distributed. Each echelon replenishes from its immediate upstream echelon. The most upstream echelon replenishes from external supplier that have infinite inventory. All echelon points adopt periodic review and echelon stock order-up-to-S policy.

![Diagram of a 4-Stage Divergent System](image)

**Figure 7 - Example of a 4-Stage Divergent System (van der Heijden et al., 1997)**

In the four stage divergent system, the upstream echelon is considered first. Assume one replenishment occurs at time \(t\). If the echelon inventory at installation \(j\) exceeds the sum of order-
up-to-level in the immediate downstream echelon: $I^l_t = S_j$. If not, the immediate downstream echelons are only partially replenished: $I^l_t = S_j - p_j \left( D^l_{t-l_{tt}} - \Delta_l \right)^+$ for $j \in V_i$ where $\sum_{i \in V_i} p_j = 1$. Second, an arbitrary successor $i$ is considered. If the echelon inventory at installation $i$ exceed the sum of order-up-to-level in the immediate downstream echelon: $I_{t+l_j}^k = S_k$. If not, the immediate successors are only partially replenished: $I_{t+l_j}^k = S_k - p_k \left( D_{t+l_j}^j - \left( I^j_t - \sum_{k \in V_j} S_k \right) \right)^+$ for $k \in V_j$.

The service level constraint is applied with the following equation: $B_j = 1 - \frac{E \left[ (D_{l_j+R}^j - I^j_t) - (D_{l_j}^j - I^j_t) \right]^+}{R_{u_j}}$ for $j \in E$.

### 2.8.4 Normal and Poisson Distributions

Ramaekers and Janssens discuss the metrics for determining the appropriate distribution for demand patterns using the Poisson loss function table (Silver et al., 1998a) (Ramaekers & Janssens, 2008). The loss function gives the expected backorder quantity, which is the amount of demand that exceeds the average demand. The expected on hand quantity is given by the safety stock less the demand over lead time plus backorders. The expected on-order inventory is the demand over the lead time.

The Pearson chart is used to determine the appropriate distribution to represent demand. Shape characteristics of demand during lead time help characterize various distributions.

Ramaekers and Janssens assert a rule for evaluation distributions:

When the demand size is described by an arbitrary probability distribution $F$ and the demand occurrence process can be described as a Poisson process, the total demand can be described by a compound Poisson distribution (Ramaekers & Janssens, 2008) (“On the choice of a demand distribution for inventory management models (PDF Download Available),” 2008)

The two characteristics that are required for this analysis are asymmetry and kurtosis. They are measured by the $\beta_1$ and $\beta_2$ coefficients. Asymmetry refers to the skewness of a random variable.
about the mean of a probability distribution. A normal distribution has no skewness and is symmetric about the mean. For example, the left tail of a probability density function is longer or thicker than the right tail if a unimodal distribution has a negative skew. The opposite is true of a positive skew for a unimodal distribution. Kurtosis also describes the shape of a probability distribution. A distribution with low kurtosis has a sharp peak, signifying a more uniform demand. Conversely, a distribution with high kurtosis would have longer tails about the mean and a flatter peak. Figure 8 gives the equations for calculating the coefficients. Note that $\lambda$ equals the mean and variance.

\[
\beta_1 = \frac{1}{\lambda} \frac{\mu D,3}{\mu D,2^3}, \quad \beta_2 = 3 + \frac{1}{\lambda} \frac{\mu D,A}{\mu D,2^2}.
\]

*Figure 8 - Ramaekers & Janssens, 2008*

In this case, $\mu$ is the demand during lead time. When mean is high in comparison to demand variance, the value of $\beta_1$ is close to 0 and the value of $\beta_2$ is near 3 (Ramaekers & Janssens, 2008). If the mean demand declines in value, or the variance increases, the Normal distributions becomes a less accurate approximation. The F distribution looks for a $\beta_1$ value roughly between 3 and B and a $\beta_2$ value of 3.

