

Rapid Deployment of Oil-Drilling Tools Utilizing Distribution Network and Inventory Strategies

by

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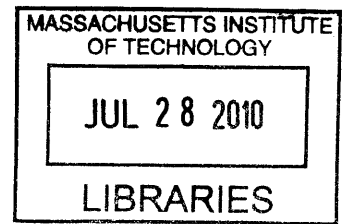
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ABSTRACT

DTS is an oil and gas services company that delivers drilling tools to six major customer districts in the continental U.S. After the tools are used at a rig, they are transported to the closest repair and maintenance (MTC) facility in either Colorado (CO) or Oklahoma (OK) where they are disassembled and reconditioned for use on a future job. The tools are modular and require custom assembly and programming, depending on the requirements of the well. On occasion, DTS receives urgent orders for drilling tools to replace failed tools or to cater to unexpected demand. These urgent orders are expected to be delivered to customer sites in less than 24 hours from when an order is received.

DTS wants to analyze the supply chain impact of consolidating MTC activities to a single facility for operational efficiencies. The rationalization of MTC activities to the CO facility affects DTS's ability to deliver tools within 24 hours due to the longer transportation times to customer districts. How can this longer transportation time be mitigated? Our research shows that using the OK facility as a postponement and distribution hub allows DTS to continue servicing expedited orders within 24 hours and results in a 28% logistics cost savings over a direct shipment method. The postponement strategy entails staging reconditioned inventory at both the OK and CO facility where they can be configured for use within 4 hours of receiving an order. By simulating the movement of inventory around the closed inventory loop, we determined that the total number of tools in the network and the MTC capacity are two important levers of control that affect the availability of reconditioned inventory to service demand. We found that we were able to fulfill a target item fill rate by calculating capital inventory required using an "order up to" inventory policy and setting facility capacity at one standard deviation above average demand.

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MISSION:

To bring stability to the VarioRam value stream, by optimizing logistics and inventories, enabling DTS to deliver configured tools within 24 hours while attaining revenue growth by maximizing available Tools-Per-Job

INTRODUCTION

DTS¹, a leading provider of drilling and exploration services to the oil and gas industry, dispatches equipment and crew to drilling sites around the continental U.S. DTS is a customer-focused company with an organizational structure built to support multiple families of tools that are designed for a specialized drilling or survey method. One of DTS's core product families is the VarioRam (VR) tools. DTS competes on service and availability of these technologically advanced tools. VR tools are demonstrably superior at drilling oil and gas wells than competitor products and are rapidly becoming the preferred tool for its application. As a result, the organization has experienced significant growth in demand for these tools over the last two years. This demand is forecast to increase further and follow industry exploration trends that lag the cycle of crude and natural gas commodity prices.

When an urgent order (call out) is received from the field, DTS is expected to deliver a VR tool in less than 24 hours to the customer site. Each tool has to be custom configured, assembled, and electronically programmed for the drilling requirements of each well before it can be delivered to the site. DTS delivers tools from its repair and maintenance hubs in Oklahoma (OK) and Colorado (CO) to 6 customer districts spread around the continental U.S. Used tools are shipped back to either facility where they are mechanically inspected, cleaned, and reconditioned before they are used for the next job.

In 2008, DTS initiated consolidation of the repair and maintenance of tools to a newly constructed facility in Colorado in order to provide economies of scale, cost efficiencies, and enhanced control over quality. By consolidating reconditioning to a

¹ Certain information related to the company has been disguised

single facility, tools need to travel longer distances to and from the customer sites. In order for the transition to be successful, DTS has to first determine what changes need to be made to their overall logistics and distribution network in order to ensure that call out jobs can still be fulfilled within a 24 hour window. Delivery delays result in significant cost overruns for the operating companies while the rig and its workers are idle and result in a loss of reputation for DTS.

The second consideration is cost and capital efficiency. Inventory has to be carefully managed as a fully assembled VR tool can cost upward of \$50K. The increased transportation lead time from CO to customer districts traditionally served by OK places a strain on the reconditioning facility to process and configure tools with a shorter turnaround time (presently about 11 hours). Moreover, the tools have to be transported using an expedited method that is 25% more costly than conventional transportation. If a mechanical spare part or VR capital equipment is not available, the job cannot be fulfilled until the required capital equipment is returned from the customer site, or replacement parts are ordered from the company's internal suppliers. As a result, DTS has to determine the *right* amount of capital inventory to support both the demand levels from customer sites and variable lead time replenishment at its facilities or face stock outs and resultant delays.

These are the three strategic imperatives we are faced with answering:

- 1) What should DTS distribution network look like in order to be capable of delivering tools to the 6 customer districts within 24 hours?
- 2) What will the impact on transportation cost, item fill rate and delivery lead times be?
- 3) What level of capital inventory is required to support the closed-loop inventory replenishment system for VR tools?

1.1 Oil and Gas Drilling Background

Baker (2001) provides a primer on the equipment, crew, and methods used to extract oil and gas from a well. Rigs have large pieces of equipment that serve one purpose: the drilling of a hole in the ground. Although the rig is large, the hole it drills is usually less than a foot in diameter at its final depth. The hole drilled needs to be deep enough to tap into oil and gas reservoirs that lie far beneath the surface, often thousands of feet below.

(Figure 1)

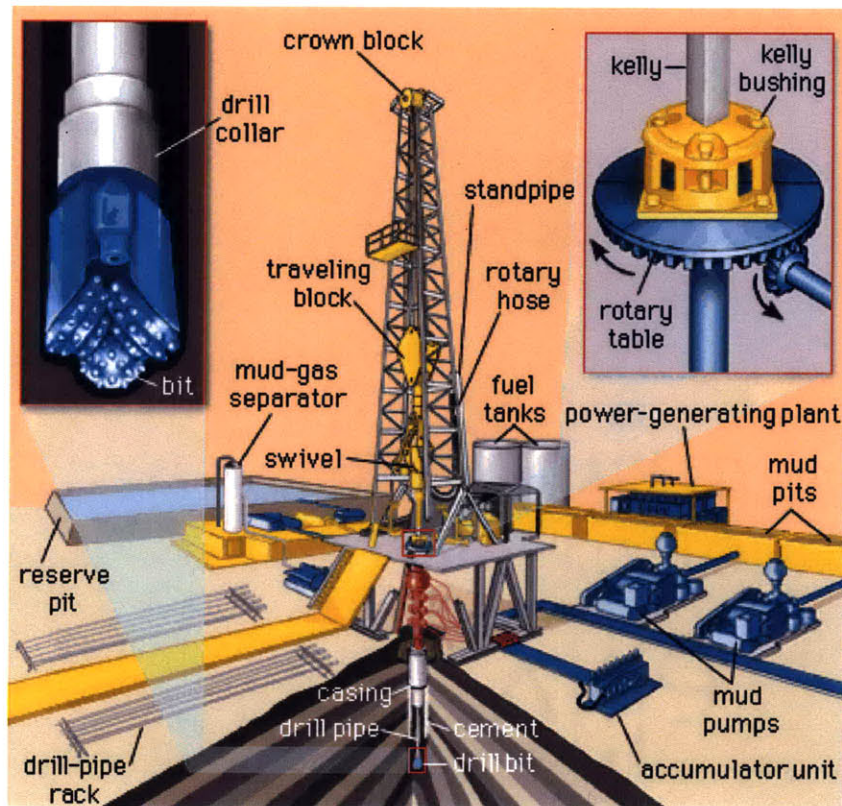


Figure 1. Oilwell drilling rig and equipment. <http://media-2.web.britannica.com/eb-media/10/27010-004-70A4ACFC.gif>

Masts and derricks can be as tall as a 16-story building (200 feet) and need to be strong in order to support the massive weight of the drilling tools, located on a drill-string, which can weigh many tons. Rig masts also have to accommodate long lengths of pipe the rig crew raises during the drilling process. The rig manager is in charge of the site and coordinates the activities of various resource and supplier companies.

1.11 Rotary Drilling

A rotary rig uses a bit that has rows of teeth or other types of cutting devices that penetrate the formation and then extract pieces as the rig system rotates the bit in the hole. Crew members attach the bit to the end of a long string of hollow pipe. By screwing together many pieces of pipe, they put the bit at the bottom of the hole, and add joints of pipe as the hole deepens (Fig. 1). The rig can rotate in one of three ways, using a rotary table; a top driver, which uses a powerful electric motor to turn the bit; or in special cases a slim downhole motor. The rotary table method is the most common, since they have been used for many years, are simple, rugged and easy to maintain. Downhole motors are used when the bits are rotated without rotating the entire string of pipe. This method is used when the rig is drilling a slant, or diverted vertically in order to better exploit a reservoir. DTS's VarioRam (VR) family of rotary drilling tools is technologically sophisticated and utilizes the downhole motor method in order to optimize the drilling capability of the rig.

1.12 Fluid Circulation – Drilling Mud

As the bit is rotated in the hole, the cuttings that the bit makes must be removed otherwise they would collect in the bit's teeth and impede drilling. The method to do this is to circulate fluid while drilling. The cuttings are carried up to the surface with the fluid through the lengths of hollow pipe that is attached to the drill bit. Powerful pumps at the surface circulate the drilling fluid (or drilling mud) where they are filtered at the surface and then pumped back down the hole. Drilling mud is usually a mixture of water, clay, weighting materials and a few chemicals, which re-circulates in steel tanks. The mud also serves the purpose to lubricate, cool and preserve the life of the drill bit and to prevent the drill hole from caving in on itself, which could result in the tool being lost in the hole.

1.13 Downhole Motor Drilling

Drilling mud powers downhole motor drilling. One major advantage of using the downhole drilling method to drill horizontally is that a horizontal well-bore drilled through a formation can allow the operating company to produce the formation better than with a vertical hole.

1.14 Drill Strings

Drill strings consist of a drill pipe and heavy-walled pipe called “drill collars.” (Fig. 1)

Drill collars are metal tubes through which the driller pumps drilling fluid. Each drill collar can weigh about 3000 lbs. Drill collars are heavy because they are used in the bottom part of the string to put weight on the bit, which pressed down on the bit so the cutters can bite into the formation. If the ten joints of a particular drill collar are used, the drill assembly would weigh about 30,000 pounds. Drill collars for VarioRam tools range in diameters from 4 in to 9 in and can be 30 to 31 feet long, requiring gooseneck trailers or semi trucks for transportation.

1.2 Oil and Gas Industry – Major Players

The oil and gas industry operates 24 hours a day, 7 days a week in all types of weather. As a result, DTS's drilling and maintenance facility operations (CO & OK) also run on a 24/7 cycle, delivering serviced and configured tools to customers and refurbishing used drilling tools that come back from the field after a job is complete. As drilling is a complex activity, no single company performs all the required work. Operating companies, usually oil companies such as ExxonMobil, Shell, Conoco, or BP, may be large players with strong bargaining power, or independent companies made up of a few individuals. Many operating companies, drilling contractors and service and supply companies are involved in exploration and drilling of a rig. Despite DTS's leadership position in drilling technology, there is still a high threat of competition and substitute rotary drilling equipment from other operators is readily available. Barriers to entry in the industry are high as directional drilling requires specific technological know-how, while capital requirements can also be high. DTS attempts to differentiate itself primarily through its technology. The VarioRam tools are rapidly becoming the preferred tool used by oil service companies for directional drilling, which has resulted in a significant increase in demand over the past 3 years. In fact, demand for VR tools often outstrips supply, and DTS is in the enviable position of having to turn away business to its competitors. Economies of scale in the industry are primarily in the ability to fulfill demand through capacity, consolidation of equipment transported, and quick turnaround of reconditioned VR tools to clusters of districts involved in oil and gas exploration.

1.21 DTS's Value Proposition

DTS has a strong competitive position in the industry, which allows them to focus on *customer service* rather than on *price*. As a result, it is vital that DTS compete by providing *reliable* VR tools and *a high service level* as defined by the ready availability of VarioRam tools at the site when needed in order to be considered a preferred vendor for the operating companies. The reliability of the tools is an important factor since breakdowns in the tools require the drill string to be removed from the hole and substitution for a back up tool, which not only needs to arrive at the site in less than 24 hrs, but also reduces available tools for new jobs. This downtime is extremely expensive to the site operator and for DTS. Tools that fail in the field need to go through a quality audit process at DTS's reconditioning facility to investigate the cause of the failure, which can remove the tool from use (reducing available tools-per-job). Failures in the field also incur expediting costs to deliver the backup tool, penalties, and loss of reputation.

1.3 The VarioRam Value Stream

The VarioRam value stream represents a closed loop inventory system with variable lead time replenishment. Tools that leave the MTC facility are returned after they are used in the field. Used tools require a complete teardown and refurbishment before they can be used for the next job. New tools can enter the system when purchased through an annual capital purchase program or in rare instances by leasing tools from another operating subsidiary outside the U.S. Tools leave the system permanently when they are scrapped, or are lost in the well. Tools temporarily leave the system when they experience failures and need to undergo a vigorous inspection and root-cause analysis process or when they are down for parts (DFP). DFP occur when mechanical spare parts required to recondition a tool is not available in inventory and have to be ordered from internal suppliers. Failures and DFPs take approximately 6% of VR units out of service at any given time. There are in total 95 VarioRam units in the network.

1.31 VarioRam Tool Configuration

VarioRam units are modular assembly units that are configured to the specification required by the site operator and can weigh between 1200-3000 lbs. VR units are made of 3 main parts:

- 1) Collars
- 2) Electronics
- 3) Mechanical and Bias Units

The tools are custom configured to the requirements of the job by selecting the appropriate collar length, bias unit width, and mechanical parts necessary to drill the formation. Electronics in the VR unit are programmed based on data inputs gathered from a site survey. VR tools have an expected useful life over 5 years; however, after they have completed a job drilling at well site (tool in hole) they are returned to a facility to be reconditioned and the 3 main parts are staged in inventory for use on a future project.

1.32 VarioRam Tool Job Cycle

Let us now take a brief overview at a typical job cycle of a VarioRam tool. (Figure 2)

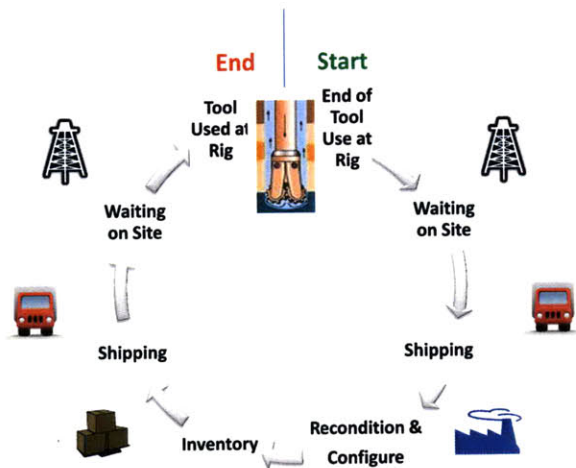


Figure 2. Job Cycle of VarioRam tools

When a tool is down in the drilling hole at a job site, it is used an average of 75 hrs with a std. deviation of 50 hrs. For every job, a back-up tool is contractually required to be available on site within 24 hours. DTS can decide where to stage the back-up tools in order to meet this requirement. After the job is complete or if the site operator decides to switch out the primary tool for the back-up tool for reasons such as experiencing a failure on one of the pieces of equipment on the drilling string, the VR tool is removed from the string and waits at the site till a truck is dispatched to collect the tool. The waiting time for the truck to collect the tool is 36 hrs with a std. dev of 12 hrs. As the job sites are typically in fairly remote areas, the truck travels empty until it picks up the tool. The tool is delivered to either the DTS reconditioning and configuration center (MTC) in Colorado or Oklahoma. The tools are reconditioned (see section 1.6 for a more detailed description of the process) and the parts are staged in configuration inventory until the

next job is received. When a new job is received from a well site, the appropriate parts to configure the tools are taken out of inventory and the tool is assembled and programmed according to the specification required. When the tool is ready to be shipped, the appropriate truck is called to transport the tool to the job site. Trucks are selected based on factors such as dimensions and weight of tools to be loaded and whether they need to be expedited (“hot-shot”) to the job site. Section (1.7) will provide more details on transportation options. The trucks are then dispatched to the job site from the MTC center. Section (1.4) will provide more information on the distribution network. When the tool reaches the site, it is unloaded from the truck and waits at the site before being assembled on the drilling string. Waiting time at the site before a tool is used averages 36 hrs with a std. dev of 12 hrs. Waiting time at the site for call out jobs is less than for normal orders.

1.4 DTS's Distribution Network

Presently, tools are repaired and reconditioned (MTC) at 2 facilities across the U.S. The facility in Colorado (CO) is closest to the Rocky Mountain basin of customer districts, such as ND and CA. The Oklahoma facility (OK) is closest to 4 customer districts such as West TX; East, TX, AR; and WV (Figure 3). About $\frac{3}{4}$ of demand originates from customer districts closest to OK, while the rest of demand originates from CO. Since transportation cost is billed by the mile, in order to minimize logistic cost and travel lead time, all demand from customer districts closest to OK would be serviced out of OK, while the Rocky Mountain districts would be served by Colorado (CO) as shown by the blue arrows. However, due to capacity constraints, and equipment shortages, DTS frequently has to deliver to customer districts closest to the OK hub from CO. This results in the use of non-preferred lanes to deliver equipment to customer sites as shown by the red arrows, which increases lead time (L/T) and delivery cost. Furthermore, DTS management has determined that consolidation of repair, maintenance and configuration of tools to only the CO facility would improve quality, capacity and labor utilization while reducing cost. Consequently, while the facility at OK will remain, the repair and maintenance capability at OK will be eliminated, which will exacerbate the issue of using non-preferred lanes to deliver VR tools since all used tools will now flow through the CO facility to be reconditioned.

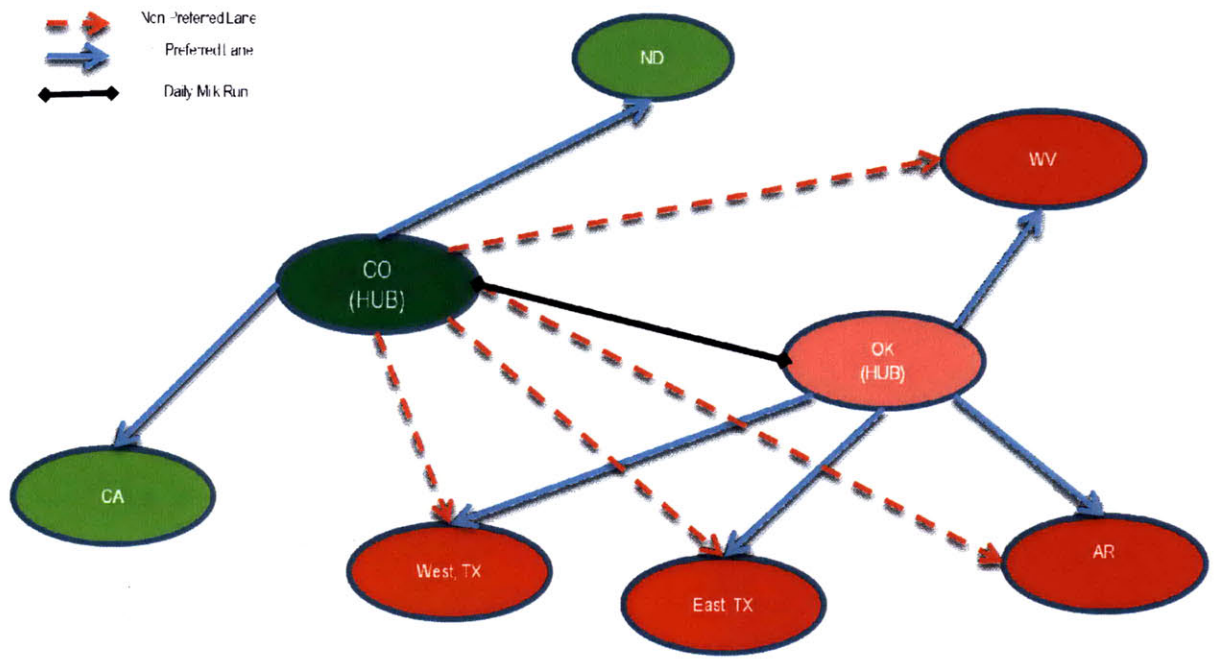


Figure 3 DTS's distribution network from 2 MTC facilities (CO, OK) to 6 customer districts

1.5 Increasing available Tools-Per-Job

Recall that DTS has more demand for VR tools than can be fulfilled by its current ability to supply these tools. The metric DTS uses to measure their availability is ‘tools-per-job’ (TPJ). TPJ is defined as average number of reconditioned tools available vs. outstanding jobs. Increasing available TPJ allows DTS to increase their revenue as there will be more clean tools available to be leased to site operators. Furthermore, increasing available TPJ also has a beneficial impact of being able to increase the on-time service level since there will be more equipment available either in inventory or staged through the cycle.

There are 2 primary levers of control for DTS to increase available TPJ:

- 1) Increasing the number of available tools by allocating more capital to purchase tools and equipment.
- 2) Reducing the overall cycle time when the tool is not generating any revenue (i.e. when the tool is out of a hole and when it is processed through the MTC facility for refurbishment.)

Increasing the number of available tools by purchasing more tools is perhaps the simplest method. However, tools are expensive and do not generate revenue during periods of low demand, which reduces the firm’s Return on Capital Employed (ROCE). Merely increasing the number of tools also masks inefficiencies and hidden waste in the process that increases the cycle time when the tool is out of the hole. The level of VR capital inventory required is a factor of demand from the field and lead-time to replenish. The higher the demand and variance or the longer the lead time to replenish and variance, the higher the safety stock required. (See section 1.63 on inventory policy.) DTS can control the amount of demand from the field by choosing which jobs to bid on. The lead time to

replenish is based on the cycle time through the process rather than in a traditional supply chain where the lead time to replenish is the lead time from a supplier. Consequently, the lead time to replenish becomes a random variable with a mean and a standard deviation where any decrease in the lead time to replenish would also decrease the amount of tools required to service demand. Consequently, the second lever, ***reducing the firm's overall cycle time when the tool is not in the hole*** is much more effective in increasing the firm's ability to service demand, without increasing capital equipment thus improving ROCE.

In order to reduce the total job cycle time, DTS has a number of stages in the process it can control:

- 1) *Waiting time at site* – Field Site Managers often request that tools be delivered to a job site before they are actually needed. The built in time buffer is a hedge due to unpredictable on-time delivery performance. The current on time delivery performance for the original tool request date ranges from 10%-20%, necessitating the hedge. If DTS is able to deliver tools at a high degree of on time performance, this buffer can be standardized, reduced or eliminated allowing tools to be delivered just-in-time.
- 2) *Transportation to/from job site* – The transport time to the job site is a factor of distance travelled / average speed. Distance travelled is a factor of which MTC hub the tool originates from (CO or OK) and the location of the job site. Thus, delivery from the closest MTC facility is the preferred method. Frequently, deliveries are scheduled from the non-preferred hub due to capacity issues or availability of parts, which increases total travel time.

3) *Reconditioning and Configuration Time* – The reconditioning and configuration time is the cycle time through the MTC facility as described in the section 1.6.

1.6 Repair, Reconditioning and Configuration Process in OK and CO

Tools that arrive in the MTC facility have to be carefully inspected for defects and reconditioned before they can be used again. (Figure 4)

Phase 1: Reconditioning Phase

The operating hours of the facility is 24 hours a day, 7 days a week, and 365 days a year. During the “receiving” step, used tools are unloaded from the arriving trucks and staged in WIP for “breaking.” In the “breaking” phase, the tools are broken down into their three part categories: collars, electronics and mechanical bias units.

Collars

The collars are washed, inspected and stored in inventory for use when required. Collars can range in diameter and length. DTS has sufficient inventory of collars, and there has not been a shortage of this item.

Mechanical Parts and Bias Units

The mechanical parts and bias units are inspected for defects and undergo a different wash and mechanical service process before they are stored in inventory for use when required. There are 4 types of bias units ranging in diameter from 4” to 9” depending on the requirement of the job. There are a few hundred mechanical part SKUs used on VarioRam units.

Electronics

Electronics go through 3 different service levels depending on the type of use. About 15% of the time, they go through a Level 1 service which takes 0.5-2.5 hrs, 80% of the time, they go through a Level 2 service which takes 3-5 hrs and 5% of the time they go through a Level 3 service which takes about 8-10 hrs. Much like maintenance intervals

on a vehicle, the service levels depend on the number of drilling hours the tool has been subjected to.

Taken together, the phase 1 reconditioning process for used tools can range upwards of 7 hour throughput time depending on the number of tools in the queue, manpower available, and the electronic service level required.

Phase 2 – Assembly and Configuration of Tool for a Job

When a tool is sent to a site, it needs to be assembled and configured to the requirements of the site.