The unit loss function table provides a probability that demand is less than or equal to safety stock. Once the safety stock service levels are set for various segments the service level gives the probability to be referenced in the unit loss function table. As a simplification, a normal distribution is offered as the ideal distribution when items have a mean lead-time demand greater than 10 units per year.

### 3.0 Methodology

In this section, we present the methodology to model the current and future states of an oilfield services company. The methodology enabled analysis of the sponsor company’s primary research topic.
3.1 Matching the Model to the Problem Statement

This section examines the business rules of the oilfield service company. These business rules are inputs for modeling company behavior. During the course of the research project, discussion helped highlight tacit business rules. Many of these rules change in the future state. This section addresses how these rules are derived during the modeling process. Additionally, the precise modeling process is discussed in detail. The model evaluates a proposed future state to directly address the research question. A systematic sensitivity analysis is then applied to the model. The sensitivity analysis addresses the robustness of the proposed future state.

3.1.1 Oilfield Services Operational Context

The sponsor company is a multinational oilfield services with several business units. Like many companies, the sponsor company’s supply chain evolved over time. Different business expansions, contractions, and mergers have led to an international supply chain. While the supply chain has met company requirements, managers at the company believe room for improvement exists. Namely, the sponsor company believes a redesigned flow of parts and products throughout existing facilities could reduce inventory costs.

As the thesis question concerns the impact of a future flow, the company is interested in identifying how business rules might change. In order to ascertain what policies would change, we first mapped the current process with key stakeholders within the company. The supply chain, logistics, manufacturing, accounting, and service implications for a given SKU were mapped and analyzed. Through phone calls and site visits, we were able to build a process map to highlight process steps and rules.

SKUs currently follow three paths through the sponsor company’s supply chain. All SKUs flow from a supplier to a manufacturing site. These manufacturing sites, located globally, act as the entry point into the company’s supply chain. A SKU could be consumed at the manufacturing site, transformed through manufacturing, or passed through. SKU’s that are passed through generally flow to a distribution center and then finally to a field site.
SKUs consumed at field sites are consumed by the oilfield services company as opposed a client company. The fundamental products of the sponsor company are services. These services are enabled by their technology and manufacturing capabilities. Even though SKUs consumed by the field are used internally, they enable the company to perform client services.

A given part changes in value based on its location in the company’s supply chain. While the true cost of the item remains unchanged, the value of the part changes. As a result, the company applies a markup to the part as it flows through the supply chain. The manufacturing sites apply a roughly 31% markup on the part value. This markup is applied to all items that are passed from the manufacturing sites to the distribution centers. The distribution center applies a markup as well. Consequently, when a part is purchased by a field site, the cost of the part to the field site includes the overhead costs of the manufacturing sites and distribution center.

These business rules, as evidenced by the role of markups, are essential in the modeling process. We captured these rules through discussions and analysis with the sponsor company. These assumptions help drive insights and frame the results from the model. For instance, item markups will change under the new system. Manufacturing sites will no longer pass through items with a markup. As a result, the markup on manufactured items may have to increase to reflect the overhead cost of manufacturing operations. Changes in business rules change the interpretation of the results and guide the sensitivity analysis.

3.1.2 General Approach

In order to understand the new business rules, we tracked the flow of different SKUs in the new process. By tracking the SKUs in the new process, we identify business rules that no longer applied. These changes were then tracked through the new system. We segmented the SKUs to enable modeling. We focus on the following characteristics:

1) Purchased parts (meaning parts that do not undergo the manufacturing process at the sponsor company)

2) Parts with a cumulative demand greater than zero for the past twelve months
3) Parts with a monthly demand that is nonnegative.

4) Parts consumed in both manufacturing sites and field sites

The model examines the inventory flow of an arbitrary part $x$, consumed at field locations or service centers. We assume that supplier inventory and service levels are out of scope. This assumption is important because supplier inventory and service levels would impact the lead time for the oilfield services company. Poor supplier service levels could increase the standard deviation of lead time and increase inventory levels for the oilfield services company. Suppliers are assumed to be able to meet all demand. Parts with no demand over the last year are inactive SKUs, and thus, they are not relevant to the calculation. Parts that are consumed in both manufacturing sites and field sites are the primary candidates for the new process flow. Parts that require inspection at the manufacturing site, or are only consumed at the manufacturing site, are out of scope. The operational complexity and/or cost that these parts bring make them poor candidates for the redesigned flow.

The proposed model is a two stage echelon model. Supply flows from the supplier to the distribution centers and then for final consumption at the field. Distribution centers serve field sites and manufacturing sites based on geographical proximity. Three total distribution centers service the entire network. Legal limitations do dictate that certain parts can only be serviced by certain distribution centers out of certain locations.

A one to one relationship between manufacturing sites and distribution centers characterizes the relationship within the model. Analysis of the sponsor company’s data reveals 95% of parts is supplied to a distribution center from one manufacturing site. Only 5% of parts are supplied to distribution centers from two or three manufacturing sites.

3.1.3 Modeling Performance with Heuristics

The future state’s centralized approach is represented by a heuristic method. The heuristic approach best aligns with the company’s business processes. The company currently uses periodic review method to approve and manage purchase requisitions. Thus, a periodic model represents the
current process the oilfield service company employs. While optimal solutions exist for multi-
echelon systems, they can be difficult to implement. Change management is key concern when it
comes to altering the flow through a supply chain. Heuristic methods are supported by literature
and use approximations to find solutions that are generally applicable(Silver et al., 1998b). The
thesis uses a heuristic method to enable the company to establish service levels based on their three
segments, as well as a review period that fits with their managerial processes and information
technology systems. Inventory levels are determined by the established service levels and review
period.

Fundamentally, the research question presented in Section 1.0 attempts to identify the best
flow of materials through existing facilities. The research question is not a pure optimization
problem. The model must be grounded in the business rules, capabilities, and structure of the firm.
A model that optimizes the future state without regard to organizational dynamics would likely not
be executable. The heuristic base stock model presented in Section 3.2.1 enables the model to
approximate the actual capabilities and likely processes of the company to understand the benefits
and drawbacks of the future state.

3.2 Data Modeling

The sponsor company provided historical data from across the organization. The data contained
SKU level information for demand, price, and location. The data was cleaned for the purposes of
clarification and modeling. The data was provided in excel format in multiple spreadsheets. Due to
the size of the data files, MySQL was used to organize and clean the data. Some data cleaning was
also conducted using Microsoft Excel.

3.2.1 Data Model

The proposed model uses a base stock policy with an order up-to model. Several metrics
are used to describe inventory levels in this model. The concept of inventory position refers to the
quantity of a given product that is on order in addition to the inventory level of that product. The
order up to level is the maximum amount of product the company wants to have in the pipeline.
The order up to level for a part is the demand during lead time and review time plus the product of the service level and standard deviation of demand during lead time and review time. The order amount for a given period is the difference between the maximum quantity and the inventory position.

The maximum quantity, discussed as the order up-to quantity, is defined by service level. Service level refers to the in-stock probability of a given item. If the target service level is 90%, that would indicate an out of stock probability of 10%. Due to the intermittent demand, a Poisson distribution is the best distribution to represent demand.

Regardless of the demand distribution, the key metric for establishing inventory levels in the model is the service level. In practice, the sponsor firm segments SKUs into three categories that carry a unique service level. Managing thousands of SKUs that each have a distinct service level would be impractical to implement using the firm's current structure and information technology systems. The three categories for service levels are high runners, runners, and strangers. High runners for EMS locations can be seen in Figure 9. High runner candidates comprise only five percent of the overall quantity of parts demanded. Runner candidates consist of nineteen percent of part demand at EMS locations.