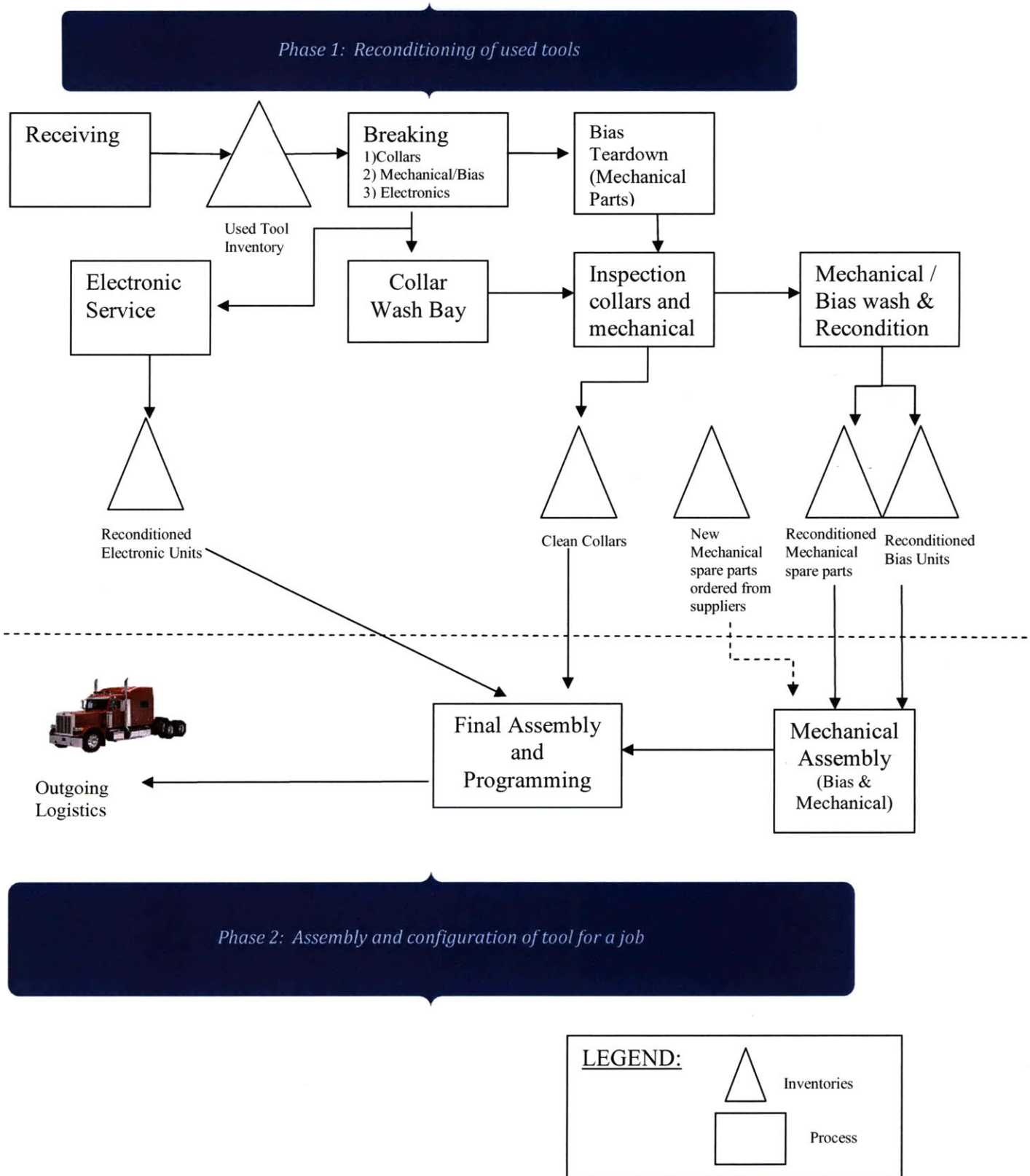
Mechanical Assembly of Bias units and Mechanical Parts

The mechanical assembly process involves pulling the appropriate mechanical parts from inventory and assembling it in a 2 hour process. In the final assembly step, the bias unit is fitted to the collar and the electronics are programmed, a process that takes 90 minutes. In total, Phase 2 takes about 3.5 - 4 hrs to complete.

Postponement Point

Phase 1 can be completed regardless of whether DTS receives an order for a tool, while phase 2 can only be completed once information about an order is known. Consequently, any postponement strategy would occur following the completion of Phase 1.

Figure 4- Diagrams the 2 phases in the reconditioning and configuration process at MTC facilities



1.61 Information Flows from the Field

DTS field service managers spend part of their time at the job site with customers. When equipment is needed to drill a well, they place orders electronically through DTS's E-trace system. Information is entered such as the type of equipment required, the configuration and when it is required at the site. Jobs are usually entered anywhere from a week to a month ahead of when they need to be delivered. These types of jobs are considered "normal." "Call out" jobs are jobs that require delivery within 24 hours of being entered in E-trace. A call out job is for delivery of a secondary backup tool, if a primary fails, or call outs can also be for new jobs received from the field. About 30% of jobs entered into e-trace are call-outs. The VarioRam supervisor at the MTC facility reviews each order and determines if he has the capital equipment available to meet the order out of reconditioned inventory. If specific parts are not available in stock, the supervisor manipulates the production schedule through Phase I / II to salvage needed parts from incoming used VR tools.

1.62 Supplier Network

CO & OK are supplied by 3 internal suppliers for capital equipment and spare parts - The main suppliers are in the U.S, Europe or Japan. These suppliers are treated as profit centers and behave independent of the MTC organization. This often results in difficulties maintaining reliable supply of parts at reliable lead times, necessitating that MTC maintains a large inventory of spares. There is an opportunity for further optimization of DTS's supply chain with increased collaboration between these supply-chain partners.

1.63 Inventory Control

The three categories of modular parts used to assemble VR units (collar, electronics and bias units) are considered capital purchases and depreciated straight line over a 5 year basis. Financial managers review annual demand forecasts during each budgeting period and determine how much new capital equipment is required for purchase. *There is no inventory safety stock policy for reconditioned inventories at the end of Phase 1. In fact, DTS attempts to maximize its revenues by taking on additional jobs to consume any inventory sufficient to build out VR units. We, however, believe that this places the ability to service jobs which require delivery within 24 hours at risk, increases order lead times, aggravates the bull-whip effect, increases logistics cost in order to expedite orders, and results in poor on time delivery performance. We believe that strategically located reconditioned inventory at each facility serves an important function to hedge against uncertainty in demand and replenishment lead times upstream in the process.*

1.64 Impact of insufficient safety stocks of tools

Due to the fact that equipment returns from the field based on a variable lead time, DTS cannot predict when the required parts will become available, which could lead to potential delays in delivering tools to a customer. The VR supervisor's job is complicated by the fact that if the inventory is not available, he has limited visibility on returning equipment from the field that might contain the required parts and when they are expected back at the facility. The VR supervisor stays in close contact with the Field Service managers to update them about the status of tool availability; however, since there is rarely sufficient inventory stock of reconditioned equipment to fulfill orders ahead of time, the VR supervisor is constantly fire fighting in order to expedite incoming used equipment from the field through the Phase 1 and Phase 2 process to deliver the next "hot" order. As a result of the lack of parts and having to catch up on back orders, even normal orders become "hot" orders that require expediting.

1.7 Delivery Mode Options:

Tools can be delivered by truck, combination truck and rail, or combination truck and aircraft. Using aircraft as a shipment mode was ruled out due to cost constraints since a plane would have to be chartered at an extremely high cost. Rail options were also ruled out since DTS would have to deliver to a rail schedule, which did not allow for the frequency and flexibility in delivery times as using a pure trucking mode. The company subcontracts deliveries of tools to various transportation companies using trucks. Tools are delivered using two types of trucks (Figure 5) (Minifloat, tandem). The weight restrictions limit the number of tools that can be carried in each load. The Minifloat can carry about 7 tools, while the Tandem can carry up to 20 tools.



Figure 5. Minifloats can carry up to 15,000 lbs (~7 tools) and Tandem trucks can carry up to 45,000 lbs (~20 tools). The tandem is used exclusively for call outs where delivery time exceeds 11 hrs.

Average speed is a factor of transport method – DOT restrictions for ‘normal’ delivery allows a driver to drive for 11 hours a day with a 10 hour rest period. ‘Expedited’ delivery allows only for the use of the tandem with a sleeper and 2 drivers, which allows the drivers to take shifts and drive for 24 hrs.

2 LITERATURE REVIEW

2.1 Network Optimization

There has been a substantial amount of research dealing with distribution network optimization issues. For the most part, the existing research focuses on three levers to maximize cost effectiveness and efficiency of delivering products to end consumers:

- 1) Production (capacity and flexibility)
- 2) Inventory (location and levels)
- 3) Logistics (mode and network)

This paper will discuss issues related to all three of these levers in order to reduce *delivery* lead times, increase tool availability and increase service levels, while ensuring that production capacity and capital inventory are deployed efficiently.

2.2 Inventory Policy

Silver et al (1998) illustrates the use of a “one period decision” inventory model, termed “The Newsvendor Model” which determines the optimal level of inventory where there is a tradeoff between the costs of keeping too much inventory (overage costs) and the costs of running out of inventory and losing sales (underage costs). This tradeoff becomes apparent when a retailer considers how much product to order for products that cannot be sold in the following period, such as a newspaper or a seasonal fashion item. The inventory model developed analyzes the historical demand pattern and constructs a histogram of probable demand during the period. An important assumption underlying this model and many algorithmic-based forecasting methods is that there is no “structural” difference between demand periods. Based on forecasted demand and known costs of overage and underage, the Newsvendor model determines the optimal

order size in order to maximize expected profit. A Newsvendor calculation was considered in the scenario where DTS would pre-configure VarioRam tools and stage these tools at a distribution hub closest to customer demand as pre-configuration would save about 4 hours of operational lead time and limit amount of resources required at OK to configure tools. This model was deemed to be unsuitable as there are potentially thousands of different possible configurations, since demand configuration is unknown before an order is received. The next question was whether the newsvendor model could be used to calculate the number of backup tools to keep in case the primary tool needed to be replaced within a 24 hour lead time window. Again, this was deemed unsuitable as backup tools were sometimes requested in a different configuration to the primary tool requiring them to be re-configured at the distribution hub. Consequently, the cost of overage was far more significant than the cost of underage, which indicated that a postponement strategy might be more appropriate.

In order for a postponement strategy to be utilized, there needs to be a high degree of component commonality. Component commonality refers to an approach in manufacturing in which two or more different components for different end products are replaced by common components that can perform the function of those it replaces. By using common components, the point of differentiation can be extended further downstream in the process, which allows one to configure the product to meet a specific customer requirement with a short lead time while carrying a smaller amount of postponement inventory. Commonality has been a subject of study for over two decades. Dogramaci (1979) authored one of the early publications on commonality. From a risk-pooling perspective, he noted that the use of common components across multiple

end items reduces forecasting errors by shortening the forecasting time horizon.

Postponement can also shorten the configuration and customization lead-time, and enhance a firm's flexibility and responsiveness in an uncertain and changing market.

Other authors that have provided extensive analysis of the benefits of postponement and proposed various postponement strategies in order to improve responsiveness while mitigating supply-chain related costs include, but are not limited to, Alderson (1950), Bucklin (1965), Zinn and Bowersox (1988), Childet et al. (1991), Maskell (1991), Stern and El-Ansary (1992), Cooper (1993), Lee and Billington (1994), Feitsinger and Lee (1997), and Pagh and Cooper (1998).

Pagh and Cooper (1998) focus on the downstream part of the supply chain and propose four different postponement/speculation (P/S) strategies varying from full postponement (configure to order) to full speculation (make to stock). According to the authors, there are three categories of decision determinants for the choice of a P/S strategy. For many companies the P/S decisions are determined by a combination of all three categories:

- 1) *Product characteristics* -They include the degree of modularity, the number of possible configurations and the cost of the final product.
- 2) *Characteristics of demand and required service lead times for final customers* – the ratio of the average total manufacturing and delivery cycle time to the required service lead times, and the degree of demand uncertainty.
- 3) *Characteristics of manufacturing and logistics system* – For instance, if there are large economies of scale for producing large batches of complete product, some degree of speculation may be beneficial. It may be more difficult to postpone products to a later stage or a downstream facility where there are special processes or specific know-how in the manufacturing process.

Chopra and Meindl, (2007) demonstrated that the use of a mixed P/S strategy, could both reduce cost and lead time over a full postponement strategy. However, we do not believe that a speculation strategy is appropriate for DTS since VarioRam equipment is highly modular. All VarioRam units are customizable from different collar diameters, parts assemblies and programming requirements that are specific to the nature of the job at the oil well. This makes it practically impossible to predict the correct configuration that a customer would order. Furthermore, the required service lead times for call out jobs are much shorter than the manufacturing cycle time, and postponement can only take place in 2 facilities in Colorado and Oklahoma.