![EMS Demand Frequency](image)

**Figure 9 - EMS Demand Frequency**

At the field level, high runner candidates comprise only three percent of overall part...
demand. Runners comprise only fifteen percent of demand. Both the field and EMS echelons reveal the long tail of demand. The vast majority of parts, in terms of quantity, are only requested three times a year. The nature of the oilfield service business implies that a stock out of a slow moving part could lead to a job being missed. Algorithmically, a high stock out cost implies a high service level. In other words, a larger stock out cost justifies a larger inventory carrying cost to avoid the stock out cost. The firm has decided, due to the extreme long tail of demand, to segment SKUs to minimize the inventory carrying cost. These managerial decisions make the heuristic method a good approximation for how the company would manage inventory in the new system.

![Field Demand Frequency](image)

*Figure 10 - Field Demand Frequency*

The key decision criteria for the model are the established service levels and the lead time. The model uses the safety stock levels to determine the cost of inventory under the new system. As service levels are set by company managers, the true benefits of the new system will be seen in inventory reduction. A reduction in inventory value will enable a reduced inventory carrying cost. The inventory costs will enable us to assess the current model and the proposed centralized model.

The base stock policy establishes an order-up-to level which is the inverse of the Poisson distribution for the appropriate service level, with regard to mean demand over the lead time and review period. Safety stock is given as the order up to level minus mean demand over lead time and review period. The average inventory level is thus the safety stock plus the average backorder. The average backorder is the cumulative Poisson distribution for demand above safety stock with
regard to average demand over lead time and review.

3.2.2 Assumptions

Key assumptions in the model include the order and reviewing costs. Additionally, lead time is an essential assumption that drives pipeline inventory cost. Holding costs are estimated at 16% for distribution centers and EMS facilities and 25% for field locations. Order costs are estimated to be an average of $173 per purchase order line for EMS locations. Ordering costs at distribution centers are estimated at $20 per purchase order line. Ordering costs at field locations are estimated to be $4 per purchase order line.

Ordering costs reflect the costs for the purchasing and reviewing activities at a given level in the firm. For EMS locations, these supplier costs include procurement activities and supplier management. The distribution centers and field locations do not have to perform these activities so the cost of the ordering activity is reduced. These cost estimations will provide the managerial costs of executing the future state in the model. It reasonable to assume that costs could increase at the distribution center as they increase their volume and responsibility. Likewise, it is also reasonable that costs could decline at EMS locations as the scale of activities decreases. Sensitivity analysis with these assumptions can help quantify a range of outcomes.

Lead time is essential for calculating pipeline inventory. A reduction in lead time directly reduces pipeline inventory values. Table 3 reveals the lead time estimations for different levels of the supply chain. The process time at distribution centers refers to the time to handle inventory at the facility. All distribution center activities to include receiving, storing, handling, and shipping are included. This figure comes directly from the sponsor company.

Table 3 - Lead Time Estimations

<table>
<thead>
<tr>
<th>Future State</th>
<th>Average Lead Time (days)</th>
<th>Current State</th>
<th>Average Lead Time (days)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upstream Leg - All Materials DSC Process Time</td>
<td>15</td>
<td>Upstream Leg - All Materials EMS Process Time</td>
<td>7</td>
</tr>
<tr>
<td>Downstream Leg - Field Demand DSC to field transit</td>
<td>18</td>
<td>Downstream Leg - Field Demand EMS to field transit</td>
<td>10 (EMS to DSC)</td>
</tr>
<tr>
<td>Downstream Leg - EMS Demand DSC to EMS transit</td>
<td>7</td>
<td>Downstream Leg - EMS Demand no transit</td>
<td>0</td>
</tr>
</tbody>
</table>
Lead time drives the pipeline inventory quantities and costs. The current state has very efficient lead time at the first echelon because the first echelon is a consumption point. Parts and components are consumed at EMS locations. However, in the future state, DSC must ship these products to EMS facilities. An important estimation for average lead time is the required process time at the DSC level. We assume that the processing time will increase from 7 days at EMS locations to 14 days under the new system at DSC locations. The processing times and lead times are included in the sensitivity analysis to strengthen the analysis.

3.4 Evaluation Criteria

Evaluation criteria for the future state system includes absolute and relative metrics. Absolute metrics include the calculated quantity of inventory in the system, to include pipeline inventory and safety stock. Other absolute metrics include the calculated working capital requirement of the new system as given by the total inventory value in the system. Relative metrics include the days of inventory outstanding and the number of inventory turns. The order and reviewing costs are calculated absolute metrics.

3.5 Sensitivity Analysis

Sensitivity analysis helps provide a range of results for the future state. Sensitivity analysis is fundamental for providing a more robust solution set to a model. A range of likely outcomes can be incorporated into the model. Different lead times, demand profiles, service levels, and ordering costs can help highlight dynamics of the model. The use of these different scenarios help highlight corner cases. In other words, outcomes that could be likely but are not represented well by the average numbers that populate the primary outcome of the model.

As a result, sensitivity analysis helps clarify the model and makes the model more representative.

In order to assess the impact of supplier lead time, we analyze reduce lead times. Using incremental reductions in lead time, we can observe the impact on EMS safety stock in both the current and proposed models. Table 4 demonstrates the impact of reduced lead times in the current mode and proposed mode. Note that the reductions in Table 4 are in units of safety stock, not
dollars. The results demonstrate that lead time reductions have greater impact on the current mode than the proposed mode. One reason for this could be the increased aggregation of the current mode which Section 5.0 discusses in greater detail.

Table 4 - Reduced Supplier Lead Time Impact

<table>
<thead>
<tr>
<th>Lead Time Reduction</th>
<th>Current Mode</th>
<th>Proposed Mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>EMS Safety Stock</td>
<td>Lead Reduction</td>
<td>DSC 1</td>
</tr>
<tr>
<td>0%</td>
<td>11,077</td>
<td>4,087</td>
</tr>
<tr>
<td>3%</td>
<td>10,810</td>
<td>4,009</td>
</tr>
<tr>
<td>5%</td>
<td>10,567</td>
<td>4,016</td>
</tr>
<tr>
<td>10%</td>
<td>10,388</td>
<td>3,905</td>
</tr>
<tr>
<td>15%</td>
<td>10,188</td>
<td>3,821</td>
</tr>
<tr>
<td>20%</td>
<td>9,938</td>
<td>3,608</td>
</tr>
<tr>
<td>30%</td>
<td>9,218</td>
<td>3,529</td>
</tr>
<tr>
<td>40%</td>
<td>8,691</td>
<td>3,251</td>
</tr>
<tr>
<td>50%</td>
<td>8,004</td>
<td>2,951</td>
</tr>
</tbody>
</table>

Additionally, we conduct a second sensitivity analysis to observe the impact of part stratification. We analyze the level of safety stock variation at the DSC level if part stratification changes from three segments to two segments. Table 5 depicts the adjustment to segments to analyze segment impact.
We change DSC part stratification in the proposed state. In the proposed state DSCs service both EMS and fields. The impact to DSC safety stock depends on the service level defined for runners. The analysis demonstrates a very small increase to safety stock (0.25%) if the service level for high runners (85%) remains the service level for the more frequently demanded runner segment. Table 6 demonstrates impact of segment reduction in the proposed state at DSCs. Note that DSC figures are in units, not dollars.

**Table 6 - Proposed State DSC Stratification Scenarios**

<table>
<thead>
<tr>
<th>Proposed State DSC Stratification Scenarios</th>
<th>DSC 1</th>
<th>DSC 2</th>
<th>DSC 3</th>
<th>Total DSC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Three Segments Stratification</td>
<td>4,085</td>
<td>4,124</td>
<td>2,772</td>
<td>10,981</td>
</tr>
<tr>
<td>HR, Runner and Stranger</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Two Segments Stratification</td>
<td>4,523</td>
<td>4,235</td>
<td>2,250</td>
<td>11,009</td>
</tr>
<tr>
<td>Runner (Service Level 85%) and Stranger</td>
<td>2,198</td>
<td>2,120</td>
<td>1,123</td>
<td>5,441</td>
</tr>
<tr>
<td>Two Segments Stratification</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