While early studies were primarily qualitative, some recent works have focused on the quantitative modeling of the benefits and criteria of various postponement strategies, for example, Lee (1993, 1996), Howard (1994), Lee and Billington (1994), Lee and Feitzinger (1995), Garg and Tang (1997), and Garg and Lee (1997). Lee (1996) presents a model that captures the effect of postponement on inventory reduction. Graman (2010) showed that reducing either product value, packaging cost, cost of postponement and/or holding cost, while increasing fill rate and demand correlation can decrease expected total cost and increase postponement capacity. We will be extending on some of these models by capturing the costs and benefits of utilizing a postponement strategy for delivering oil drilling tools to customer sites by calculating the savings in logistics costs, lead times and the increase in service levels by utilizing a postponement strategy.

2.3 Setting Safety Stocks

See Silver et al (1988) for calculation methods of setting up safety stock using an order up to level system “S” based on the desired item fill rate (IFR), lead time (L). Order up to Level: $S = x_L + k\sigma_L$. We use the order up to level calculation as an approximation for total capital inventory required in a closed inventory system.

Forecast demand over the lead time = x_L

Safety Stock = $k\sigma_L$, where k = safety stock factor

σ_L =Root Mean Square Error (RMSE) over the Lead Time

Q=Avg demand over review period

G(k) = Unit Normal Loss Function

$G(k)=(Q/ \sigma_L)* (1-IFR)$

Given G(k), the value of k can be found in Silver et al (1988) Table B.1, Appendix B or calculated with the following approximation.

$$k = (a_0 + a_1z + a_2z^2 + a_3z^3) / (b_0 + b_1z + b_2z^2 + b_3z^3 + b_4z^4)$$

where

$$z = (\ln(25/(G(k))^2))^{0.5}$$

$$b_0 = 1$$

$$a_0 = -5.3925569$$

$$b_1 = -7.2496485 * 10^{-1}$$

$$a_1 = 5.6211054$$

$$b_2 = 5.07326622 * 10^{-1}$$

$$a_2 = -3.8836830$$

$$b_3 = 6.69136868 * 10^{-2}$$

$$a_3 = 1.0897299$$

$$b_4 = -3.29129114 * 10^{-3}$$

2.4 Inventory Optimization Model

Optimal placement and calculation of safety stocks in a simple serial supply chain was originally given in Simpson (1958). Lee and Billington (1993) inventory optimization model determines how much inventory is needed at each stage in the supply chain so as to minimize total inventory. Clark and Scarf (1960) demonstrated that in a serial system, a simple order-up-to “S” policy is optimal. That is to say that during each review period, stock on hand, plus stock on order minus backlogged demands plus stock in transit to downstream stockpoints is increased to the order-up-to-level S. This paper will utilize an order-up to “S” policy to calculate safety stocks required in the DTS network to account for stock on hand, stock in transit to the customer sites, stock held at customer sites and stock in transit back from customer sites for capital inventory. We will determine if this inventory policy can achieve the desired item fill rate (IFR) for inventory that flows in a closed-loop system with variable replenishment lead times.

Inderfurth and Minner (1998) formulated an optimization problem for a general inventory system, which depends on the structure of the multi-stage manufacturing and distribution system and the service measure utilized. They also considered the impact on flexible manufacturing capacity and the ability to expedite material. They found that most inventory policies are set under rigid assumptions that is atypical of a manufacturing environment, namely that upstream insufficiency in safety stock would cause a delay in the succeeding stage which would propagate over the entire system. In reality, demand uncertainty is both buffered by safety stocks as well as emergency actions such as rescheduling production and expediting internal processes, which will avoid delays in downstream stages. Consequently, safety stocks just need to cover demand variability up

to a maximum reasonable amount. The capability of flexible response on an operational level means that fixed planned manufacturing lead times incorporated into MRP systems are actually fairly variable. As a result, under the no-delay assumption, safety stock determination can be decomposed into a multi-stage buffer allocation and a single-stage buffer sizing problem at all stockpoints. Simpson (1958) shows how in a pure serial system, safety stock optimization can be performed with a simple algorithm, which is valid for the case where service measures related to stockout occurrences are considered. Inderfuth and Minner (1998) proposed the optimal safety stock policies given for all basic structures of multi-stage systems and different types of service measures.

2.5 Logistics and Delivery Mode

Liu et al (2003) found that mixed truck delivery systems with both direct and hub and spoke deliveries saved about 10% distance travelled on average from a pure hub and spoke delivery network. They found that direct shipments should be used when the lead time requirements are tight, the goods need to be isolated or the shipment is large (maxing out the capacity on the truck.) Furthermore, they found that transportation cost could be further reduced if each delivery vehicle could visit several customer locations provided that the capacity of the truck was not exceeded, which they termed direct shipment with milk runs. However, whenever a milk run is included a decision on vehicle routing was necessary on each milk run. Furthermore, they found that when order size was small, a vehicle could visit several stops in a collection or redistribution trip, which they termed a hub and spoke model with milk runs. This paper will study the hub and spoke model which enables DTS to obtain economies of scale in transportation by transporting multiple tools from point of origin to destination. Furthermore, it could improve service levels by increasing the delivery frequency. This could be most useful in routes between the repair and maintenance facility in Colorado, and the assembly and redistribution hub in Oklahoma where multiple tools can be carried on a truck between the two facilities. Some researchers have studied the design and operation of hub-and-spoke systems, in which the hub location is a critical decision to the efficiency of delivery systems. For example, O' Kelly (1987), Campbell (1996), Abdinnour-Helm and Venkataramanan (1998), and Pirkul and Schilling (1998) solved the location and allocation problem that determines locations of hubs and the assignment of nodes to each hub. O. Kelly and Bryan (1998) considered the above problem with economies of scale

taken into account, where the marginal cost decreases with flow volume. O.Kelly et al (2001) found that smaller cities such as Oklahoma City, Pittsburgh, Indianapolis, and Knoxville serve major gateway functions because of advantages such as their location with respect to other cities, and their presence on the East-West trunkline of the U.S. Interstate highway network.

3 METHODS - Part I: Determining Logistics Strategy to fulfill call out orders within 24 hours and optimize logistic costs

What should DTS distribution network look like in order to be capable of delivering tools to the 6 customer districts within 24 hours?

3.1 Logistic Options

With the use of a single MTC facility in Colorado, there are 3 logistics options to deliver tools to the 6 customer districts with associated lead time impact and cost impact. Since call out jobs have to reach the customer site within 24 hours, the first thing we will attempt to analyze is whether any of the transportation options can be eliminated because call-outs cannot be delivered to the customer site within 24 hours. Recall that normal delivery means that the truck is driven for 11 hrs a day with a 10 hr rest period as mandated by D.O.T. requirements, while expedited delivery uses a tandem rig and team driver which allows a truck to be driven 24 hrs/day. Consequently, there is no benefit to use expedited delivery for customer districts within an 11 hr L/T zone:

- 1) **Direct Method** – Tools are stored, configured and delivered from Colorado directly to the 6 customer districts using a point-to-point methodology each day depending on orders. (Figure 3)
- 2) **Hub and Spoke Method** – Tools to customer districts closest to OK are consolidated on a single truck each day and shipped from CO to OK where they are cross-docked and shipped to the customer districts. Tools for “call-out,” and back orders are expedited using Tandem direct from Colorado.
- 3) **Postponement Method** - An order up to level of inventory is established for Colorado based on demand and lead time to replenish. Tools that return to

Colorado are reconditioned, and tools in excess of the safety stock level in Colorado are sent to Oklahoma to be staged for orders originating from districts close to Oklahoma. When an order is received, the tool is configured within 4 hours and transported to the customer site from the preferred hub.

Common Assumptions across Logistics Options:

- 1) Tool orders for the same district on the same day, assuming inventory is available, can be consolidated on the same lane and truck for milk-runs.
- 2) Normal Orders do not require expedited delivery mode, while call-out orders are shipped using expedited mode when the transport lead time > 11 hrs. If inventory is not available, any backorders are shipped using expedited delivery mode only if transport lead times exceeds 11 hrs.
- 3) Reverse logistics is the same for all modes, since it is more important to reduce cost than lead time on the reverse journey. The appropriate truck picks up tools from customer districts and transports the tool to either the CO or OK hub depending on which location is closer. Since we cannot predict when tools will be ready for pick up, we assume one tool per truck from the customer district to either the OK hub or CO hub. Tools that are shipped to OK are then consolidated on a truck and shipped back to CO for reconditioning.

3.2 Building a Simulation Model of the Network

In order to simulate the cost and lead time impact of transporting tools to the 6 customer districts, a Monte Carlo simulation model was built in Microsoft® Excel and run n=365 days. The user is required to input the following data to run the simulation:

Simulating Annual Logistics Cost of the three Logistics Options

User Inputs:

1. Average number of VR tool demand per day and std. deviation of daily demand for Normal Jobs (Table 11). A normal distribution is assumed.
2. Average number of VR tool demand per day and std. deviation of daily demand for Call-Out Jobs (Table 11). A normal distribution is assumed.
3. Minimum and Maximum weight of VR tools
4. Allocation of tools to each customer district (probability of daily demand from each customer district) (Table 4)
5. Truck Type and Maximum Load Capacity of each Truck (Figure 5)
6. Transport Cost & Lead Time to each customer district by truck type (Table 1)
 - a. Normal Delivery Cost
 - b. Expedited Delivery Cost (team drivers)
7. Transport cost for milk-run between Colorado and Oklahoma Hubs (Table 1)
8. Transport cost for reverse logistics (Table 2)
9. Distance to each customer district (Table 3)

3.3 Determining Total Logistic Cost to deliver tools to customer district based on delivery Method

Direct Delivery Method

Step 1: The model randomly simulates daily demand levels assuming a normal distribution around the mean μ and the std deviation σ to find the daily demand 'n.' In order to get positive integers, any negative values are assigned a value of 0, and fractions are rounded up to the closest integer.

Step 2: The demand of 'n' tools is then assigned to up to 6 customer districts based on the probability of daily demand of each district.

Step 3: For each tool, a weight is simulated using a uniform distribution between the min/max weight of each tool.

Step 4: Using a lookup function, the appropriate truck is selected based on the weight requirements for shipment to each district

Step 5a: Based on the truck selected, a lookup table determines the total cost to ship the tools to the various districts on that day.

Hub and Spoke Delivery Method

(Step 1-4) above

Step 5b: Tools that are destined for customer districts close to the OK hub are first sent to the OK hub. Then the appropriate truck is selected to transport the tool to the final destination to minimize cost, while meeting the weight limits.

Postponement Method

Safety stock is kept at Colorado to cater to demand at customer districts closest to Colorado. Any residual VR units above this level of safety stock are transported to OK where they are stored until orders are received from customer districts closest to OK. The transportation cost is to deliver tools from the hubs to customer district and the daily truck route between Colorado and Oklahoma to transport clean tools to OK and dirty tools back from the field.

What will be the impact on transportation cost and delivery lead times?

3.4 Simulation of Lead Time to deliver call out jobs to districts based on delivery

options:

Call out jobs have to reach customer districts within 24 hours. When a call out job is received, DTS takes 4 hours to configure the tool to the requirements of the job prior to shipping the tool from its facility leaving 20 hours for shipping. Delivery lead times depend on the driving time to each district. We assume standard driving times for normal delivery mode, and use of team drivers for districts that are beyond an 11 hour driving radius. Based on the random generation of call out demand, we calculate the min, max, and average transport lead times from order placement to delivery for the 3 logistics options.

3.41 Modeling Assumptions and Inputs

Truck Type	Max Load Capacity	Origin	Destination							
			CA	West, TX	East, TX	AR	WV	ND	OK	CO
Minifloat	15000	OK	\$3.50	\$3.50	\$3.50	\$3.50	\$3.50	\$3.50	\$3.50	\$3.50
Minifloat	15000	CO	\$3.50	\$3.50	\$3.50	\$3.50	\$3.50	\$3.50	\$3.50	\$3.50
Tandem	45000	OK	\$4.15	\$4.15	\$4.15	\$4.15	\$4.15	\$4.15	\$4.15	\$4.15
Tandem	45000	CO	\$4.15	\$4.15	\$4.15	\$4.15	\$4.15	\$4.15	\$4.15	\$4.15
Tandem (Expedited)	45000	OK	4.35	4.35	4.35	4.35	4.35	4.35	4.35	4.35
Tandem (Expedited)	45000	CO	4.35	4.35	4.35	4.35	4.35	4.35	4.35	4.35

Table 1 Front Haul Rates per mile to deliver tools to customer districts

Reverse Logistics	Destination	Origin							
		CA	West, TX	East, TX	AR	WV	ND	OK	CO
Minifloat	OK		\$ 3.50	\$ 3.50	\$ 3.50	\$ 3.50			\$ 3.50
Minifloat	CO	\$ 3.50	\$ 3.50	\$ 3.50	\$ 3.50	\$ 3.50	\$ 3.50	\$ 1.75	
Tandem	OK		\$ 4.15	\$ 4.15	\$ 4.15	\$ 4.15			\$ 4.15
Tandem	CO	\$ 4.15	\$ 4.15	\$ 4.15	\$ 4.15	\$ 4.15	\$ 4.15	\$ 2.08	

Table 2. Reverse Logistic cost / mile to deliver tools back to CO

Distance	CA	West, TX	East, TX	AR	WV	ND	OK	CO
CO	1,046	663	1,140	937	1,454	693	685	-
OK	1,346	428	464	314	1,112	1,297	-	686

Table 3. Mileage charge chart for delivery to customer districts

Normal	Daily Tool Demand	CA	WV	AR	ND	East TX	West TX
		Average	6	0	7%	8%	24%
Std dev	2.20						

Call-Out	Daily Tool Demand	CA	WV	AR	Williston	East TX	West TX
		Average	2	0	5%	4%	24%
Std dev	0.93						

Table 4. Average number of tools demanded each day and allocation to the different customer districts

4. Results and Discussion - Part I: Logistics Strategy

What should DTS distribution network look like in order to be capable of delivering tools to the 6 customer districts within 24 hours?