We analyze the level of safety stock variation at the DSC level in the current state under a two segment model. In the current state, DSC’s only service field locations. Like the proposed state, the impact to DSC safety stock relies on the service level defined for runners. A nearly equivalent level of safety stock between three segments and two segments can be achieved if the service level for runners is defined at 82.5% in the two segment model. This assumes the three segment model maintains a runner service level of 85%. Table 7 demonstrates impact of segment reduction in the current state. Note that DSC figures are in units, not dollars.
**Table 7 - Current State DSC Stratification Scenarios**

<table>
<thead>
<tr>
<th>Current State DSC Stratification Scenarios</th>
<th>DSC 1</th>
<th>DSC 2</th>
<th>DSC 3</th>
<th>Total DSC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Three Segments Stratification</td>
<td>334</td>
<td>641</td>
<td>395</td>
<td>1,369</td>
</tr>
<tr>
<td>Runner and Stranger</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Two Segments Stratification</td>
<td>374</td>
<td>759</td>
<td>423</td>
<td>1,556</td>
</tr>
<tr>
<td>Runner (Service Level 85%) and Stranger</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Two Segments Stratification</td>
<td>178</td>
<td>348</td>
<td>210</td>
<td>736</td>
</tr>
<tr>
<td>Runner (Service Level 70%) and Stranger</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Two Segments Stratification</td>
<td>335</td>
<td>654</td>
<td>374</td>
<td>1,363</td>
</tr>
<tr>
<td>Runner (Service Level 82.5%) and Stranger</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**4.0 Results**

The analysis does not reveal a significant reduction in inventory or inventory holding costs when the proposed model is compared to the current model. The model examines the drilling segment as well as the testing and wirelines segment. The analysis considers only purchase and non-inspection parts. However, when the actual current state data is contrasted with the proposed model, there does appear to be a reduction in inventory. This distinction will be discussed in greater detail in Section 5.0. The proposed model reduces safety stock nearly 67%. Pipeline inventory increases 60% in the future model. Total system inventory declines 59% in the proposed model. We define total system inventory as safety stock plus pipeline inventory. Days of inventory on hand (DIO) is calculated as 47 days. Inventory turnover in the proposed model is 8 inventory turns per year. Inventory turnover is calculated as \[ \frac{360}{\text{DIO}} = 8 \]. Figure 11 depicts the respective inventory levels for the current and proposed model.
The proposed model improves the inventory levels at EMS facilities and distribution center locations when compared to the actual current state data. Field sites are unaffected in terms of safety stock required. Figure 12 demonstrates the reduced safety stock levels across different echelons. The proposed model not only reduces inventory at EMS locations, but also reduces the required safety stock at DSC locations. In Figure 12, the current state uses company provided safety stock data. The proposed state results come from the data model. Higher runners use an 85% service level, runners use a 70% service level, and strangers do not hold safety stock. Poisson distribution applies for parts with a demand frequency of less than 10 months per year.

The proposed model increases the pipeline inventory within the supply chain when
compared to the actual current state data. Under the current model, there is zero lead time (excluding transit time for supplier which remains unchanged between models) for consumption at EMS locations as it is the first echelon. However, in the proposed model, there is lead time between the DSCs and EMS facilities. As a result, the pipeline inventory increases, as demonstrated in Figure 13. In Figure 13, the current state includes EMS processing time for all demand of 7 days which was provided by company managers. The future state includes DSC processing time for all demand of 15 days.