What will be the impact on transportation cost and delivery lead times?

By running the demand and transportation inputs through our model that simulates DTS's logistics network, we obtained the following results for the annual logistics costs for the three logistics modes (Table 5).

		Logistics Options:		
		Postponement	Hub & Spoke	Direct
Logistics Cost		\$ 6,880,611	\$ 7,734,629	\$ 9,590,702
	Postponement Savings vs. Direct		Postponement Savings vs. Hub & Spoke	Hub & Spoke Savings vs. Direct
Savings % by Logistic Option		28%	11%	19%

Table 5 Logistic cost and savings of the three logistics options

There is a 28% cost savings from using a postponement methodology over direct shipments and 11% savings using postponement over the hub & spoke option. The savings in the Postponement method vs. Direct shipment method arise primarily from:

- 1) Consolidation of tool transport between CO and OK. Recall that in the postponement strategy a truck carries reconditioned tools from CO to OK and picks up used tools from OK for the backhaul journey. This results in tremendous economies of scale.

- 2) Due to the shorter travel distances between the OK hub and East Tx, AR and WV districts, travel time is less than 11 hrs. Consequently, the less costly Minifloat minifloat can be used to expedite tools for call out jobs, which saves \$0.85 / mile.

The savings in the Postponement method vs. the Hub & Spoke method primarily arises from how call-out jobs are delivered to the customer districts. With no inventory staged at OK, call out jobs have to be shipped direct from CO and incur significant expediting costs since the Tandem tandem semi has to be used, which cost \$0.85/mile more than standard shipping. We recommend using the *postponement method* as it results in the lowest logistics cost.

There is an instance where using the direct delivery method is less costly: single site delivery to either West Tx, East Tx, AR or WV.

It is least costly to use the direct delivery method *IF* there are 1 or more tools that need to be delivered to the *same district* on the same truck on a given day. (i.e. there is only one delivery scheduled to a single district on a given day.) This example is illustrated below

Table 6 & Table 7)

Table 6 Cost per tool to deliver (D)irect from Co to a single district (Minifloat)

No. Tools	West, TX (D)	East, TX (D)	AR (D)	WV (D)
1	\$2,319	\$3,988	\$3,281	\$5,090
2	\$1,159	\$1,994	\$1,640	\$2,545
3	\$773	\$1,329	\$1,094	\$1,697
4	\$580	\$997	\$820	\$1,272
5	\$464	\$798	\$656	\$1,018
6	\$386	\$665	\$547	\$848
7	\$331	\$570	\$469	\$727
8	\$290	\$499	\$410	\$636

Table 7. Cost per tool to deliver to a single district using (H)ub & spoke network (Minifloat)

No. of tools	West, TX (H)	East, TX (H)	AR (H)	WV (H)
1	\$3,894	\$4,022	\$3,494	\$6,288
2	\$1,947	\$2,011	\$1,747	\$3,144
3	\$1,298	\$1,341	\$1,165	\$2,096
4	\$974	\$1,006	\$874	\$1,572
5	\$779	\$804	\$699	\$1,258
6	\$649	\$670	\$582	\$1,048
7	\$556	\$575	\$499	\$898
8	\$487	\$503	\$437	\$786

However, since tools often need to be delivered to multiple customer districts on a given day, the Hub & Spoke / Postponement methods are less costly due to economies of scale of shipping multiple tools between CO and OK. This is illustrated in the matrix below (Table 8 & Table 9):

Table 8 Logistic Cost to deliver a tool to each of 2 customer districts using direct method

District 1/ District 2	West, TX	East, TX	AR	WV
West, TX		\$6,307	\$5,599	\$7,408
East, TX			\$7,269	\$9,078
AR				\$8,370
WV				

Table 9 Logistic Cost to deliver 2 tools to 2 customer districts using hub & spoke / postponement method

District 1/ District 2	West, TX	East, TX	AR	WV
West, TX		\$5,520	\$4,992	\$7,786
East, TX			\$5,119	\$7,914
AR				\$7,386
WV				

4.1 Transportation Lead Times

Figure 6, Figure 7 and Figure 8 show transport lead times to the districts vary by option chosen:

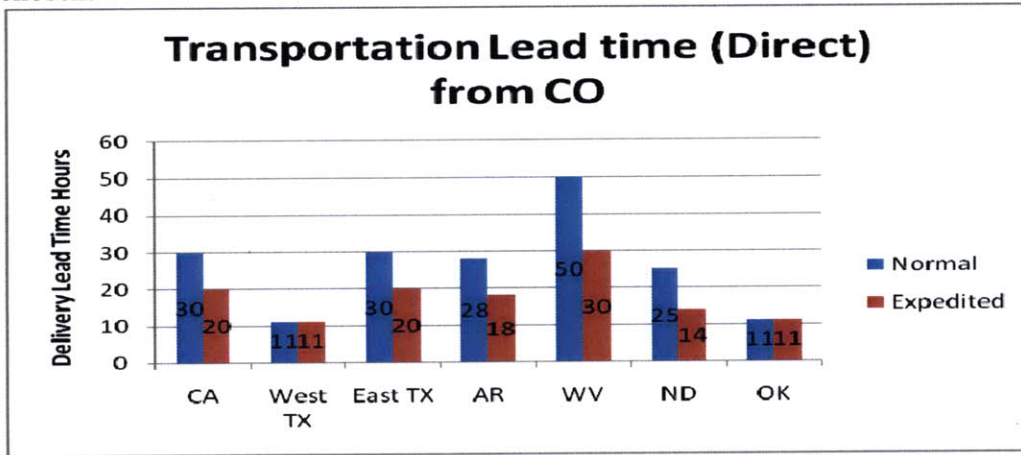


Figure 6. Transport Lead time from CO

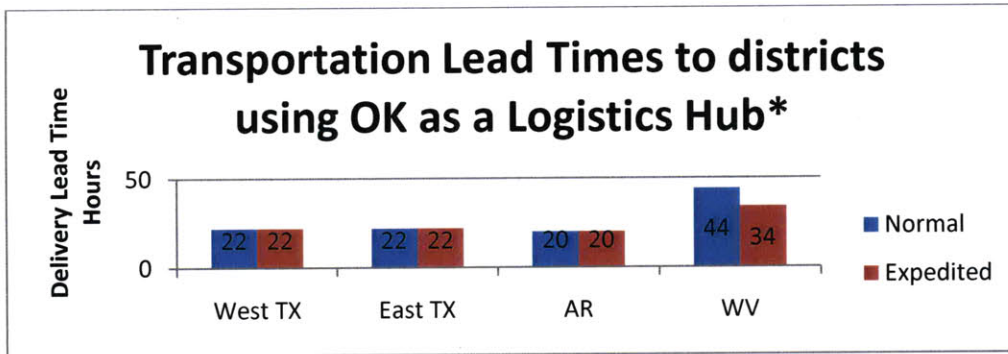


Figure 7. Transport Lead time from CO using OK as a logistics hub. *Includes 2 hour load/unload time in OK

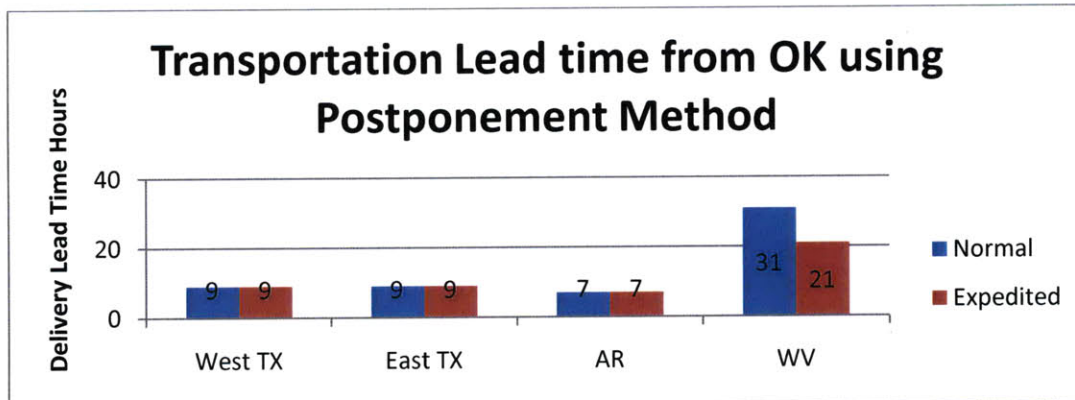


Figure 8. Transportation lead time to customer districts using postponement

Once again, the postponement method has the shortest delivery lead times because capital equipment is staged close to customer demand and configured only when an order is received. We ran a simulation of a year worth of demand to determine if call out jobs could be delivered to the field in under 24 hours using the three logistics options. We assume a 4 hour configuration time for each tool, and a 2 hour load/unload time at OK under the hub and spoke method in addition to the transportation time. The results are presented in Table 10 below:

Call Out L/T Performance	Logistics Options:		
	Postponement	Hub & Spoke	Direct
Avg Delivery Time (hrs)	14.66	23.24	20.22
Std dev. In delivery Time	3.26	3.90	5.03
Min Delivery Time (hrs)	11	18	15
Max Delivery Time (hrs)	25	36	34
Delivered to basin >18 hrs	27%	100%	68%
Delivered to basin > 24 hrs	5%	74%	42%
Maximum on-time service level for Call Outs	95%	26%	58%

Table 10. On time delivery performance for Call-Outs using expedited delivery methods

The table shows that the postponement method allows 95% of call out deliveries to be made in the 24 hour window. The longest lead time (max delivery time) is associated with deliveries to WV, which take 21 hrs travel time + 4 hours to configure. By cross-checking these results with the percentage of overall demand originating from WV, we find that 5% of demand comes from WV. We would recommend that DTS managers “kaizen” the process to reconfigure tools. If tools can be configured in less than 4 hours, there is a better chance of being able to reach WV in less than 24 hours. For the hub and spoke method, call out jobs were routed through the OK hub to reduce logistic costs;

however, this increased the transport lead times due to the longer distance travelled and the time to cross-dock the tools. The direct method is also not preferable since 42% of tools take more than 24 hrs to deliver to the field, due to the long transport distances from CO to East Tx, WV, AR and ND. This means that the maximum on time delivery rate that can be achieved for call out jobs is 58%. The postponement method has the shortest average delivery time at about 15 hrs vs. 20 hrs for direct and 23 hrs for hubs and spoke.

Taken together, we recommend that DTS implement the *postponement* method as it results in the lowest logistics cost (approx. 28% savings vs. direct shipments, and 11% vs hub and spoke) and the highest probability of being able to deliver call-out jobs to customer sites in 24 hours or less. We eliminate consideration of the two other logistic options as the on-time delivery rate is significantly below 95%. There is additional cost associated with the postponement method, however, since the OK hub will have to be staffed and equipped to configure tools. We recommend that spare part inventory supermarkets be available at both CO and OK as it is critical to have the parts on hand to configure tools within the 4 hour configuration window.

5 Methods - Part II: Modeling Inventory Flows in a Postponement System

What level of capital inventory is required to support the closed-loop replenishment system for VR tools? What will be the Item Fill Rate (IFR)?

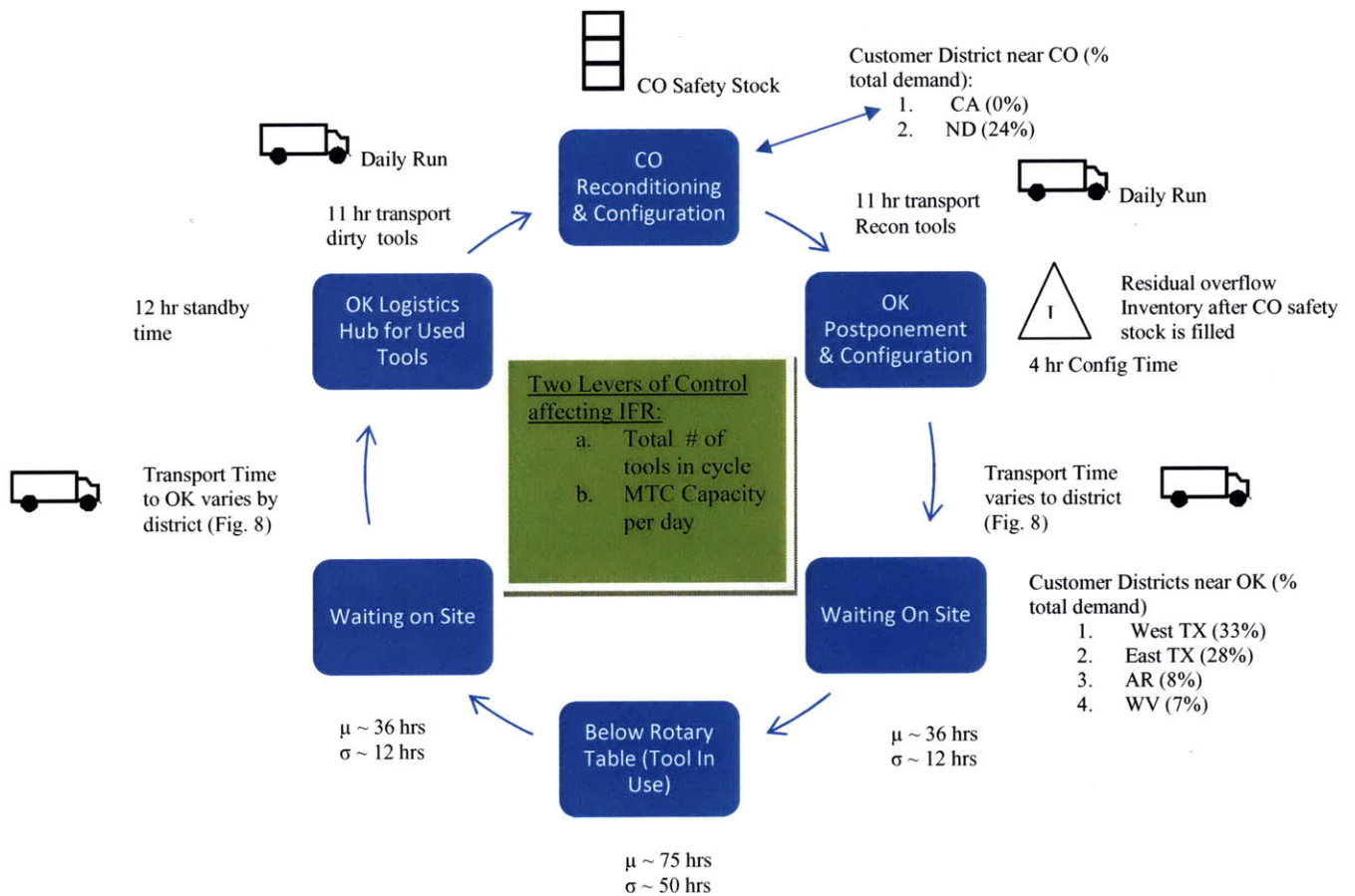


Figure 9. Shows the structural representation of material flows in the simulation model

5.1 Simulating Demand under three scenarios

Total VR Demand for normal and call-outs was generated using a random number generator following a normal distribution. We first generated daily demand for normal and call out jobs per Table 11 for a 365 day period:

Three Scenarios		Normal	Call out	Total
Baseline	Average	6	2	8
	Std dev	2.67	1.11	2.87
Low	Average	4	2	6
	Std dev	2.06	0.88	2.41
High	Average	10	4	14
	Std dev	3.34	1.44	3.98

Table 11. Three scenarios of demand for normal and call out jobs

We randomly allocated this demand to the 6 districts based on historical usage rates

Table 12:

Normal Demand	CA	WV	AR	ND	East TX	West TX
	0	7%	8%	24%	28%	33%
Call-Out Demand	CA	WV	AR	ND	East TX	West TX
	0	5%	4%	24%	35%	32%

Table 12 Proportion of demand originating from each district by order type

5.11 Modeling Tool Replenishment Lead Times

Figure 9 shows the movement of VR tools within the closed-loop cycle. In order to estimate replenishment lead time at different stages of the cycle, we analyzed historical company data.

Configuration Lead Time

The time to configure a VR tool to a customer’s order was determined to take about 4 hours.

Transportation Lead Times

We estimated the transportation time between the hubs and customer districts.

Transportation lead times are shown in Figure 8.

Waiting time on Site

The average waiting time on site before the tool is installed on the rig, and when it is waiting to be picked up after use was determined to be 36 hrs with a standard deviation of 12 hrs.

Below Rotary Table

Below rotary table hours is the time taken when the tool is in use and mud is being pumped to drill a hole. Based on company data, below rotary table hours are listed in Table 13 below. We simulated the below rotary table time using a normal distribution with the mean, std. dev and minimum drilling hours as listed in Table 13:

Table 13. Average and standard deviation of time tool spends below the rotary table.

Below Rotary Table Time	CA	West TX	East TX	AR	WV	ND
Average (hrs)		82.88	83.08	59.39	71.58	63.24
Std dev		54.44	52.34	38.11	51.59	35.19
Min		10.5	8.2	11.4	8	7

OK Logistics Hub

Used tools are sent back to OK, where they wait an average of 12 hours before the truck that makes daily deliveries of clean tools to replenish OK inventories collect the dirty tools to be transported back to the CO facility for reconditioning. The journey from OK to CO takes an additional 11 hours.

Total Replenishment Lead Time

By simulating the lead time through the various stages in the cycle, we calculated the average replenishment lead time at the CO facility to be 9 days with a standard deviation of 2 days (Figure 10).

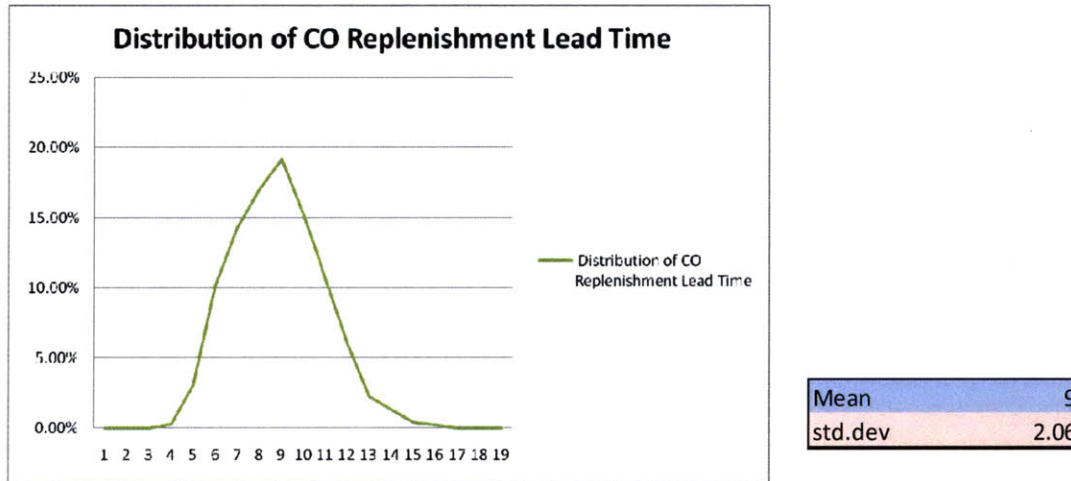


Figure 10. Shows the distribution of CO replenishment lead times is normally distributed with a mean of 9 days.

5.2 Safety Stock Positioning and Deployment Strategy

Visual control of inventory will help the VR supervisor determine their ability to fulfill upcoming demand. We recommend setting up a safety stock level at CO (Section 5.3) in order to fulfill local demand at the Rocky mountain basin (CA, ND). Used tools that enter CO facility to be reconditioned will first be used to replenish the CO safety stock level. Once the safety stock level at CO is filled, the remaining tools will be transported to OK to be staged as inventory to fulfill the postponement strategy.

5.3 Calculation of Safety Stock Required

Based on the level of demand required, we calculated the total capital inventory required in the system and safety stock level at CO using the Silver et al (1988) methodology of a continuous review, order-up-to-level system $S = x_L + k\sigma_L$. (Where S = Total capital inventory required, x_L is demand for normal orders and call outs over the lead-time, and $k\sigma_L$ is the safety stock level.) The same formula was used to calculate both the safety stock level at CO and the total capital inventory required in the system. We used the average replenishment lead time of 9 days. We did not consider a review period, since used tools could return from the field at any time. Although the replenishment L/T is variable with an average of 9 days and a standard deviation of 2 days, we found it was adequate to calculate σ_L using a L/T of 9 days since the inventory flows around a closed loop and self-adjusts with (+) variances cancelled by (-) variances as long as L/T is normally distributed and the MTC capacity level did not constrain the replenishment rate.

6. Results & Discussion - Part II: Modeling Inventory Flows in a Postponement System

What level of capital inventory is required to support the closed-loop replenishment system for VR tools? What will be the Item Fill Rate (IFR)? What should the capacity be at the MTC facility in CO?

Table 14 shows the calculation of safety stock levels required in CO per Silver et al (1988) and in the total network in order to support the level of demand in the base, low and high scenarios. The full calculation for the baseline scenario per method described in Section 2.3 & 5.3 is illustrated in Table 15

In the base scenario, in order to maintain a 95% item fill rate, there needs to be at least 91 VarioRams available in the network. An adjustment has to be made for VRs taken out of the network for “failures” and “down for parts (DFPs).” Assuming 6% of VRs are removed from the network due to failures and DFPS, the adjusted VR units needed in the network are $91/(1-6\%) = 96$ units. (Table 14)

The number of VR units required to fill safety stock at CO is equal to $k\sigma_L = 6$ units. That is to say, once CO has 6 VR units in inventory, all the remaining reconditioned VR units will be transferred to OK.

Safety Stock BASE				Adjusted for DFP and Failures (6%)
CASE	CO	OK	Combined	
90% Item Fill Rate	5	7	8	
95% Item Fill Rate	6	10	11	
98% Item Fill Rate	8	13	14	
Order Up-to Levels				
90% Item Fill Rate	24	69	88	93
95% Item Fill Rate	25	71	91	96
98% Item Fill Rate	26	74	94	100
Average Demand	2	6	8	
Average Replenishment L/T			9	
Safety Stock Low Case	CO	OK	Combined	Adjusted for DFP and Failures (6%)
90% Item Fill Rate	5	6	7	
95% Item Fill Rate	6	8	9	
98% Item Fill Rate	8	11	12	
Order Up-to Levels				
90% Item Fill Rate	20	52	68	72
95% Item Fill Rate	22	54	70	75
98% Item Fill Rate	23	57	73	78
Average Demand	1	5	6	
Average Replenishment L/T			9	
Safety Stock High Case	CO	OK	Combined	Adjusted for DFP and Failures (6%)
90% Item Fill Rate	7	9	9	
95% Item Fill Rate	9	12	13	
98% Item Fill Rate	11	17	18	
Order Up-to Levels				
90% Item Fill Rate	41	116	150	160
95% Item Fill Rate	43	120	155	164
98% Item Fill Rate	45	124	159	170
Average Demand	3	11	14	
Average Replenishment L/T			9	

Legend:
Safety Stock at CO
Total # of VR required
Starting Inventory at CO

Table 14. Calculation of safety stock level at CO and total # of VR required to fulfill the IFR under base, low and high demand scenarios listed in Table 11.

Desired IFR	Base Case	CO	OK	Combined	Adjusted for DFP and Failures (6%)
	Average Demand	1.9	6.1	8.0	
	Std dev	1.32	2.41	2.77	
	$\sigma L+R$	3.97	7.24	8.31	
90%	Gu(k)	0.047	0.085	0.096	
95%	Gu(k)	0.024	0.042	0.048	
98%	Gu(k)	0.009	0.017	0.019	
90%	z	3.05	2.86	2.81	
95%	z	3.27	3.09	3.05	
98%	z	3.54	3.37	3.33	
90%	k	1.28	0.99	0.92	
95%	k	1.59	1.33	1.27	
98%	k	1.96	1.73	1.68	
90%	Capital Inventory Required	24	69	88	93
95%		25	71	91	96
98%		26	74	94	100
90%	safety stock	5	7	8	
95%		6	10	11	
98%		8	13	14	

Legend:
Safety Stock at CO
Total # of VR required
Starting Inventory at CO

Table 15. Shows the calculation of the safety stock and order up to levels for VR units based on the desired IFR

6.1 MTC Capacity Level

We are cognizant of the fact that having excess capacity available 24 hrs / day at the MTC facility is expensive in terms of manpower and equipment. Excess capacity in the plant results in idle workers waiting for tools to arrive from the field to recondition, while too little capacity results in a buildup of dirty tools in CO, which reduces the availability of reconditioned tools to service demand and decreases the item fill rate.

As a heuristic rule, we recommend that capacity at the MTC facility be set at 1 standard deviation above the average demand level of the network. In the base scenario, this would be set at 11 tools / day (Table 16).

Three Scenarios		Normal	Call out	Total	Facility Capacity/day (avg + std dev)
Baseline	Average	6	2	8	11
	Std dev	2.67	1.11	2.87	
Low	Average	4	2	6	8
	Std dev	2.06	0.88	2.41	
High	Average	10	4	14	18
	Std dev	3.34	1.44	3.98	

Table 16. Illustrates the heuristic rule of setting MTC capacity at one standard deviation above average total demand

6.2 Simulation of Daily Inventory Flows in the CO and OK facilities

Based on the safety stock calculations for the base case (Target IFR 95%) as shown in Table 14 and a reconditioning capacity of 11 tools /day we ran a simulation of daily inventory movement over 365 days (Figure 11).

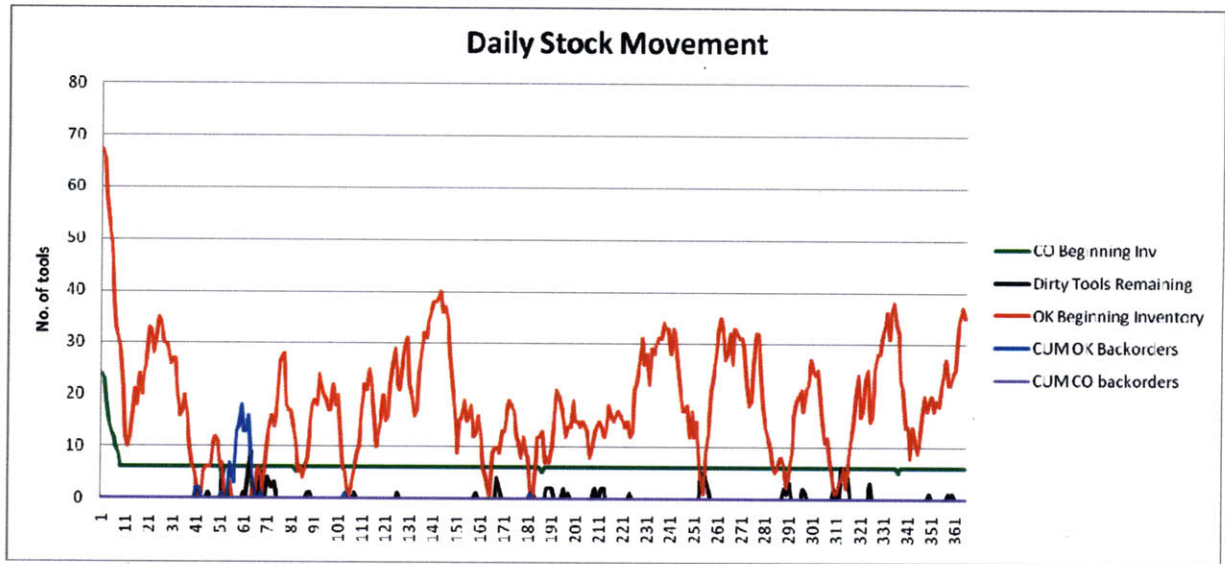


Figure 11. Daily stock movement of VarioRam units in CO and OK under the base scenario

Inventory Performance	CO	OK	Combined System	avg dirty tools remaining	avg OK replenishment	Average OK SS Level > Planned SS level @95%	Average CO SS Level	Average OK SS Level	Avg OK beg Inv	Avg OK backorders	# PD shipped	% Revenue optimized
Actual Cum Item Fill Rate	100%	95%	95%	0.3	5.96	87%	6	24	18	0.33	2918	100%
Actual Item Fill Rate	100%	97%	97%							Total Demand:	2918	
Actual Demand	2	6.08	8									

Table 17 Inventory Key Performance Indicators for a 365 day simulation of the base case scenario

Figure 11 shows the starting inventory at CO of 25 units and OK at 66 units, for a total of 96 units in the network. Over the first 9-11 days, inventory in the hubs deplete rapidly at an average demand rate of 8 tools / day. Dirty tools do not return from the field until about day 9. The facility begins to recondition up to 11 tools / day with the black line in Figure 11 showing the number of dirty tools remaining in the facility at the end of the day

(ie. Days 61-71). The dark blue line from days 51-61 indicate that some backorders occur at the OK facility. If there are stockouts at OK, DTS managers can use their discretion to clear these backorders by shipping tools direct from CO. CO safety stock runs an average of 6 tools /day based on setting the safety stock level at CO at 6 tools, and is stable due to the fact that tools that return from the field are first used to replenish CO safety stocks and any excess tools are transported to OK on the daily milk run. Table 17 shows the inventory performance statistics based on the simulation. In this simulation run, the network has an actual IFR of 97%. On average 0.3 tools /day are not reconditioned on the same day the tool is received and there are 0.33 tools/day on backorder at OK. In total, the number of VR units shipped from the two facilities (2918 units) matches the number demanded over the period (2918 units). Over a fixed period, the average replenishment rate at OK (5.96 tools/day) will *always* lag the average demand rate from OK (6.08 tools/day) reflecting the fact that the rate of demand is the pacemaker in the cycle. It is critical that the MTC capacity be set above the pacemaker or there will be a buildup of dirty tools and inventory will be completely depleted. Figure 12 & Figure 13 show the simulation under the low and high demand scenarios respectively. Using the same methodology to calculate safety stocks as shown in Table 15 and setting the facility capacity per Table 11, we find that the results are consistent with expectations of IFR of at least 95% (Table 18, Table 19). The model behaves robustly over multiple simulation cycles suggesting that the method used to calculate total capital inventory required in the network and the heuristic rule of setting MTC capacity is valid.

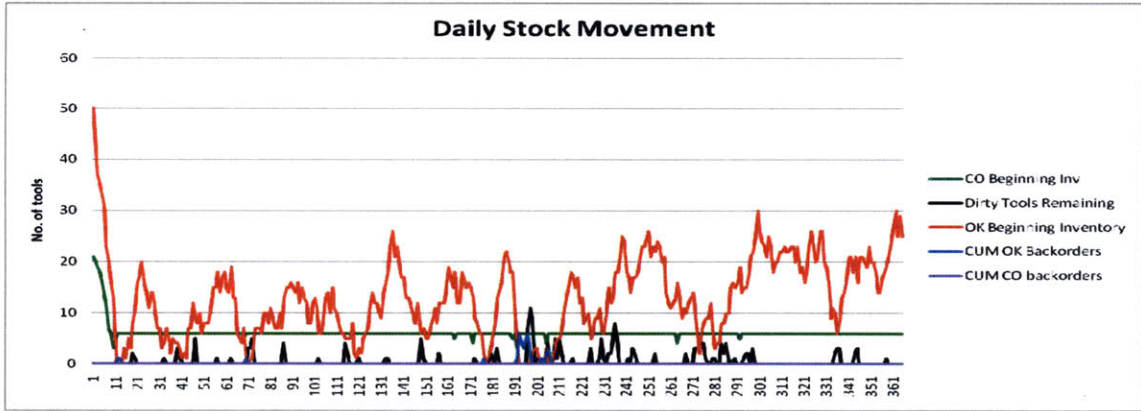


Figure 12. Daily stock movement of VarioRam units in CO and OK under the low scenario

Inventory Performance	Actual Demand and IFR			Inventory Performance Indicators								
	CO	OK	Combined System	avg dirty tools remaining	avg OK replenishment	Average OK SS Level>Planned SS level @95%	Average CO SS Level	Average OK SS Level	Avg OK beg Inv	Avg OK backorders	# PD shipped	% Revenue optimized
Actual Cum Item Fill Rate	100%	96%	96%	0.5	4.44	91%	6	17	13	0.10	2190	100%
Actual Item Fill Rate	100%	97%	97%							Total Demand:	2190	
Actual Demand	1	4.55	6									

Table 18. Inventory Key Performance Indicators for a 365 day simulation of the low scenario

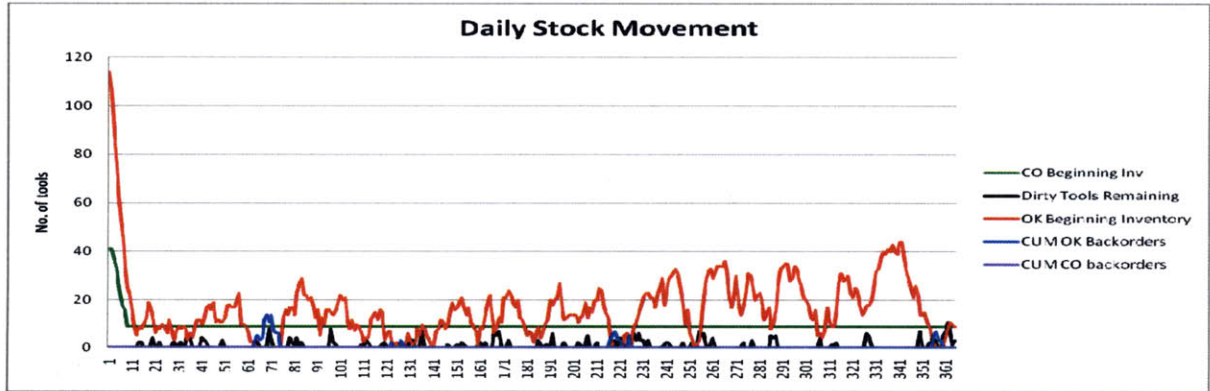


Figure 13. Daily stock movement of VarioRam units in CO and OK under the high scenario

Inventory Performance	Actual Demand and IFR			Inventory Performance Indicators								
	CO	OK	Combined System	avg dirty tools remaining	avg OK replenishment	Average OK SS Level>Planned SS level @95%	Average CO SS Level	Average OK SS Level	Avg OK beg Inv	Avg OK backorders	# PD shipped	% Revenue optimized
Actual Cum Item Fill Rate	100%	93%	93%	0.9	10.61	97%	9	27	16	0.38	5301	100%
Actual Item Fill Rate	100%	96%	96%							Total Demand:	5301	
Actual Demand	4	10.92	15									

Table 19. Inventory Key Performance Indicators for a 365 day simulation of the high scenario

6.21 Sensitivity Analysis – Reducing replenishment Lead Times allows increased revenue

With more reliable deliveries to the field, there is an opportunity for DTS to reduce the waiting time at site from an average of 36 hours and a std. deviation 12 hrs to an average of 6 hrs and a std. deviation of 3 hrs. This would reduce the average replenishment lead time from 9 days to 7 days. The impact is that total inventory required in the network can be reduced from 96 units to 79 units (18% reduction) as shown in Figure 14 below. Alternatively, with 96 VR units, and a reduction in L/T by 1 day, DTS can cater to increased demand of two units /day which results in increased revenue.

Safety Stock Required	Combined (Adjusted for 6% DFP/Failure)			Safety Stock Required L/T 7 days	Combined (Adjusted for 6% DFP/Failure)		
	CO	OK			CO	OK	
90% IFR	5	7	8	90% IFR	4	6	7
95% IFR	6	10	11	95% IFR	5	9	10
98% IFR	8	13	14	98% IFR	7	12	13
Order Up-to Levels				Order Up-to Levels			
90% IFR	24	69	93	90% IFR	19	55	76
95% IFR	25	71	96	95% IFR	21	58	79
98% IFR	26	74	100	98% IFR	22	60	82
Average Demand	2	6	8	Average Demand	2	6	8
Average Replenishment L/T			9	Average Replenishment L/T			7

Figure 14. Reducing replenishment lead times from 9 days to 7 days reduces safety stock required by 18% or allows fulfillment of an extra 2 tools / day of demand

6.22 Sensitivity Analysis – Inadequate Facility Capacity

Using the base case scenario of 8 VR units demand per day, we restricted the MTC facility capacity to 8 units (Figure 15). As can be seen in Table 20, the IFR drops to 70%. VR units have a demand rate at OK of about 6.01 units /day but can only be replenished at an avg rate of 5.74 units /day. Dirty tools build up at CO as they initially arrive at a quicker rate than they can be reconditioned. The lack of available clean tools increases the number of back orders, as represented by the dark blue line, to approximately 29 units at the end of day 365. This figure matches Table 20, showing there are about 2881 units shipped vs. 2910 units of demand. Without inventory, call-outs cannot be delivered on time.

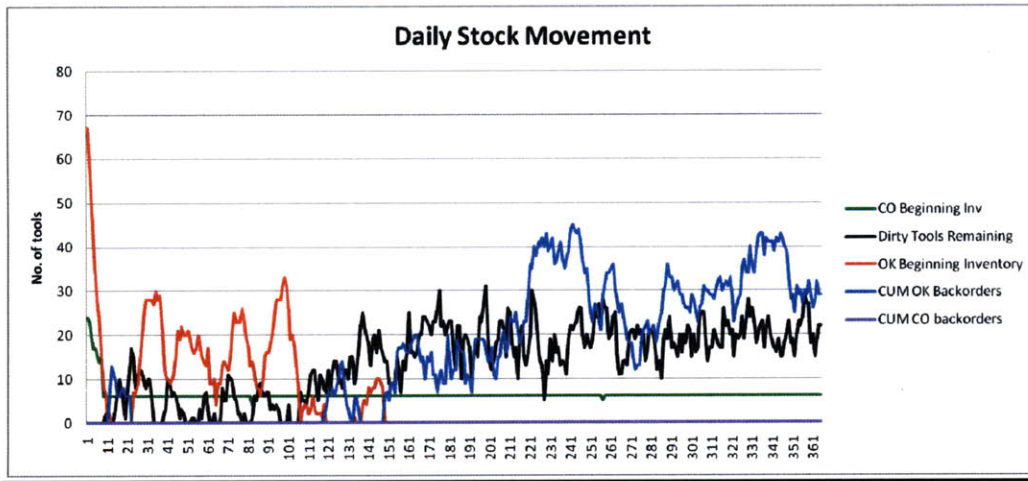


Figure 15. Daily stock movement in base case scenario with MTC capacity restricted to the demand rate

Inventory Performance	Actual Demand and IFR			Inventory Performance Indicators									
	CO	OK	Combined System	avg dirty tools remaining	avg OK replenishment	Average OK SS Level>Planned SS level @95%	Average CO SS Level	Average OK SS Level	Avg OK beg Inv	Avg OK backorders	# PD shipped	% Revenue optimized	
Actual Cum Item Fill Rate	100%	33%	33%	13.9	5.74	27%	6	11	5	16.03	2881	99%	
Actual Item Fill Rate	100%	70%	70%							Total Demand:	2910		
Actual Demand	2	6.01	8										

Table 20. Inventory Performance Statistics for Base case with MTC capacity restricted to the demand rate

6.23 Sensitivity Analysis – Inadequate VR capital inventory in the network

Figure 16 shows the result of having too few VR units in the network. Based on our safety stock calculations for the base scenario, we were required to have 96 units of VR in the network; however, we restricted the number of tools to 80 VR units. As a result of not having enough units, the IFR drops to 56% and results in about 90 units of backorders at OK by the end of the year (Table 21.) MTC facility managers in CO can use, at their discretion, the 6 VR tools in safety stock to reduce backorders at OK. Nevertheless, depleting the safety stock in CO will decrease the IFR in CO.

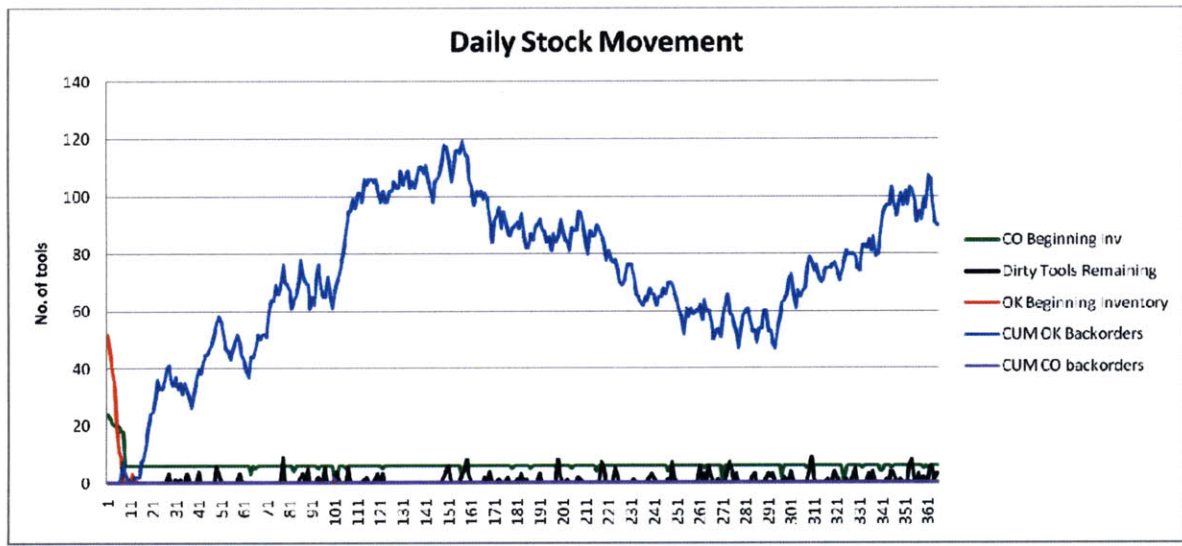


Figure 16. Shows that having too few VR units in the system quickly depletes inventories and increases the # of backorders

Inventory Performance	Actual Demand and IFR			Inventory Performance Indicators									
	CO	OK	Combined System	avg dirty tools remaining	avg OK replenishment	Average OK SS Level > Plan level @95%	Average CO SS Level	Average OK SS Level	Avg OK beg Inv	Avg OK backorders	# PD shipped	% Revenue optimized	
Actual Cum Item Fill Rate	100%	2%	2%	0.8	5.58	5%	6	6	1	71.61	2787	97%	
Actual Item Fill Rate	100%	56%	56%							Total Demand:	2877		
Actual Demand	2	5.95	8										

Table 21. Inventory performance degrades without having adequate VR units in the network.

6.24 Sensitivity Analysis – Excess VR units in the Network

Under the base scenario (demand of 8 units / day), the calculated number of VR required to fulfill a 95% IFR is 96 units. We increased the number of VR units available to 125 units to see the impact on inventory movement and IFR (Figure 17). We found that there would be no stock outs (Table 22), and DTS could also reduce the MTC capacity to about 9 units a day, rather than the recommended 11 units/day, illustrating the tradeoffs between excess inventory and a slower rate of reconditioning VR units.

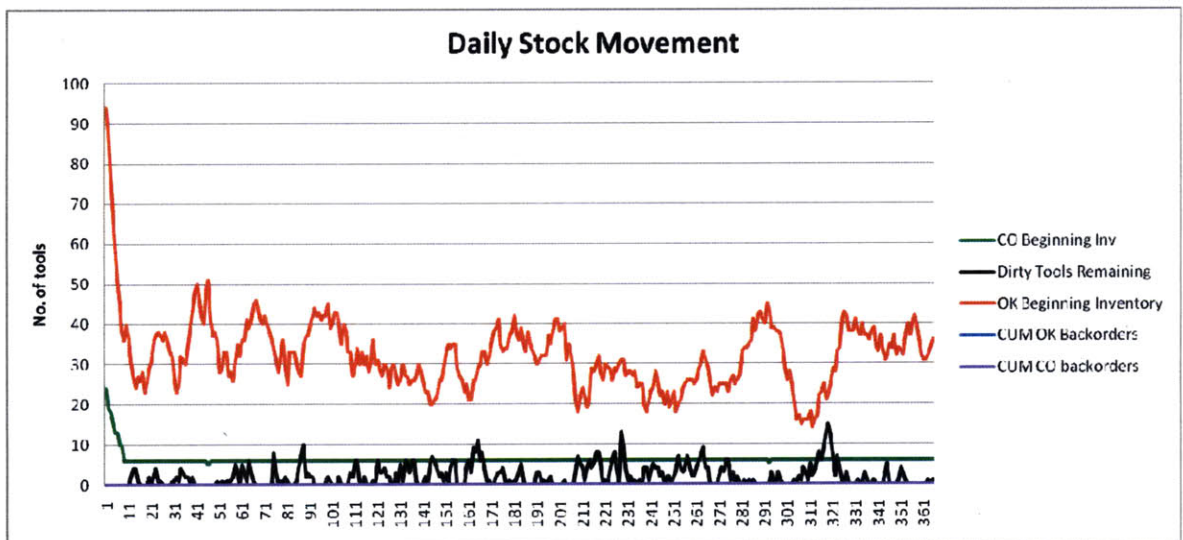


Figure 17 Shows that with more VR units than required, there are no stockouts

Inventory Performance	Actual Demand and IFR			Inventory Performance Indicators									
	CO	OK	Combined System	avg dirty tools remaining	avg OK replenishment	Average OK SS Level > Plan level @95%	Average CO SS Level	Average OK SS Level	Avg OK beg Inv	Avg OK backorders	# PD shipped	% Revenue optimized	
Actual Cum Item Fill Rate	100%	100%	100%	2.0	6.14	100%	6	38	32	0.00	2976	100%	
Actual Item Fill Rate	100%	100%	100%							Total Demand:	2976		
Actual Demand	2	6.27	8										

Table 22. Shows an IFR of 100% when there are more VR units than required in the network

7. CONCLUSIONS

The consolidation of MTC to a single facility in Colorado allows for increased plant efficiencies and quality in the reconditioning process. One major downside is the longer transportation lead times from CO to customer districts traditionally served by the OK facility. We have determined that even with sufficient capital inventory and capacity at the plant, a direct point-to-point strategy from CO to customer districts would result in over 40% of call-out orders arriving late due to the long transportation lead times.

A hub and spoke logistic strategy would result in increased cost efficiencies of 11% in transportation vs. a direct strategy due to the consolidation of tools transported between CO and OK on a single truck. Unfortunately, this strategy does not solve the inherent lengthy transportation lead times in the network and will still result in 74% of call-out demand arriving after 24 hours.

A postponement strategy, in the author's opinion, represents the best of both worlds. Tools returning from the field will be reconditioned at CO. A truck will be scheduled daily to transport clean tools from CO to OK. At OK, the truck will load dirty tools that were returned from the field and transport these tools back to CO. The clean tools arriving in OK will be staged in inventory and configured when a job is received, a process that takes up to 4 hours. We estimate that with inventory calculated using an order up to level, 95% of call-out jobs can be delivered in less than 24 hours. This represents on-time delivery to all districts, with the exception of WV, which we estimate to take about 25 hours. We believe that through "kaizen," DTS will be able to reduce the configuration and loading time of the tools to under 4 hours, allowing on time deliveries to WV. A postponement strategy is also associated with the lowest logistics costs. As

inventory is staged closer to customer demand, fewer call-out jobs will require using team drivers to expedite delivery. Assuming an average demand of 8 tools a day and 30% call-outs, the postponement method results in a total logistics savings of about \$2.7M/ yr or 28% over the direct method and 11% over a hub and spoke network. These savings, however, have to be factored against the increased operational cost at OK to configure tools, load trucks and store both tools and service parts. As DTS is a service-oriented organization, we believe that the justification for utilizing a postponement strategy lies on the ability to deliver tools within a 24 hour window rather than the cost savings involved.

In order to ensure that DTS is able to deliver a high service level, as defined by the item fill rate, availability of reconditioned tools staged in inventory is paramount. Operational managers at DTS have two levers of control affecting the availability of tools. The first is the number of tools in the network and the second is the daily capacity of the MTC facility to recondition VR tools. DTS has to manage both these levers carefully since investing in more capital inventory is costly and decreases the firm's Return on Capital Employed (ROCE), while too much plant capacity results in increased labor costs, capital equipment and idle capacity.

We utilized a continuous review order up to "S" inventory policy ($S = x_L + k\sigma_L$ where x_L is the demand over the lead time and $k\sigma_L$ is the safety stock level) to calculate total number of units required in the network and the max level of safety stock required in CO. Once safety stock levels in CO are filled, overflow inventory is staged at OK. As a heuristic rule, we recommend that MTC capacity be set at one standard deviation above average demand in order to allow a quick turnaround of reconditioned tools and

replenishment of inventory at OK. A simulation created in Excel ® modeling the behavior of inventory flows, back orders, and dirty tools over a year suggests that this methodology is valid and robust over a wide range of scenarios and delivers an IFR consistent with the target. The simulation tool also allows DTS to diagnose problems in their network by either adjusting the two levers of control or shaping demand coming from the field by selectively reducing the number of jobs bid on when safety stocks are low.

Our research shows that a postponement strategy supported by calculated safety stocks and an MTC capacity of $(\mu_{\text{demand}} + \sigma_{\text{demand}})$ allows DTS to achieve the project charter of delivering configured tools within 24 hours to customer sites while rationalizing logistics cost.

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