![Pipeline Inventory Comparison](image)

*Figure 13 - Pipeline Inventory Comparison*

Inventory holding costs decline in the proposed model in comparison to the actual current data. We define inventory management costs as holding costs plus the order and review costs. The current state and proposed model have equivalent manpower costs. The field weekly review cost is $50 per field location per week assuming eight to nine full time employees. The EMS weekly review costs is $500 USD per center per week assuming one full time employee per center. The DSC annual cost is $480 thousand assuming three full time employees. The total material flow is $146 million per year at a total cost of $8.4 million per year including holding costs and manpower costs. The inventory cost represents 6% of annual demand. In other words, the cost of managing inventory per $1 purchase cost of inventory is 6%. Figure 14 shows the improvement in inventory holding cost for the proposed model against the current actual data.
5.0 Discussion

The proposed model shows that the average safety stock can decrease by $13.1$ million. The difference could be due to the change in the system between the proposed model and the current system. On the other hand, the difference could be due to inefficiencies in the current system that were changed in the proposed model. In particular, the use of the Poisson distribution accounted for some of the difference. Additionally, the difference can also be attributed to the difference between modeling and actual data. We validated these findings through a sensitivity analysis.

Figure 15 demonstrates a key reason why the proposed model may not actually lead to an inventory reduction. The chart depicts the level of aggregation at the first echelon (upper echelon). The chart shows the number of locations an item is stocked at the upper echelon. The current state actually has a greater level of aggregation than does the proposed model. These results suggest that there is no additional risk pooling effect in the proposed model. These findings contradict the inventory savings and reductions the model produced.
Figure 15 - Upper Echelon Inventory Concentration

Figure 16 provides a direct comparison between the proposed model and a model of the current state. This analysis helps highlight the potential error introduced in the modeling process. The inventory reductions discussed in the Results Section are in relation to the actual data, not a model of the actual data. The model of the current system assumes that all materials are supplied through EMS facilities. The model assumes that only materials demanded by field locations will go through DSC locations. This analysis, seen in Figure 16, shows an inventory reduction of only 2%.

Figure 16 - Safety Stock Comparison Model to Model

Figure 17 provides a direct comparison between the proposed model and a model of the current state with regard to pipeline inventory. This sensitivity analysis shows that the proposed model increase pipeline inventory by $4 million. The increase in pipeline inventory is due to the material processing time at the upper echelon. Table 8 shows a comparison of the lead times used in the
analysis. In the current mode, 7 days of processing time take place at the upper stream echelon (EMS). In the proposed model, 15 days of processing time take place at the upper stream echelon (DSC). However, even if the DSC maintains the 7-day processing time of the current state, the pipeline inventory still increases. In this case, the current model has pipeline inventory of $6.5 million and the proposed model has pipeline inventory of $7.3 million. The increase is due to the fact that the majority of demand by value belongs to EMS locations. 63% of demand by value belongs to EMS locations. The proposed mode increases the transit time to satisfy demanded value when EMS facilities are no longer the upper echelon.

![Image 17 - Pipeline Inventory Comparison Model to Model](image)

Figure 17 - Pipeline Inventory Comparison Model to Model

Table 8 - Lead Time Comparison

<table>
<thead>
<tr>
<th>Future State</th>
<th>Average Lead Time (days)</th>
<th>Current State</th>
<th>Average Lead Time (days)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upstream Leg - All Materials</td>
<td>15</td>
<td>Upstream Leg - All Materials</td>
<td>7</td>
</tr>
<tr>
<td>DSC Process Time</td>
<td></td>
<td>EMS Process Time</td>
<td></td>
</tr>
<tr>
<td>Downstream Leg - Field Demand</td>
<td>18</td>
<td>Downstream Leg - Field Demand</td>
<td>10 (EMS to DSC)</td>
</tr>
<tr>
<td>DSC to field transit</td>
<td></td>
<td>EMS to field transit</td>
<td>18 (DSC to field)</td>
</tr>
<tr>
<td>Downstream Leg - EMS Demand</td>
<td>7</td>
<td>Downstream Leg - EMS Demand</td>
<td>0</td>
</tr>
<tr>
<td>DSC to EMS transit</td>
<td></td>
<td>no transit</td>
<td></td>
</tr>
</tbody>
</table>

In order to demonstrate the impact of the Poisson distribution in the proposed model, we conduct a second scenario analysis using normal distribution. This sensitivity analysis uses normal distribution for all types of demand, regardless of frequency. In the proposed model, Poisson distribution was used when the average demand over lead time was less than 10. Figure 18 shows the difference in total inventory. Safety stock increases from $8.7 million to $11.7 million in the proposed model with a normal distribution. These findings reveal that the use of a Poisson distribution provides a better fit for the demand pattern and reduces inventory. The company current
does not use a Poisson distribution, so the use of the Poisson distribution skews the analysis. On the other hand, these findings reveal that a Poisson distribution can improve the current system.

![TOTAL INVENTORY (MILLION USD)](image)

<table>
<thead>
<tr>
<th>TOTAL INVENTORY (MILLION USD)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Safety Stock</strong></td>
</tr>
<tr>
<td><strong>CURRENT STATE</strong></td>
</tr>
<tr>
<td>6.5</td>
</tr>
<tr>
<td>26.0</td>
</tr>
</tbody>
</table>

*Figure 18 - Normal Distribution Comparison*

6.0 Conclusion

This thesis examines the cost impact of material flow through a multi-echelon supply chain. The results of the thesis apply to companies that seek to evaluate centralization of material flow through distribution centers. The thesis uses an order-up-to base stock model to evaluate the proposed centralized multi-echelon system. Historic demand and lead time data populate the model to demonstrate impact of the proposed alternative material flow. Sensitivity analysis for service level and probability distribution explain differences between the proposed alternative and the current state. Potential safety stock reduction is 2%, which is mainly due to the improved coordination for materials flowing to the final echelon in the supply chain. However, pipeline inventory increases by 12% as a result of longer lead times.

The findings do not support a change to the proposed model because the proposed model does not aggregate demand enough to offset increases in pipeline inventory. The models suggest reductions in inventory levels and cost are due to the use of a model against actual data and the use of a Poisson distribution instead in exclusive use of a normal distribution. The thesis reveals that lead time reduction is critical. Pipeline inventory can be larger than safety stock. A reduction in
safety stock with an increase in pipeline inventory can lead to a more inefficient supply chain. A company can determine if this is the case by examining where the majority of value is consumed. For the oilfield services company, the EMS facilities consume the majority of value even though those parts are slow moving. As a result, the EMS facilities are strong candidate as the upper echelon in the company’s supply chain. We recommend the company use a Poisson distribution to more accurately match demand patterns. The Poisson distribution would enable a better inventory policy for slow and infrequent demand.

The thesis demonstrates importance of aggregation in order to support reductions in inventory across a supply chain. However, reductions in lead-time could also serve to reduce pipeline inventory. The cost impact of using increased airfreight could serve as a next step in the analysis for the oilfield services company. Additionally, increased forecast accuracy could also enable inventory reductions. If the oilfield services company were to improve forecast accuracy, they could dynamically adjust service levels by part as opposed to segment. This could enable a more robust inventory management plan. However, this approach could increase management and information technology costs. Further analysis could help the oilfield services company assess the inventory impact of these approaches.

The thesis examines primarily quantitative data to assess the current state and proposed network flow. However, there are other elements of consideration that warrant analysis. Currently, EMS locations add a markup, often tax defined, to all purchase parts that flow to DSC and Field locations. Absent an activity based cost analysis, the transfer prices make it difficult to assess the efficiency of personnel and systems with regard to material handling at an EMS facility versus a DSC. This treatment could obscure true inventory holding costs at different locations in the supply chain. It could be beneficial to do an activity based costing analysis to determine accurate holding cost factors at EMS, DSC, and Field locations.

Merger and acquisition activity presents interesting opportunities for the oilfield services supply chain. Manufacturing activity could increase as a result of merger and acquisition activity.
Integration of different supply chains may support the proposed model. If M&A partners share parts in the future, coordination at regional DSC could enable reductions in safety stock not previously accounted for. Centralized planning and materials management at DSC could make change management during integration more effective. Joint DSCs could make the identification and execution of cost synergies more attainable. More research would be required to assess the impact of M&A activity on the supply chain.
References:


