Distribution Network Modeling and Optimization for Rapid and Cost-Effective Deployment of Oilfield Drilling Equipment

by

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ABSTRACT

AAA, a large oil and gas field services company, is in the business of providing drilling services to companies that extract and market hydrocarbons. One of the key success factors in this industry is the ability to provide comprehensive drilling solutions on short notice and in demanding conditions; fast and reliable delivery of drilling equipment to well sites is critical to maintaining customer satisfaction and market share. The company is considering a reconfiguration of its tool distribution network in order to facilitate a more rapid and cost-effective delivery of drilling tools to drilling sites. Specifically, the company is considering using either a "pure" hub-and-spoke distribution setup, with one of its major facilities – OK – serving as a logistics hub, or a hub-and-spoke system with postponement capabilities, whereby the OK facility will also have certain assembly and configuration capabilities.

This thesis develops a model of the AAA distribution network and creates a simulation of the flow of drilling tools through the two alternative network configurations. As customer service levels and logistics costs are evaluated under various levels of end-user demand, both network setups are shown to increase the effectiveness and cost-efficiency of tool deliveries. The key finding is that the hub-and-spoke with postponement design appears to be superior in terms of logistics costs and timely deliveries.

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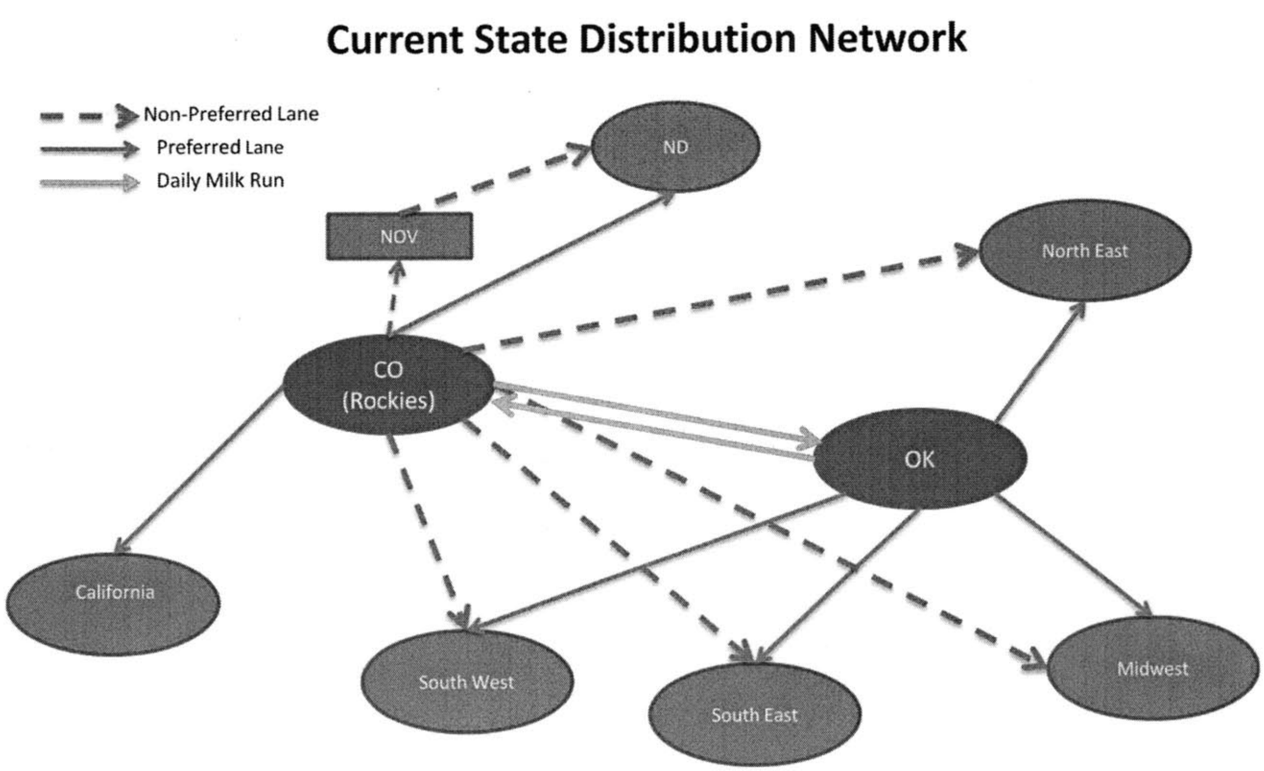
1 INTRODUCTION

1.1 Motivation for a Thesis

XXX (AAA), an oil and gas field services company, is considering consolidating its tool repair and maintenance operations in the US, and is seeking to understand what effect such consolidation may have on:

1. The service levels it provides to its customers
2. The overall cost of logistic deployment of drilling equipment

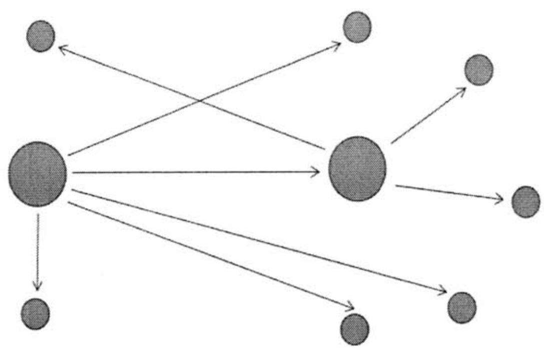
The company also wishes to know how to reconfigure its existing distribution network to ensure timely and consistent deliveries of drilling equipment to its clients across the US. The diagram below shows the current state of the AAA network.



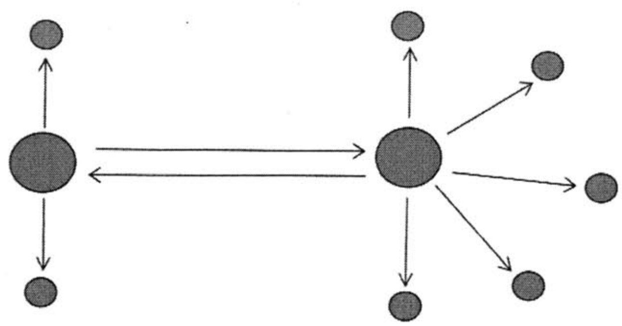
The two nodes in the middle of the network– XXX City (CO) and XXX City (OK) – are a maintenance center and a logistics hub, respectively. The nodes surrounding the two central ones are districts (basins) where end-user demand originates. At present, the CO facility is a full service maintenance center, meaning it has the capabilities to accept tools coming from the field, tear them down, clean them, perform inspection and repair, reassemble them, and do final configuration on equipment to be sent out to drilling rigs. The OK facility is currently a logistics hub; however, it can potentially be converted to a location with certain maintenance capabilities. The two locations provide tool delivery service to rigs that are closest to them by using the so-called preferred transportation lanes. Oftentimes, however, the right type of drilling equipment may not be available at the location closest to the rig, and an order gets filled from the other facility, via non-preferred lanes, resulting in higher transportation costs and increased lead times.

The senior management of the company has decided to explore the possibility of setting up a hub-and-spoke distribution network, with most tools being processed in CO, moved to OK in bulk, and distributed to end-users from there. Doing so would require establishing a daily "milk run" between the two facilities, designed to move used tools from OK to CO, and reconditioned ones from CO to OK. Since around 80% of end user demand is located closer to the OK facility, it is believed that staging more ready-to-be-used inventory at OK should decrease response time and thus increase service levels.

Essentially, the network will go from using an ad-hoc point-to-point delivery method:



To relying on a hub-and-spoke distribution setup:



Besides decreasing the response time, the hub-and-spoke configuration should help AAA minimize the use of non-preferred transportation lanes and reduce overall logistics costs.

This thesis explores the possibility of reconfiguring the AAA distribution network by:

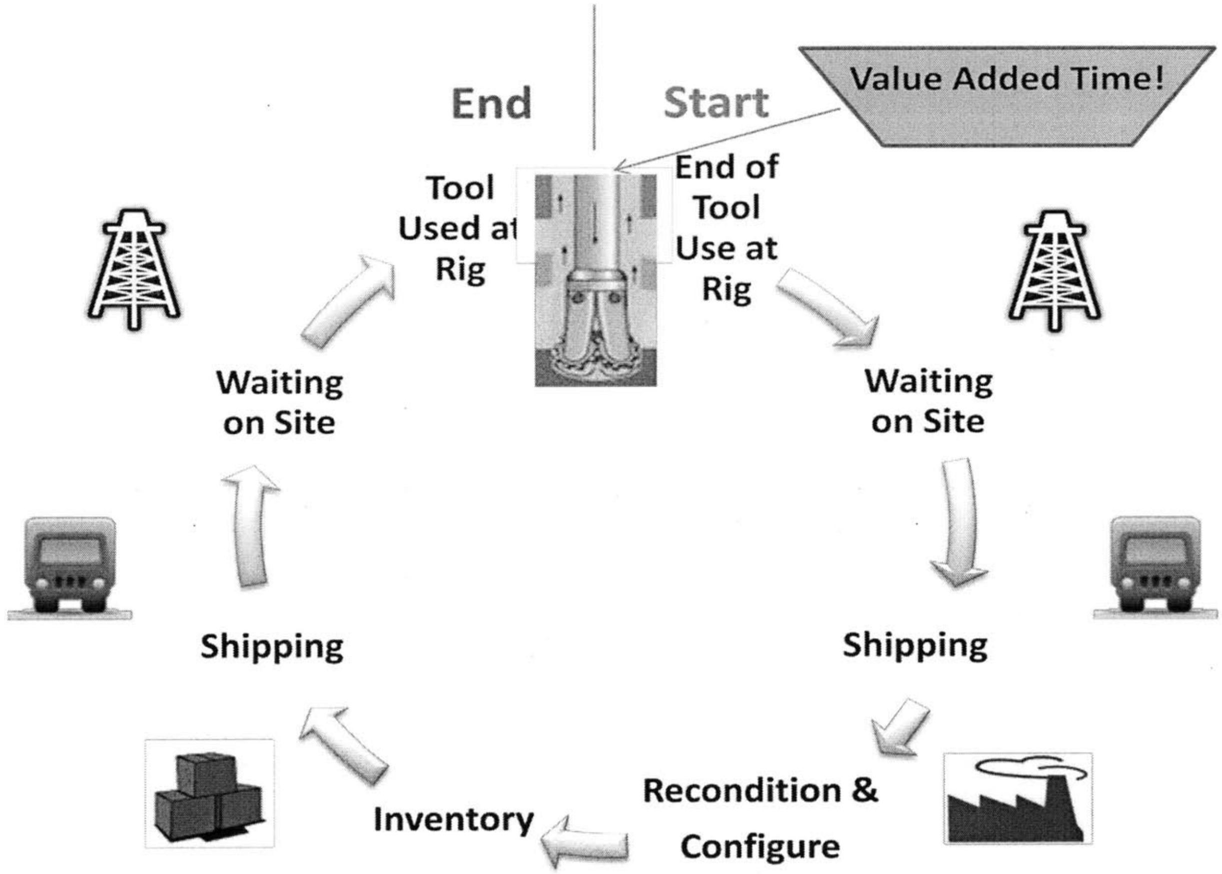
a) Creating a Microsoft Excel-based model of the system
b) Simulating end-user demand
c) Estimating service levels that AAA can deliver to its clients under various demand scenarios and resource constraints
d) Providing recommendations as to how to deploy resources, such as tool inventory and maintenance center capacity, in the most effective and cost-efficient manner

1.2 Business Overview

The Oilfield Services strategic business unit (SBU) at AAA provides equipment and services necessary for oil and gas well drilling and measurements. AAA's clients are oil and gas exploration companies that extract oil and gas from various types of land formation. The SBU's role is to provide drilling services, which include the use of drilling equipment owned by AAA. The XXX and XXX (C&N) segment of Oilfield Services provides directional drilling, measurement while drilling and logging while drilling services.

According to Hoover's, Inc. research, drilling a well entails creating a hole in the ground by using a drill "bit" attached to a rotating drill "string," that is made up of drill pipe (metal, hollow pipe). Specially formulated fluid is pumped into the wellbore to carry cuttings to the surface. Periodically, the drill pipe is removed from the drilled hole ("tripped out") and a pipe of a larger diameter – "casing" is cemented in place to prevent the walls of the wellbore from collapsing. After drilling is finished, a well is prepared for production in a process known as "well completion." The casing is perforated at the necessary depth to allow oil and/or gas to flow up the well. Contracts for drilling typically spell out prices in terms of a "dayrate." Multi-well drilling contracts typically have fixed dayrates, while the rates for a single well change according to market supply and demand situation. High demand can push dayrates above $15,000. Also, some contracts are priced on a combination of dayrate and "footage" – how deep a well is expected to be. The C&N business provides the drilling services only, while other segments of AAA offer a full range of related services.

The following graphic contains a visual representation of a generic cycle that every drilling tool goes through.



After drilling is finished or if a tool breaks down, it is extracted from the wellbore and stored at the job site. When a truck arrives, the tool is loaded onto it and transported to a maintenance center. At the center, the tool is torn down, cleaned, reassembled and configured to the specifications of the next job. After that, there may be a period of time when the tool resides in inventory, waiting for deployment. It is then transported to the next job site and may spend some time there before it is lowered into the wellbore.

Since drilling is the only activity that actually generates revenues for the C&N business – the "tool in hole" time that clients are billed for, the objective is to understand how long it takes to perform all of these activities, what the variability is for every stage of the cycle, and then attempt to reduce the overall cycle time. As the total duration of this "replenishment cycle" shortens, more tool inventory becomes available for deployment thus increasing customer service levels.

AAA receives two types of orders for drilling services – "planned" and "call out." A planned order is an order that is submitted by a field service manager several days to several weeks in advance of when drilling services are to be provided. A call out order is an order that needs to be filled right away. It can be submitted by a drilling operation already in progress (e.g. when the primary drilling tool breaks down), or it can come in from a new customer. Since customer service is a key factor in maintaining and gaining market share in the oil and gas services industry, the way AAA handles call out orders, which make up 29% of all orders, is of utmost importance. It is critical that tools are delivered to ongoing jobs in a timely manner, as there are tangible and intangible costs associated with tardiness.

1.3 Thesis Structure

Chapters 1 and 2 provide an overview of the thesis; Chapter 3 outlines the analytical approach used to model the AAA distribution network and simulate demand levels, followed by Chapter 4, which contains an analysis of relevant historical data, such as demand levels and on-time delivery statistics. Chapter 5 goes over the modeling logic in some detail, and Chapter 6 contains an analysis of network effectiveness and efficiency under different configurations. Chapter 7 presents an analysis of how changes to key modeling inputs affect the levels of key performance indicators, and Chapter 8 goes over the annual logistics spend estimates. Chapter 9 builds on the previous chapters and describes the results of scenario analysis, whereby the effects of various demand levels on the company's key performance metrics are explored. Finally, Chapter 10 presents conclusions and recommendations.

1.4 Key Terms and Definitions

The following terms are used throughout the thesis:

Service levels—a) Average on-time deliveries: percentage of orders that are shipped out on-time for a calendar year, with call outs having to go out within 24 hours of being received. For modeling purposes, if a repair and maintenance center is unable to ship out a call out order within 24 hours, such order is considered delayed, thus reducing the service level. As an example, if 1,000 orders were received in a given year and 950 of them were filled on-time, the average service level for the year is 95%. **b) Lowest level of on-time deliveries (lowest service level):** records the lowest level of on-time shipments during a year, on a monthly basis. For instance, if during January 80 out of 100 orders were shipped out on-time, and all shipments thereafter have been perfect, the lowest service level is 80% (with average service level for the year being around 99%). Of course, maintaining the lowest service level above a certain threshhold is much more demanding in terms of resources committed.

Lost Sales – percentage of orders that AAA cannot fill due to insufficient tool inventory or maintenance center capacity constraints. It should be noted that there may be monetary costs associated with lost business opportunities, as well as damage to the AAA reputation in the market.

XXX (MD) – a family of drilling tools considered for this thesis.

XXX (FS) – another type of drilling equipment under consideration.

Job – a drilling operation that may last several days or weeks and use more than one kind of drilling equipment.

"Dirty" tool – a tool that was used for drilling and is coming back to a repair and maintenance facility. All "dirty" tools are torn down, cleaned, inspected, repaired and reassembled.

"Used" tool – a piece of equipment that is damaged or is otherwise not in a working condition. All "used" tools on the shop floor are marked with red stickers.

"Ready" tool – a tool that has been inspected and is ready to be deployed. All "ready" tools on the shop floor at the repair and maintenance facility are marked with green stickers.

Hot shot delivery – delivery that uses team drivers, so that the truck can go to a destination non-stop. This mode of delivery is used to fill call out orders from rigs that are outside of the 11-hour driving range. According to the Department of Transportation regulations, a single driver can only drive for 11 hours, after which they must rest for 10 hours.

Field Service Manager (FSM) – a person overseeing and coordinating drilling activities at a drilling site

Rigging up – the process of getting the equipment ready for drilling.

Standby time – the total time a tool spends at the well site before it is lowered into the well bore. This metric includes time to rig up and idle time at site.

Tripping out – the process of extracting a drilling tool from the well bore. It can take up to 24 hours, depending on the depth the tool is operating at.

Down For Parts (DFP) – a drilling tool that is not in circulation due to lack of certain spare parts. DFP is measured as a percentage of all drilling tools on AAA books. A high percentage is common when there is a shortage of spare parts.

Failed tool – a tool that is out of order

Drilling Mud – liquid that is used to remove cuttings from the wellbore, cool the drill bit and maintain stability of the wellbore walls.

Backup tool – a tool, with a configuration identical to the primary tool, that is located either at the job site or in close vicinity of the site. The backup is used if the primary drill malfunctions.

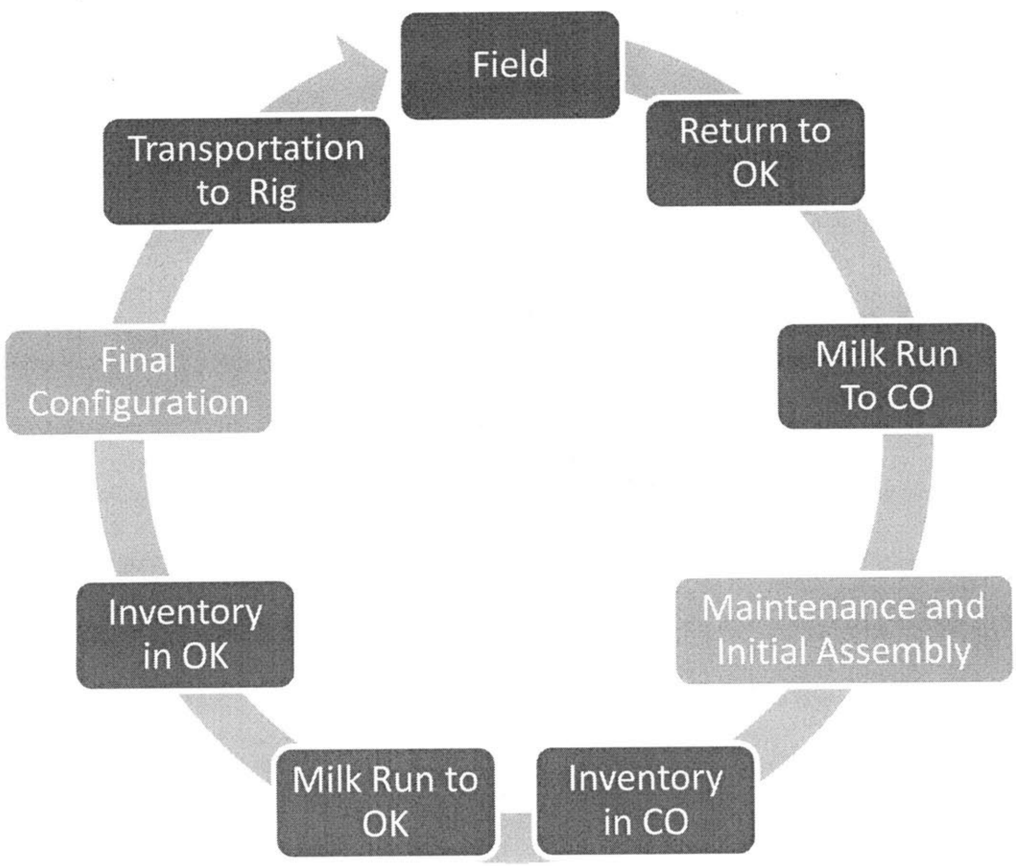
Basin – a district where there is a cluster of drilling sites. The basins considered for this project are: South West, South East, Rockies, Midwest, and North East.

2 METHODS

2.1 Approach

The objective is to create an Excel-based analytical tool which allows AAA to perform an analysis of effectiveness and efficiency of its tool processing & distribution network. Given a set of inputs and constraints, the model simulates the performance of the system over a period of one year and calculates the service level as well as the total amount spent on logistic deployment. It enables the user to gain a better understanding of which delivery network configuration is superior under a given set of assumptions. Specifically, a pure hub-and-spoke and a hub-and-spoke with postponement capabilities in OK are evaluated.

Activities modeled: The model traces the flow of drilling tools through the entire replenishment cycle, as depicted below.



The output is a set of key performance metrics:

1. Average service level for a calendar year
2. Lowest service level for one year, on a monthly basis
3. Percentage of lost sales
4. Logistics spend

While the output numbers are for a one year term, the model runs the simulation for a period of 40 years, and then averages the results; such average estimates are a lot more stable and representative than results from a run for a single year.

Key inputs are

1. Demand level and volatility
2. Number of drilling tools in circulation, based on DFP %
3. Capacity (throughput) of the maintenance facility in CO
4. Daily capacity of the milk run service at the negotiated rate
5. Final assembly and configuration capacity at OK
6. Delivery rates for different truck types and destinations
7. Rig standby time: average, standard deviation
8. Rig wait time for pick up: average, standard deviation

All inputs can be varied to assess their effect on key performance metrics.

2.2 Structure

The model simulates the following activities:

1. Demand levels – planned and call out across five basins
2. Transportation to and from rigs, cost and lead time
3. Rig standby time, duration
4. Drilling, duration
5. Wait time for pickup
6. Daily milk run between CO and OK
7. The flow of tools through the repair, maintenance and assembly activities
8. Tools inventory levels
9. Likelihood of having the right equipment on hand when tool inventory levels are low

All simulation modules are based on either estimates derived from historical data, or, if such data are not available, on expert opinions of staff at AAA. The model is designed to be fully dynamic, meaning that as more current information becomes available, it can be incorporated into the model quite easily, and the outputs are recomputed automatically.

Key Insights for Modeling

Considering that the system under consideration is an essentially closed one (meaning there are a fixed number of drilling tools that are available at any given point in time), it is possible to model inventory stocks and flows with a high degree of accuracy. With demand driving the flow of drilling tools through the system, a tool is either at a rig, in CO/OK, or in transit. Activities that take place at these three major locations can be further refined as follows:

Field:
Transport to the rig
Waiting on Site
Drilling
Waiting to be picked up
Transport to the mtc. facility
Transport between two hubs

CO
Waiting for a teardown
Teardown
Cleaning
Repair
Assembly
Configuration
Inventory

OK
Inventory
Configuration

Estimates of the duration of these activities are used as inputs for the model to mimic the movement of tools between the field and the two hubs. In addition, the number of tools available for immediate drilling is further constrained by the number of units that are DFP (Down for Parts). With some of the equipment unavailable for deployment, this imposes a constraint on how many jobs AAA can handle at any point in time.

Therefore, the model takes the number of units available for drilling, simulates demand levels at various locations, runs through all the constraints imposed by the capacity of individual elements of the system, allocates tools to points of demand, calculates the cost of delivery, and, finally, determines the service level that can be attained given the constraints. The model allows the user to vary the constraints and thus perform "what if" analysis to better understand the economic and service level effects of relaxing the constraints.

Two Versions of the Model Created

Two models of the AAA logistics and inventory system are developed. The first one treats OK as a pure logistics hub, without any tool configuration capabilities. The second one considers OK a logistics hub with configuration capabilities, where drilling tools are subjected to job-specific final assembly and configuration. This network setup enables a postponement strategy, since a tool can be custom configured in OK, which is closer to most active drilling rigs. The following is a conceptual discussion of anticipated benefits of the two network configurations.

Model 1 – OK is a logistics hub; pure hub-and-spoke configuration

The rationale behind this option is a reduction of logistics spend, achieved through sending tools for planned orders to the hub - OK - first, and then distributing them to individual drilling sites. The key feature of this setup is that all planned orders are assembled and configured in CO, and then shipped to OK, via a daily milk run, to be deployed to job sites. Considering that around 80% of all rigs are closer to OK, this strategy reduces the total amount spent on tool deliveries, assuming a sufficiently high daily demand level. In addition, implementing this strategy may result in better service discipline at the CO facility, as all incoming "dirty" tools need to be processed as quickly as possible and sent to OK via a daily milk run.

On the other hand, implementation of this strategy may lead to higher labor costs, as every tool that is shipped via a milk run to OK needs an extra loading and unloading, compared to the point-to-point delivery model. In addition, utilizing the hub-and-spoke network increases the amount of time it takes to get the tool ready for a shipment to a well site by around 24 hours, which is how long it takes to do a round trip from OK, the site receiving the "dirty" tools, to CO, the repair and maintenance facility. In a high demand situation, AAA would face a tradeoff between using the hub-and-spoke model, which reduces logistics costs, and having a tool out in the field for an extra 24 hours, possibly generating revenues.

Another key feature of this network configuration is that most call out orders will be fulfilled from CO, with delivery trucks going point-to-point and not using the hub in OK. Since call outs must be filled ASAP, with some orders requiring an even shorter lead time, the hub-and-spoke model does not work for these emergency requests, since the driving time between CO and OK is around 11 hours. The extremely time sensitive nature of tool delivery necessitates a rapid configuration and a direct shipment from CO with this type of network.

Model 2 – OK is a logistics hub with configuration capabilities

This model is similar to the first one in using the hub-and-spoke design for all planned orders, but it differs in the way call outs are handled. "Dirty" tools return to OK, they are then delivered to CO via a daily milk run, and they are torn down, cleaned, repaired and assembled at this location. However, final assembly and configuration is not performed at CO; cleaned, repaired and partially assembled tools are returned to OK via a milk run, and become a part of the inventory of tools ready for job-specific final assembly and configuration. Since the logistics hub is now a postponed differentiation center as well, this changes the way call out orders are handled. When there is sufficient inventory of such partially configured tools, a call out order is filled from OK in the following fashion: the techs receive the order and select a tool of the right size from the inventory, then they perform the final mechanical assembly and electronic configuration to prepare the tool for the depth and type of formation it will be operating in. Once that is completed, the team will load the tool onto a truck for a delivery to the well site.

Since OK is closer to most drilling sites than CO, this network configuration enables a faster response time to unexpected orders from the field. It also enables a reduction in total logistics costs, since a significant percentage of call outs are filled from the hub closest to the rigs – OK. The service level, an extremely important metric for AAA, increases as well. On the other hand, implementing this approach requires maintaining service technicians and spare parts at both locations, which leads to increased operating costs.

The following is a summary of expected costs and benefits of the two network configurations:

	Pros	**Cons**
Pure Hub-and-Spoke	Faster deliveries to rigs	Higher labor costs
	Better service discipline in CO	More time spent in transit
	Lower logistics costs	

	Pros	**Cons**
Postponement	Most rapid response to call outs	Higher labor costs
	Lowest logistics costs	Need for staff and inventory in OK
	Enhanced availability of drilling equipment	

Ways to generate management insights from the two models

The two models are used to compare cost performance and service levels delivered by the two alternative network configurations – pure hub-and-spoke (Model 1) and hub-and-spoke with postponement (Model 2). The total amount of logistics spend is also compared to total shipping costs under a hypothetical point-to-point setup, whereby all orders are filled directly out of CO. The next step is to vary demand levels and other variables in the system and analyze what happens to the inventory levels at the two hubs, routes taken by delivery vehicles, costs of shipping and overall service levels AAA is able to provide.

Since future demand levels and patterns are impossible to predict accurately, a scenario planning analysis is carried out to gain an understanding how the two network configurations respond to:

1. Moderate demand – base case scenario
2. Low demand – 25% lower than base case
3. High Demand – 50% to 75% higher than base case

It must be noted that the models created are fully dynamic and allow the user to vary any of the constraints and assumptions and get a sense of how they affect costs and service levels. For instance, increasing the total number of tools available or decreasing the number of tools that are DFP (down for parts) may lead to a certain reduction in logistics costs and possibly an increase in service levels.

2.3 Modeling Logic Flowchart

The following chart presents the logic of the model, using the hub-and-spoke with postponement configuration as an example.

1. Tool in External Cycle (5 – 9 days)

- Shipping
- Standby
- Drilling
- Waiting for pickup
- Shipping back

2. Tool arrives in OK

- Shipping charge calculated

3. Tool moved to CO via a milk run

- Arrives the next day
- Cost of milk run updated

4. Tool in CO

- Tear down and cleaning
    - Enough capacity? – processed and added to inventory
    - Not enough capacity? – not processed and added to backlog
    - Any existing backlog is processed if there is spare capacity
- Inventory updated
    - Cleaned tools added to inventory
- Rockies (local) demand generated
    - Enough inventory AND capacity? – perform final configuration, fill Rockies demand and update inventory
    - Not enough inventory OR capacity? – delay order, add to backlog, update service level
    - Any existing backlog is processed if there is inventory and spare capacity
- Fully configured tools shipped to Rockies, shipping charges calculated (regular or hot shot)

5. Cleaned, partially assembled tools moved to OK via a milk run

- Arrives the next day
- Cost of milk run updated

6. Tool in OKC

- Added to beginning inventory
- Planned and Call Out demand generated
    - Enough inventory AND capacity? – perform final configuration , fill demand and update inventory
    - Not enough inventory OR capacity? – delay order, add to backlog, update service level
    - Any existing backlog is processed if there is inventory and spare capacity
- Fully configured tools shipped to rigs, shipping charges calculated (which basin, regular or hot shot delivery)

7. Tool back in the External Cycle (Step 1)

3 DATA ANALYSIS

3.1.1 Central Tendencies and Variability

The following is a discussion of relevant summary statistics, which have been computed based on 20 months of historical demand data (08/2008 – 03/2010), with commentary on how they affect the cost and benefit dynamics of the system.

Calendar days with non-zero demand – 80%

Average # of units demanded per day on non-zero demand days – 3.94 tools

Average demand for all days – 3.17 tools per day

Planned order units shipped – 71% of total

Call out order units shipped – 29% of total

Average shipment size for planned loads – 1.39 tools

Average shipment size for call outs – 1.11 tools

It is apparent that planned shipments are larger, with every third shipment containing more than one tool, and that most - roughly 9 out of 10 - call out orders ask for a delivery of just a single tool. Considering there has been a significant slowdown in the oil and gas drilling industry over the last two years, there is reason to believe that business will pick up. Assuming there is sufficient inventory of drilling tools, the cost savings from a hub-and-spoke distribution model should become more significant, since more tools will be moved between CO and OK via the milk run service.

Over the last two years four MD configurations have accounted for more than 80% of total demand for this family of tools:

Configuration	% of Total Demand	Cumulative %
XXX1	29%	29%
XXX2	19%	48%
XXX3	14%	62%
XXX4	14%	76%

The implication is that if the configurations of tools in inventory are distributed according to historical averages (e.g. 29% of AAA's inventory is XXX1 units), then, given a random call out order, there is roughly a 48% chance that it is going to be for one of the XXX1 and XXX2 models, and a 76% chance of it being one of the four types listed above. Of course, availability of these units has a significant impact on the company's service levels. Therefore, AAA must ensure that:

1. Spare parts for these units are available (to reduce these units from being DFP)
2. Such units are available for rapid final configuration and deployment

3.1.2 On-time Delivery Performance

Whenever an order reaches the maintenance facility, the field service manager and/or directional drilling coordinator enter an estimated ship date and time (hours) for the tools. When determining the estimated ship date and time, they consider the urgency of the order and inventory availability; these estimates are often communicated to clients. Looking at historical data, the actual date and time of shipping can be compared to the estimate to get a sense of how accurate these estimates are and how late, on average, actual shipments are compared to estimated dates/times. It turns out that only 26% of all shipments went out earlier than estimated or on time; 74% were shipped later than estimated. Moreover, there appears to be significant variability in the distribution. The mean "delay" is 20 hours, and the standard deviation is 56 hours. Also, the distribution is skewed to the right – there are far more late shipments then early ones, with the longest delay of 29 days. Since AAA is a service oriented organization and one of its major goals is 95%+ service levels, there is clearly room for improvement.

It is also worth examining whether the estimated vs. actual shipment time performance is worse for call out orders, since such orders arrive unexpectedly and need to be filled ASAP. As might be expected, the performance for planned orders is superior to that for call outs. Specifically, looking at the difference between estimated ship dates and actuals yields:

Planned orders

Early or on-time shipments	**29%**
Shipments later than estimated	**71%**
Mean, days	**0.39**
St. dev	**1.62**

ASAP Orders

Early or on-time shipments	**20%**
Shipments later than estimated	**80%**
Mean, days	**1.63**
St. dev	**3.17**

Considering that many call out orders must be filled within 24 hours, the data indicate that relatively few orders are filled within that window: an average delay of 1.63 days (39 hours) indicates that roughly half of call out orders are shipped later than 39 hours after they are due to go out. The standard deviation of actual vs. estimated performance for call outs is 3.17 days, which shows that many call outs are filled significantly outside of the desired 24-hour window. Based on our conversations with technicians at the maintenance facility, the staff is forced to prioritize jobs on the fly, depending on how urgent a particular order is and what type of tool inventory is available.

It is not uncommon for a tool to break down and stop circulating mud (the fluid used to cool the drill bit and remove the cuttings) in the well bore. If that happens, the pressure inside the wellbore may change and lead to a loss of structural integrity. In such cases, a backup drill is used immediately. However, with the backup drill in the borehole, there is now no extra drill on site. An order for another tool is sent to the hub, and it is essential that a backup unit arrives ASAP. Since the rig is now operating without a backup, should the tool malfunction, the operation at the rig will stop and maintaining the stability of the well may become very challenging. Under such a scenario, AAA must get the backup tool to the rig ASAP. This is why the techs must make sure that such orders are filled ASAP. Needless to say, such ad-hoc prioritization disrupts the workflow and causes other callout orders to be delayed.

3.1.3 Demand Generated by Individual Basins

The geographic distribution of demand is as follows:

Basin	% of Total Demand
South West	33%
South East	28%
Rockies	24%
Midwest	8%
North East	7%

As the data indicates, 24% of all demand originates from Rockies, the district that is closest to CO, where all deliveries are point-to-point. Therefore, the CO facility needs to maintain sufficient inventory levels of drilling tools to satisfy this demand. This is one of the inputs of the model, allowing the user to select an inventory level that optimizes the performance of the system under a given set of constraints.

Furthermore, the historical calls out demand levels for the individual basins are as follows:

Basin	% of Total Demand
Midwest	4%
North East	5%
Rockies	24%
South East	35%
South West	32%

Comparing these statistics to the overall average percentage for call outs of 29% and looking at the previous table, it becomes clear that basins with higher demand levels also generate an above average number of call out jobs. Also the revenue generated by call outs, on a per tool basis, is:

Order Type	Revenue	# of Tools used	Rev per Tool
Call Out	$XXX	560	$XXX
Planned	$XXX	1363	$XXX

It appears that call out jobs generate more revenue than planned ones. Since service levels are of critical importance to AAA, the way it handles call out requests for South West and South East needs to be analyzed very carefully, as it has a significant impact on the top line of the company.

The demand data broken out by basins is summarized as follows:

	Midwest	North East	Rockies	South East	South West
# of days in sample	567	567	567	567	567
# of days with demand	80	70	229	238	272
% of days with demand	14%	12%	40%	42%	48%
Average for days with demand	1.89	1.84	1.86	2.17	2.13
St. dev	1.13	0.85	1.14	1.46	1.47

3.1.4 Drilling

Analysis of tools dispatched to the field indicates that 21% of all tools shipped out return with zero “pumping hours”, meaning that such tools have not been “down hole”. The implication is that roughly a fifth of all units coming back to the hub require less service time than is needed for a tool that was “down hole”. Since it is the company’s policy to thoroughly inspect such tools upon return (as they may have been damaged during shipping or while sitting at the rig), the maintenance turnaround time for such tools is not much shorter than for "dirty' ones.

As far as the 79% of tools that do go "down hole" are concerned, the following are the averages and standard deviations of "below the rotary table hours" – actual hours of operation in the ground:

Basins	Average Below Rotary Table Hours	St. Deviation
Midwest	59.4	38.1
North East	71.6	51.6
Rockies	63.2	35.2
South East	83.1	52.3
South West	82.9	54.4

It is apparent that there is quite a bit of variability in the amount of time the drills spend in the ground. Hence, the actual amount of drilling time for a particular job is essentially unpredictable, and the only way to manage the returns is to dispatch a truck when the field service manager decides to start "tripping the tool out." Depending on the depth the tool is operating at, the trip-out time can take between 12 and 24 hours, which means that in many cases a truck will have enough time to travel from OK to the drilling site and do a pick up shortly after the tool is extracted from the well bore. Effective communication between the field service manager and the logistics group at the hub is essential to reducing the amount of time a tool sits at the rig after being used.

3.1.5 Waiting Times at Rigs

There are two distinct waiting times that matter for our analysis – 1) waiting time before a tool is used – standby time and 2) time a tool spends waiting to be picked up after completion of a job. While no hard data exist to accurately calculate the average time spent waiting at rig, we estimate that:

1. For call out orders, a tool spends a negligible amount of time sitting around. It is critical to have the tool “in hole” for such jobs, and most units are deployed right away. Most of the non-value added time comes from “rigging up” – getting the tool ready to drill. This process takes between 24 and 48 hours
2. For planned orders, a drilling tool may spend more time waiting to be deployed; it may also sit at the site while another piece of equipment necessary to start drilling is being delivered (e.g. MD waiting for FS). The standby time, including set up is estimated to be between 18 and 66 hours
3. Based on interviews with the logistics team, it can sometimes take up to 56 hours for a tool to be picked up after it is taken out of the ground. In general, however, equipment is picked up after about 42 hours after the end of use.

3.1.6 Transportation To and From Well Sites

The following is a list of distances and driving times from OK to the basins that it services:

	Distance	**Driving Time**
XXXX, TX	428	9
XXXX, TX	464	9
XXXX, AR	314	7
XXXX, WV	1,112	21

According to the Department of Transportation regulations, a driver can drive for a maximum of 11 hours, followed by 10 hours for rest. Therefore, the actual lead time to XXXX, WV, assuming a single driver, is 31 hours. It is possible to use team drivers, in which case a truck can go essentially non-stop; it costs between $0.1 and $0.3 extra per mile to use team drivers.

3.1.7 Transportation Between CO and OK –"Milk run"

The distance between the two sites is 686 miles, equivalent to 11 hours of driving time. Therefore, it is possible to use a single driver for a one way trip between the two facilities. According to our research, the cost per mile for a milk run between CO and OK is at least $3.50 per mile, and can be as high as $4.50. Since this rate exceeds the rate per mile that is charged for transporting individual tools from CO to rigs (e.g. $1.67 per mile), more than one tool must be on the milk run truck for the hub-and-spoke configuration to make economic sense. The costs of delivery on a per-tool basis are based on point-to-point shipping rates and distances between CO and the basins that are closer to OK:

Basins	Cities	Distance	Rate from CO	Cost to Deliver
South West	XXX	663	1.67	**$1,106.38**
South East	XXX	1,140	1.67	**$1,902.97**
Midwest	XXX	937	1.67	**$1,565.29**
North East	XXX	1,454	1.67	**$2,428.51**

Logically, for the hub-and-spoke system to enable savings, the total transportation cost per tool (milk run + direct delivery out of OK) must be lower than the appropriate cost to deliver in the table above. Since the total distance traveled increases with the introduction of a hub, the CO to OK leg must cost significantly less on a per tool basis. Intuitively, the more tools are loaded on the milk run truck, the cheaper the total shipping cost per tool is. The following analysis establishes the minimum number of units on the milk run truck for per unit costs to be reduced, assuming the rate per mile for the milk run service of $3.50.

	Tools on Milk Run Truck						
Basin	2	3	4	5	6	7	8
South West	$1,755	$1,355	$1,155	$1,036	$956	$899	$856
South East	$1,802	$1,403	$1,203	$1,083	$1,003	$946	$903
Midwest	$1,606	$1,206	$1,007	$887	$807	$750	$707
North East	$2,644	$2,244	$2,045	$1,925	$1,845	$1,788	$1,745

According to the calculations above, it is less expensive, compared to a direct delivery, to ship a tool to the South West basin only if, on average, there are more than four tools on the milk run truck. If there are fewer than five tools on the truck, the point-to-point method is preferable from the cost standpoint.

Of course, any given milk run shipment is likely to contain tools going to different basins; therefore, the analysis in the table above suggests that, on average, at least three or four tools must be on every milk run trip from CO to OK for the hub-and-spoke model to make economic sense.

3.1.8 Capacity of the CO Maintenance facility

According to our findings, the current repair, assembly and configuration capacity of the CO facility is around 6 tools per day. The management expects the maximum throughput to increase to 12 units per day within the next 12 months. Analysis of the factors affecting these estimates is beyond the scope of this project; hence these limits are used as constraints in our model.

4 PURE HUB-AND-SPOKE AND HUB-AND-SPOKE WITH POSTPONEMENT MODELS

Inventory Modeling

The key insight to modeling inventory stocks and flows at the two facilities – CO and OK is that they represent a "closed system," with essentially a fixed number to tools circulating between the field and the two hubs. The number of tools in circulation is limited by the total number of units on the books and factors reducing tool availability, such as DFP and Lost-in-hole (tools left in the ground). The inventory part of the replenishment cycle acts as a buffer and allows the maintenance facility to achieve a more balanced work load. However, should this buffer become thin due to high demand, the work flow at the maintenance facility can become erratic and much less efficient.

Since the ultimate objective is to reduce the duration and cost of all non-value-adding activities and maximize tool availability, the location and levels of inventory can have a significant impact on achieving that objective. Specifically, staging more inventory closer to the point of actual demand – at OK in this case – should result in better service levels. If such a strategy can also lead to reduced costs, logistics spend in particular, it would lead to a better reputation in the market and an enhanced profitability for AAA.

The model is designed to track the flow and levels of inventory in the system and calculate the costs of delivering drilling equipment to well sites. The inventory module of the model is built to reflect what happens to drilling tools after they come back from the field. A tool enters the inventory part of the model when it returns to OK.

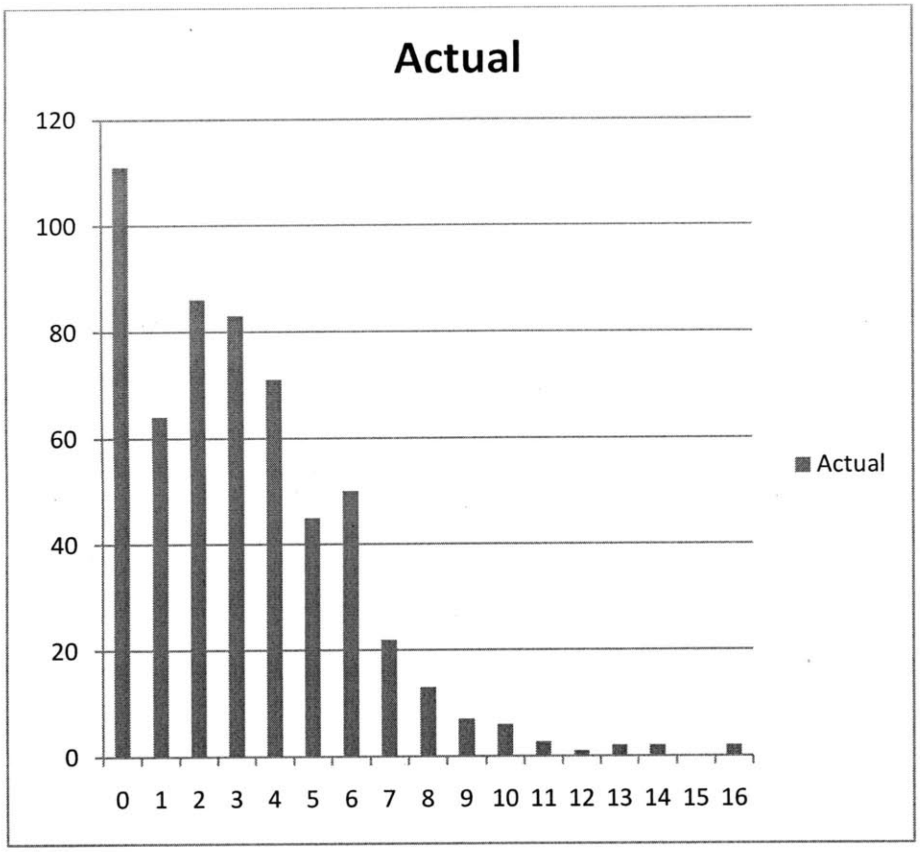
4.1.1 Model 1: Pure Hub-and-spoke

Please see Exhibit 1 in the Appendix for a diagram of steps that a tool goes through, with the pure hub-and-spoke configuration, before it is ready for deployment out of OK. As mentioned before, at the maintenance stage of the cycle (shaded in yellow in the diagram), a tool gets torn down, cleaned, repaired (if necessary), fully assembled and configured to the specs of the next job. A ready-to-be deployed unit is then transported to OK and resides in inventory until shipment date.

4.1.2 Monte Carlo simulation of demand

Objective: Simulate demand by type of order and location.

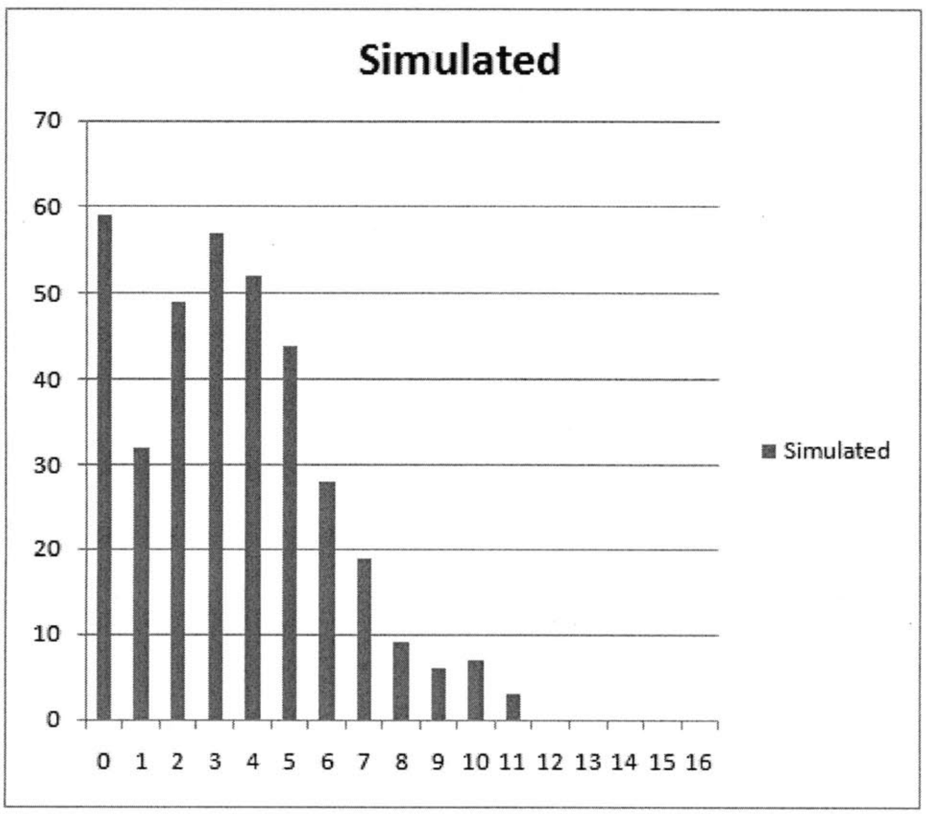
As mentioned previously, while historical demand data is available, it is expected that demand levels will fluctuate going forward, so a Monte Carlo simulation of daily demand is constructed. The Monte Carlo approach (a mathematical technique for simulating demand levels based on a known or assumed probability distribution) is used to generate randomized demand patterns, stress the simulated network and observe its performance. In order to get a sense of the underlying distribution of demand for AAA equipment, the following histogram of daily demand for the last 20 months is created:



Horizontal axis – demand filled per day, vertical axis – frequency of occurrence

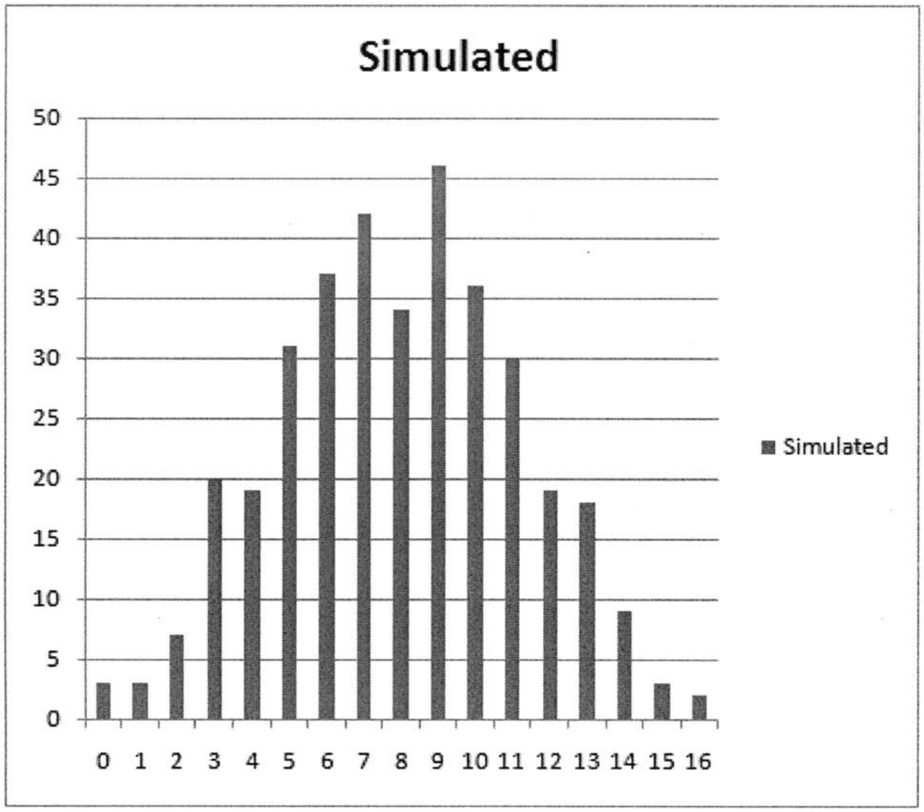
Frequency		%
0	111	**19.58%**
1	64	11.29%
2	86	15.17%
3	83	14.64%
4	71	12.52%
5	45	7.94%
6	50	**8.82%**
7	22	**3.88%**
8	13	**2.29%**
9	7	**1.23%**
10	6	**1.06%**
11	2	**0.35%**
12	1	**0.18%**
13	2	**0.35%**
14	2	**0.35%**
15	0	**0.00%**
16	2	**0.35%**

It is clear that demand distribution at such relatively low levels – around 3.2 tools per day on average – appears to be Poisson distributed. Since there can be no demand below zero tools per day, the distribution has a long right tail. Considering that the mean of the distribution is between 3 and 4, it is worth noting that the sum of probabilities of 6+ tools per day (18.87%) is approximately equal to the probability of having zero demand (19.58%). This means that the simulation may use the Normal distribution with a minimum of zero to sample from to create Monte Carlo trials. The following histogram represents demand simulated with a Normal distribution with mean of 3.2, standard deviation of 2.7, and all negative data points being converted to zero demand. The shape of the distribution appears to be quite similar to what the actual data looks like.



Horizontal axis – demand filled per day, vertical axis – frequency of occurrence

Should demand levels increase, as is currently expected by AAA, the shape of the distribution should become more Normal. At higher demand levels there will be fewer days with zero demand. The following is a histogram generated with a Normal distribution, mean of 8 and a standard deviation of 3.5:



Horizontal axis – demand filled per day, vertical axis – frequency of occurrence

At higher demand levels, the data looks increasingly more Normal; however, as standard deviation of demand goes up as well, there is likely to be a "fat tail" on the left (more zero demand days) and a "long tail" on the right (more days with high number of tools requested). It is the latter that can put the processing and logistics system under strain. Since no historical data for such high and volatile demand levels exist, the model allows the user to simulate the performance of the system under any combination of demand level and volatility. In this sense, a simulation based approach is superior to a static optimization based on historical averages.

With the overall demand simulated as described above, the next task is to split it up into planned and call out, and distribute it along the five basins that demand can originate from. Based on the historical percentage of 29% for call out orders and other empirical estimates as shown below:

	Midwest	North East	Rockies	South East	South West
% of Total Demand	**8%**	**7%**	**24%**	**28%**	**33%**
% of all Call Out Demand	**4%**	**5%**	**24%**	**35%**	**32%**
# of days in sample	567	567	567	567	567
# of days with demand	80	70	229	238	272
% of days with demand	**14%**	**12%**	**40%**	**42%**	**48%**

29% percent of overall demand, on average, is allocated to call outs, with 71% making up planned demand. Then these two demand streams are assigned to individual basins in the following fashion: For planned orders, every basin has a probability of generating an order equal to historical averages:

	% of Total Demand
Midwest	8%
North East	7%
Rockies	24%
South East	28%
South West	33%

A random number between 0 and 100 is generated to assign a basin name to a trial, and a string of basin names produced in this fashion is created. The result is that, on average, 33% of all observations in such a string are South West, in line with empirical data. Then, depending on the level of planned demand, the model cuts the length of the string at the demand level and calculates how many observations there are for each of the five basins. It should be noted that the string is 50 names long, which should be sufficient for all reasonable demand levels. Comparison of actual and simulated data over a two-year period confirms that:

	MCB	NEB	RCB	SEB	SWB
Simulated	8%	8%	24%	27%	34%
Actual	8%	7%	24%	28%	33%

The result is an allocation of the total number of planned orders to individual basins in a randomized fashion. A similar analysis is performed for call out orders. Since the historical percentage allocations for call outs are somewhat different, the simulation takes the estimates below and allocates the total number of call our orders per day accordingly.

	Call out %
Midwest	4%
North East	5%
Rockies	24%
South East	35%
South West	32%

Summary: the Monte Carlo demand simulation generates randomized orders by type – planned and call out, and basin – Midwest, North East, Rockies, South East and South West.

4.1.3 Shipping Lead Times Simulation

Objective: Simulate the shipping lead times for tools traveling from maintenance center to rigs and back. Determine what the standard deviation of such lead times is.

Since the hub-and-spoke configuration assumes that most planned orders will go through the OK hub, and most call outs will be filled out of CO, it is possible to determine how long it takes for a tool to make a round trip. Specifically, call outs, which make up 29% of demand, travel in the following fashion:

CO -> Rig -> OK -> CO

While planned orders make use of the OK hub twice:

CO -> OK -> Rig -> OK - > CO

It should be noted that orders going to the Rockies basin do not use the hub-and-spoke system and go through the following flow: **CO -> Rig -> CO**.

Therefore, considering the breakdown of total demand between basins, driving times and the fact that all call outs are sent out with "hot shot" delivery out of CO, it is possible to calculate how long a tool spends in transit when going to and from a particular basin.

Basin	**% of Total Demand**	**Distance**	**Drive Time, hrs**
South West	33%	428	9
South East	28%	464	9
Rockies	24%	693	11
Midwest	8%	314	7
North East	7%	1,112	31

	Planned, round trip time, hrs	**Call out, round trip time, hrs**
South West	18	18
South East	18	18
Rockies	22	22
Midwest	14	14
North East	62	**52.0**

As the table above indicates, a tool going out to the North East basin via a regular delivery spends, on average, 62 hours on the road (31 hours each way). However, if it travels to the site via a hot shot, the total in-transit time is 52 hours (21 hours there and 31 hours back).

The model simulates a distribution of daily demand by location, as described in the preceding section, and generates shipping times based on level and location of demand. The average travel time and its standard deviation are then computed, based on 1,000 Monte Carlo simulation runs. The average time in transit is between 22 and 23 hours, depending on simulated demand. The standard deviation is between 10 and 11 hours.

Summary: the average in-transit time under the hub-and-spoke configuration is around 23 hours, with the standard deviation being around 11 hours.

4.1.4 Simulation of the "External Cycle"

Objective: to simulate duration of activities that take place outside of the two main facilities and estimate the average and standard deviation of how long a tool is "out in the field." A single simulation trial involves summing up durations of the four stages described below.

The simulation consists of four stages that make up the "external cycle":

a. Shipping
b. Standby at rig
c. Below the rotary table hours
d. Waiting for tool pickup

a. Shipping

As previously discussed, transportation to and from the rig takes on average 23 hours, with a standard deviation of around 11 hours. A simulation based on the Normal distribution with a lower bound of zero is used.

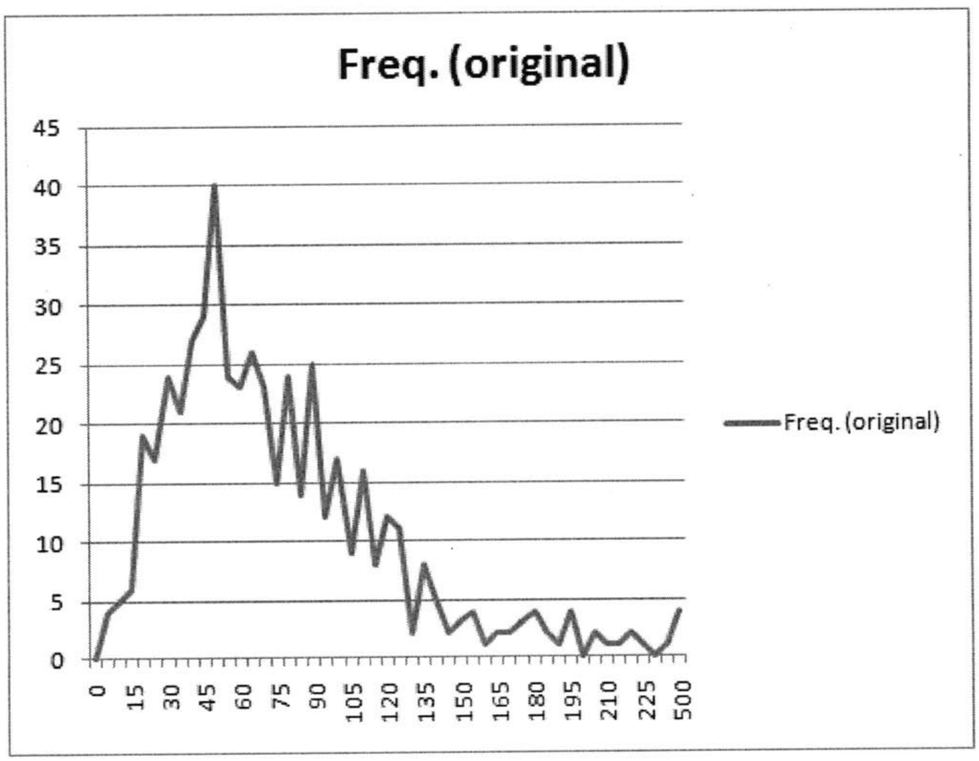
b. Standby at rig

Based on interviews with people in the field, this process takes on average 42 hours, with most rig-ups being completed between 18 and 66 hours. Therefore, a mean of 42 and a standard deviation of 12 hours are used to simulate standby time. The distribution is assumed to be

Normal, and the lower bound of 5 hours is enforced. The logic behind this limit is that it cannot take less than 5 hours to prepare the tool for drilling and lower it into the well bore.

c. Below the rotary table hours

Analysis of historical data indicates that 21% of all tools shipped out return with zero "pumping hours" – revenue generating drilling time. Backup tools that are never used make up a large portion of the 21% tools with zero pumping hours. Tools that do go "down hole" spend the following number of hours "below the rotary table" (time a tool spends in the ground, which includes drilling time and/or circulating mud):



Horizontal axis – number of hours, vertical axis – frequency of occurrence

The histogram of below the rotary table hours for the last 20 months reveals that distribution of below the rotary table hours is definitely not Normal. There are two factors affecting this distribution:

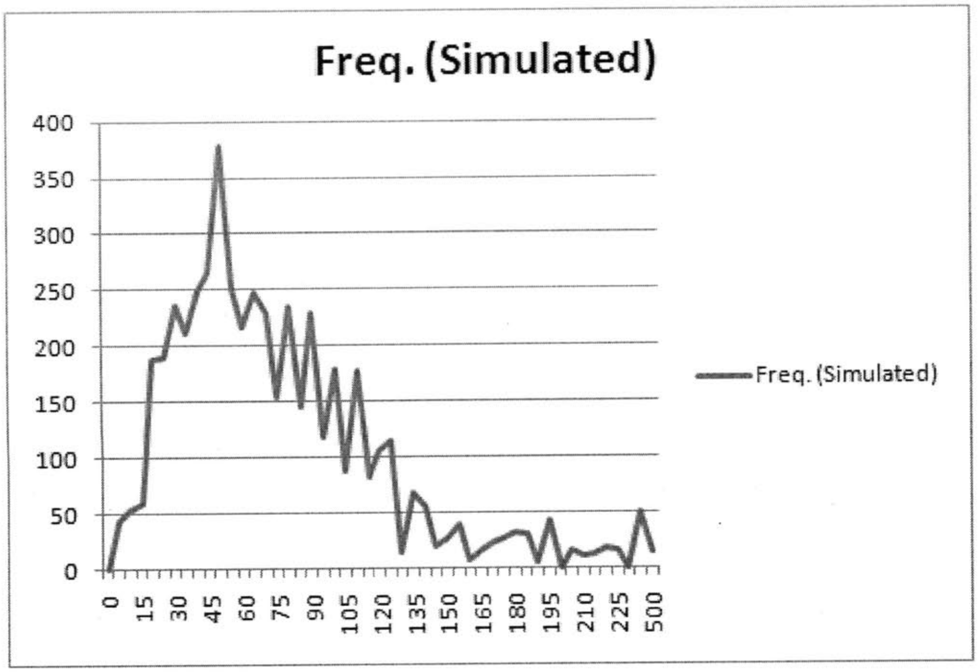
1. Some formations make it more likely that a drilling tool will break down
2. Some clients are known to be rough on equipment and may not follow the suggested operating procedures

All in all, the mean of the data set set is 73 hours and the standard deviation is around 47 hours.

For modeling purposes, it was decided to construct a probability distribution based on actual historical data, and run simulation trials based on such distribution. There are several reasons for doing this:

1. Since locations of oil and gas fields are known and fixed to a large extent, the makeup of formations drilled will be stable going forward, which should result in the distribution of below the rotary table hours to be stable over time as well
2. The amount of time a tool spends "in the hole" in not directly correlated with the level of demand for tools in general
3. AAA has been working with a portfolio of clients, and their FSMs (field service managers) have certain drilling habits and techniques that will not change overnight

Running random numbers through the constructed distribution results in the following set of below the rotary table hours:



Horizontal axis – number of hours, vertical axis – frequency of occurrence

As expected, the simulated distribution mimics the actual data quite closely.

d. Waiting for tool pickup

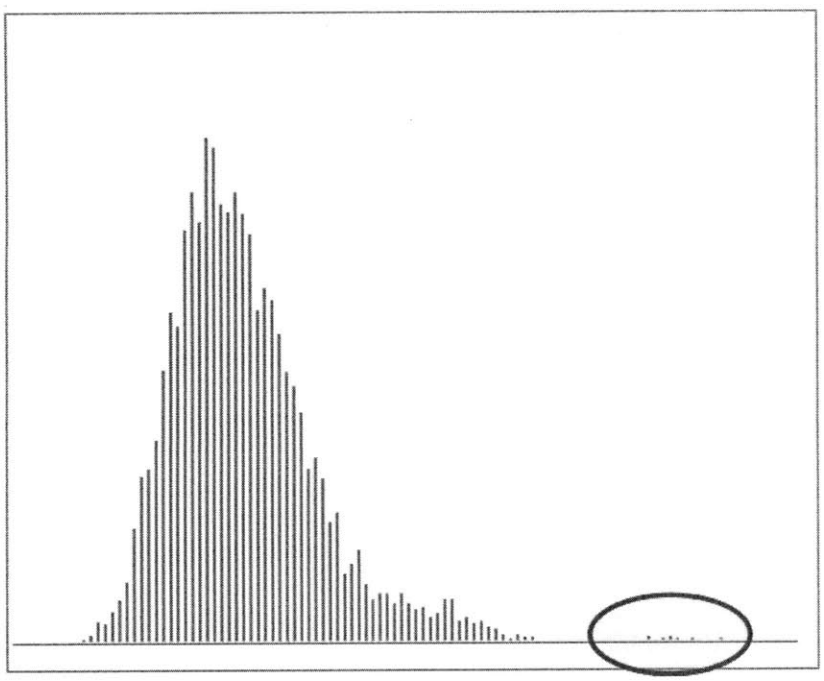
After the end of drilling, a tool generally sits at the well site waiting to be picked up and transported back to the hub. While no hard data exists to calculate measures of central tendency and variability of "waiting for pickup" time, the staff at AAA believes that it takes between 12 and 60 hours for a tool to be packed up. For simulation purposes, an average time of 42 hours is used, with a standard deviation of 12 hours.

The simulated durations of the four stages discussed above are added up to arrive at an estimate of how long a tool is out in the field; this represents one trial. Five thousand runs are done to arrive at the average of the external cycle time and its standard deviation.

	Shipping	Standby Time	Below the Deck	Waiting for pickup
Mean	**21.9**	**42**	**75**	**42**
St. dev	**11.1**	**12**	**48**	**12**

	Simulation				
Count	**Normal**	**Normal, min 5**	**Data-Based**	**Normal**	**Total Cycle Time (hrs)**
1	24.4	47.9	192.5	55.9	320.7
2	15.6	43.7	102.5	44.5	206.3
3	11.8	6.9	37.5	55.7	111.9
4	24.9	51.8	117.5	43.2	237.4
5	32.4	55.7	67.5	51.6	207.3
6	30.3	30.5	27.5	28.0	116.3
7	33.6	43.1	102.5	52.1	231.4
8	33.0	22.6	57.5	67.2	180.3

The shape of resulting distribution of external cycle times is as follows:



The non-Normal nature of the distribution of below the deck hours contributes to the presence of a noticeable right tail for the overall external cycle.

The average length of the external cycle is between 7 and 8 days, with a standard deviation of around 2.1 days. These estimates are essential in determining how long a tool is likely to be out in the field.

Summary: the "external cycle" module simulates all activities that take place out in the field, sums up their individual values, averages them across 5,000 trials, and arrives at an estimate of how long a drilling tool is likely to be in the external part of the replenishment cycle.

4.1.5 Stock and Flow Model of Inventory

Objective: to model the flow of tools through the entire tool replenishment cycle and determine what service levels are achievable under a given set of inputs and constraints

The inventory module is the heart of the model, since it aggregates outputs from all other simulations and traces the flow of tools through the system. Please refer to Exhibit 3 for a snapshot of the inventory flow worksheet.

The model allows the user to enter the amount of MD tools that AAA has on its books, adjusts it based on the current DFP percentage, and calculates the number of units actually available to perform work. This figure initializes beginning inventory level. The beginning inventory is augmented on a daily basis by tools coming from the OK facility via a milk run. The number of tools coming back to the OK facility is determined by how many tools are out in the field, and the average time of the "external cycle" calculated in the simulation.

As an example, let's suppose that 4 tools left the OK facility on day 1. With an external cycle time of, say, 6 days, these tools are likely to return to OK on day 7. Subsequent to that, they will be loaded on the milk run truck and transported to CO, which may take up to another 24 hours. Then, after the tools are processed, they are loaded on the truck again and moved to OK, which takes another 24 hours. Consequently, a tool going out on day 1 is likely to be ready to be shipped out again on day 9. Hence, the total cycle time is 8 days, assuming there is sufficient capacity and long delays along every step of the cycle.

Day 1	Leave OK
Days 2 -7	Field
Day 8	Come back to hub and move to CO
Day 9	Processing and shipping to OK

Of course, reality is much different, and it is not very likely that all 4 tools that went out on the same day are going to come back at the same time. Therefore, the returns of tools from the field must be dispersed in time according to the standard deviation of the duration of the external cycle simulated in Part 5.1.4. In order to accomplish this, a vector of 365 random numbers is created with:

a) a mean of zero

b) standard deviation as calculated in the external cycle simulation

c) a sum of all numbers equal to zero

The intent is to randomize the number of tools coming back to OK on a daily basis. It is necessary to have a set of random numbers with a sum of zero to make sure that inventory at the end of the period is equal to what it was in the beginning. If the sum is anything other than zero, ending inventory levels at the end of the simulated year will be distorted. This randomization is designed to be used for relatively high levels of demand – 7 per day or more –

and the main tab of the spreadsheet contains a dialog box that allows the user to turn this feature on or off.

With the available inventory calculated as described above, the CO facility is then subjected to two types of demand – planned and call out. The levels of such demand are pulled from the demand simulation worksheet, and an analysis is performed to determine whether or not the facility can meet this demand. Two obvious constraints on ability to fill demand is the throughput capacity of the facility, and the number of tools in inventory at that time. The first constraint is an input into the model, and the second one is calculated on a period-by-period basis as described above.

However, the mere fact that inventory is available does not mean that a given call out order can be filled right away. There are 15 configurations of drilling tools, and one cannot always be easily converted into another. Knowing what demand levels for specific configurations are and assuming that the makeup of the overall pool of inventory is tied to demand patterns, the goal is to determine what the probability of filling a call out order with a given level of inventory is.

Intuitively, assuming that the XXX1 configuration accounts for around 29% of total demand (and for around 29% all tools in circulation), a XXX1 call out order has an approximately 29% chance of being filled out of inventory, if there is only one tool on hand. If there are, for instance, 4 tools in inventory, than the expected number of XXX1 units on hand is over 1, and it is likely that a call out order for this configuration will be filled from stock.

This analysis is extended to all 15 configurations, and the model calculates the probability of having the right inventory available for call out orders. The number of units that are likely to be filled from stock constrains how many call out orders can be filled in one day. If inventory on hand is not sufficient to fill an order, it is recorded as delayed and thus affects the overall service level. One last point is worth mentioning here: this logic only affects service levels when the inventory of tools is low, thus accelerating the deterioration of system performance as average inventory levels go down.

The next step in the model is to launch the assembled and configured tools into the "external cycle," calculate the level of ending inventory for that period, and determine the effects on customer service levels. If a call out order is not filled on the day it is received, it is recorded as delayed. Having completed the cycle, the model moves forward one period and the same logic is applied. Two measures – overall inventory levels and unfilled orders/backlog are carried forward and adjusted based on performance during the next time period. Please refer to Exhibit 3 in the Appendix for a snapshot of how inventory flows and stocks are tracked on a daily basis.

This part of the simulation model runs for 365 days, and then computes three summary statistics for the period:

1. Average service level
2. Low point in service level during the year, on a monthly basis
3. Percentage of lost sales

The first metric –average service level – indicates the percentage of all orders that were configured and shipped within the required time window. For the purposes of this model, shipping on the same day of order receipt is considered satisfactory.

Since averages usually don't tell the whole story, the second metric shows how low the service level dropped during the year. It is conceivable that a spike in call out demand can be coupled with a low level of inventory for a period of several days, which will lead to a temporary drop in service level. Even though this decline can be reversed shortly afterwards, its effects on the network performance are picked by this summary statistic.

Lastly, should the level of demand exceed available capacity, AAA will experience lost sales. It is common practice within the field services organization at AAA to negotiate the availability, type and timing of equipment deployment for planned orders, so the model computes lost sales as a cumulative sum of unfilled orders at the end of the year, divided by total demand. As mentioned previously, lost sales result in both monetary and reputational damage to AAA.

Summary: the inventory module evaluates the demand on the system against a set of resources and constraints, and tracks the flow of drilling tools between the field and the service hubs. Key performance metrics such as average service level, lowest service level and lost sales are computed as well.

4.1.6 Total Logistics Spend Simulation

Objective: to simulate logistic deployment of various sizes and types of drilling equipment and calculate the annual spend on delivering tools to and from the field.

This part of the model takes the demand allocated to specific basins, generates type/weight/size of tool that needs to be transported, selects the right type of truck for the tool, and determines how expensive the trip to and from the field is likely to be for a particular shipment. The major drivers of logistics cost are: rates per mile, distance and type of delivery (regular vs. "hot shot"). Please see Exhibit 4 in the Appendix for an example of shipping rates for a single type of truck.

The rate paid per mile is determined by the size and weight of the equipment being transported. The weight and size ranges for MD and FS are as follows:

	Weight range		Length Range (feet)	
FS	2,000	4,000	30	30
MD	1,200	3,000	10	20

In addition, the historical demand percentages for the two types of equipment are:

	% of Demand
FS	9.70%
MD	90.30%

Since every truck type has a certain weight and size limit, a simulation is built to select a particular weight and size combination and assign a truck that can carry this tool to its destination at the lowest available rate. For example, if a randomly selected MD tool weighs less than 1,500 pounds, it can be carried by truck type XXXX ("One Ton"), which costs $1.3 per mile out of OK. The 1,500 pound limit makes this truck unsuitable for transporting heavier equipment. Similarly, if the selected tool is a FS, which will happen 9.7% of the time in the simulation, then a truck that can carry a 30ft tool must be used. Lastly, for "hot shot deliveries", the model selects the higher delivery rate per mile and adds it to the total amount spent on logistics.

According to historical data, the average shipment size for planned orders is 1.38 tools per shipment, and the mean for call outs is 1.11. These estimates are used to adjust the number of trucks that are used to deliver equipment to drilling sites. Also, it is assumed that the truck of the right size is always available. This may not be a 100% valid assumption, since sometimes a truck of larger size that needed may be available, which of course means a higher rate per mile, or no trucks may be available for a period of several hours. However, AAA is comfortable with the assumption of on-demand vehicle availability. The following is an example of round trip shipping costs for call out shipments for 5 days:

Day	Midwest	North East	Rockies	South East	South West
1	-	-	2,975	4,108	3,586
2	-	7,862	-	6,390	2,165
3	-	-	5,551	6,390	3,586
4	5,060	-	-	6,390	3,586
5	-	-	5,551	4,108	2,165

Furthermore, AAA will have a negotiated milk run rate to carry multiple tools between the two hubs on a daily basis. The rate is likely to be between $3.5 and $4.5 per mile. Such milk run will have a capacity of between 10 and 15 tools per day each way. While this may become a constraint if demand levels increase above these levels, it is assumed that AAA can get another truck on that route when needed and for a similar rate. The model assumes that the milk run takes place when there are "dirty" tools to be transported to CO or fully configured ones to be moved to OK. If none of these conditions is met, the milk run does not take place on that day. The inputs for shipping rates, milk run rate, "hot shot" surcharge and the average number of tools shipped at once are all variable, allowing the user to get a sense of how total logistics costs for the year change as these assumptions are altered.

Summary: the logistics module uses a Monte Carlo simulation and lookup functionality to generate the type of equipment to be shipped, select the right truck type for shipment and aggregate shipping costs over a period of a year.

4.2 Model 2: Hub-and-spoke with Postponement

4.2.1 Functionality

Model 2 explores an alternative configuration of the AAA network. The inputs of the model are shared between model 1 and Model 2, and both models are driven by the same demand level and allocation between planned and call out, and between basins. Basically, Model 2 uses the same demand simulation and a modified set of constraints and available resources to simulate what the key performance metrics are for a period of 365 days.

Similar to Model 1, outputs include: average service level, low point in service level during the year, percentage of lost sales and total logistics spend for the year. The outputs of two models are combined on one worksheet called Dashboard, which also has an Inputs section where the user can vary the key variables and immediately see what the effect is on KPIs and how the two network configurations differ in terms of cost and performance. Please refer to Exhibit 5 in the Appendix for a snapshot of the Dashboard worksheet. The Outputs section also contains a category called "Savings vs. Point-to-point". This calculation compares the total logistics spend under each network configuration with total logistics costs that would be incurred if there was no hub-and-spoke system at all, and all orders, planned and call out, would have to be filled out of CO.

4.2.2 Key differences from the hub-and-spoke model

Summary: please refer to Exhibit 2 in the Appendix for a diagram of the replenishment cycle under the Hub-and-spoke with postponement setup. The key difference between this setup and the previous one is in the way final tool configuration is performed (stages affected are highlighted in yellow). With only initial assembly taking place in CO, drilling equipment is shipped to OK without having a job-specific setup. With the bulk of the available inventory residing in OK, this allows the facility to "customize" tools as orders, call out orders in particular, are placed. Specific differences are outlined below.

a. Transportation lead times

Due to the fact that most of the inventory will be staged at OK, the hub closest to most demand points, the average transportation lead time to rigs is shorter with this network configuration. Specifically, based on simulation results, average round trip shipping time for all orders is between 21 and 22 hours (vs. 22 – 23 hours under the pure hub-and-spoke setup), and the standard deviation is somewhat lower, around 10 hours (vs. 11 with the pure hub-and-spoke configuration). The fact that fewer hot shot deliveries are required explains lower variability in shipping time.

b. Inventory model

Under this configuration, all dirty tools are torn down, cleaned, repaired and assembled in such a way that the final assembly and configuration can be done at the postponement hub – OK. The flow of tools for both planned and call out orders is now:

CO -> OK -> Rig -> OK - > CO

The goal is to maximize the level of inventory ready for final configuration at OK. Such pooling effect leads to a higher probability of being able to fill a call out order out of tools on hand in OK. As discussed previously, the driving time to most drilling sites out of OK is considerably shorter, so the tools can get to the job site earlier, thus increasing service levels and boosting customer satisfaction.

Since the CO facility will still have to service the Rockies basin, some inventory will have to remain in CO to satisfy that demand. With Rockies accounting for 24% of total demand, the level of clean tools inventory that is kept at CO should most likely be below 24% of total inventory available. There are two reasons for this:

1. There is a daily inflow of "dirty" tools from OK, which can be used to fill the Rockies basin demand
2. In order to take full advantage of the inventory pooling effect in OK, as much inventory as possible should be staged there

The model allows the user to select the minimum level of inventory to be maintained in CO.

Another difference is the addition of one more constraint – the final assembly and configuration capacity in OK. The number of techs on the OK facility floor will limit how many configurations they can do in one day. Ideally, in order for the postponement setup to work most effectively, this "late stage differentiation" capacity must be around 76% of the repair and maintenance throughput of CO (to make sure that OK does not become a bottleneck). It would also make sense to have yet more capacity in OK, since this hub is one step closer to 76% of total demand, and is exposed to larger number of unpredictable call out orders. The model is designed to have the capacity at OK as a variable input.

c. Logistics spend calculation

The key difference here is that, out of four basins serviced by OK, three are within 11 hours of driving time. This implies that not only can tools get to well sites faster, but AAA also does not have to pay a premium rate for "hot shot" shipping to these three districts. Only the North East basin requires an expedited delivery of call out orders. In addition, a quick look at the table below reveals that shipping rates for most types of trucks are higher out of CO due to the fact that the terrain in the Rockies is much more… rocky. Therefore, filling most call outs out of OK will result in savings on the logistics front.

Type	Weight	Length	Rate out of OK	Rate out of CO
6,031	6,000	12	1.3	3.8
6,032	1,500	6	1.3	1.66
6,033	15,000	40	1.95	1.67
6,034	30,000	40	1.35	1.95
6,035	45,000	40	2.03	4

Exhibit 6 in the Appendix contains a snapshot of the Excel worksheet dedicated to the Hub-and-spoke with postponement model. Exhibit 7 presents an explanation of the logic underlying the simulated daily flows of the tool inventory.

5 ANALYSIS OF NETWORK EFFICENCY AND EFFECTIVENESS

The model, constructed as outlined in the last section, allows the user to perform the following tasks:

1. Perform an analysis of service levels delivered and logistics costs incurred of the two network configurations, given a set of assumptions about inventory availability, system capacity and demand levels
2. Perform a "what if" analysis by changing one or more inputs and constraints at a time and looking at the effect on performance and cost of operations
3. Come up with a set of conditions under which it becomes worthwhile to move away from the point-to-point delivery method and use one of the hub-and-spoke configurations
4. Understand how to allocate budget dollars (e.g. expanding maintenance facility capacity or acquiring more inventory) and use the model for supply chain planning

The first step of the analysis is to understand the relationships between the key inputs of the model and its outputs. Using the following set of inputs and corresponding outputs generated as a base case, the goal is to vary inputs one at a time and determine what the effect is on key performance metrics. Once such "partial derivative" effects are established, one can move on to more complex tasks, such as scenario analysis.

Inputs	
Demand, tools per day	8
Standard Deviation of Daily Demand	3
Number of MD on Books	95
DFP	3%
Failed	3%
CO Maintenance Capacity, tools per day	10
OK Final Configuration Capacity, tools per day (for Postponement Only)	10
Standby Time on Site Average, hours	42
Standby Time Standard Deviation	12
Waiting for Pickup time average, hours	42
Waiting for Pickup time standard deviation	12
Cost of Milk Run, dollars per mile	3.5
Hot Shot (Expedited) Rate Markup, dollars per mile	0.20
Average Shipment Size - Planned	1.38
Average Shipment Size - Call Out	1.11
Minimum Inventory level for Rockies, % of total (for Postponement only)	10%
# of days in backlog to start expediting planned shipments	2
Randomization of returns (for demand level > 6 per day)	Yes

The last two options require further explanation. The "# of days in backlog to start expediting planned shipments" input allows the user to set the level of tools in backlog (unfilled orders) as the average daily demand times the number of days entered into this cell. The logic behind this is as follows: if, due to low inventory or capacity constraints, the maintenance center has accumulated a certain level of backlog, then all shipments – planned and call outs – to basins outside of the 11-hour driving radius will be expedited, thus incurring the hot shot rate and increasing logistics costs. The "Randomization of returns" option allows the user to turn on and off the feature of using a random vector to affect tool returns from the field.

Outputs		
	Pure Hub-and-spoke	Hub-and-spoke with Postponement
Average on time deliveries	95%	99%
Lowest level of on time deliveries	91%	98%
Percentage of Lost Sales	0.00%	0.00%
Logistics Spend	8,161,550	6,370,698
Savings vs. Point-to-point	17%	35%

The Outputs table summarizes the key performance metrics for a one year cycle – service levels (as average on-time deliveries and lowest level on-time deliveries), lost sales, annual logistics spend, and savings vs. the point-to-point delivery network.

The Output table indicates that, under this set of assumptions and constraints, the Hub-and-spoke with postponement configuration, compared to the Pure Hub-and-spoke setup, delivers a 4% point higher average service rate, a 7% point higher minimum service rate, no lost sales, and a total logistics spend that is $1.8MM lower. Of course, one needs to be mindful of the fact that there are costs associated with running a postponement operation in OK. Also, these are the results of one simulation trial; if the model is rerun, the results will be slightly different. This is the reason why the simulation is run 40 times and the results are averaged for in-depth scenario-based analysis (discussed in Part 8).

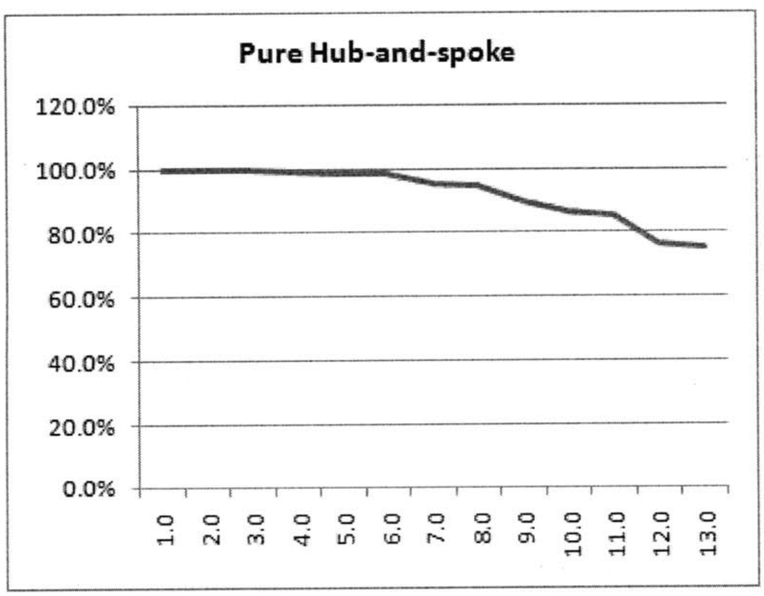
6 SENSITIVITY ANALYSIS

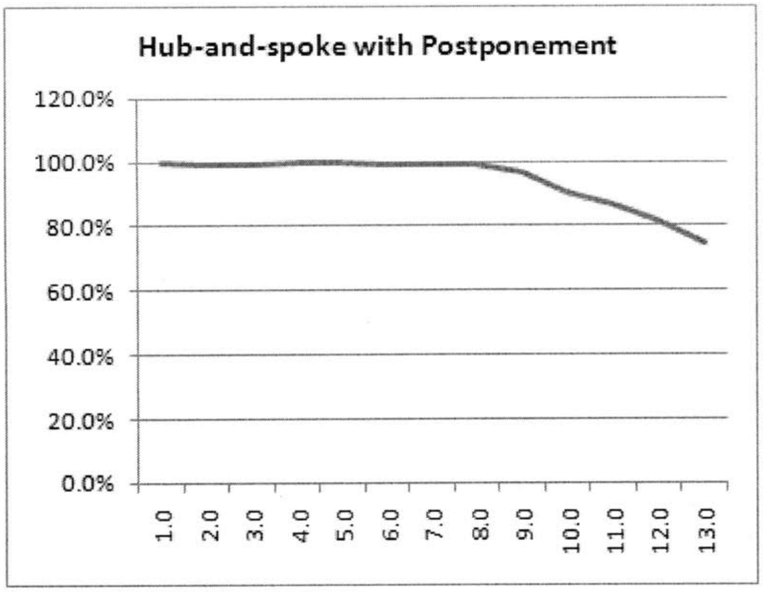
The following is a set of charts that show how two of the key performance metrics – average on-time deliveries and percentage of lost sales – respond to changes in one parameter at a time. The simulation is rerun once for every value of five key inputs – demand level, standard deviation of demand, number of tools available, maintenance facility capacity, and idle time at rig,

6.1 Demand

Base case = 8 tools per day.

Average On-time Delivery

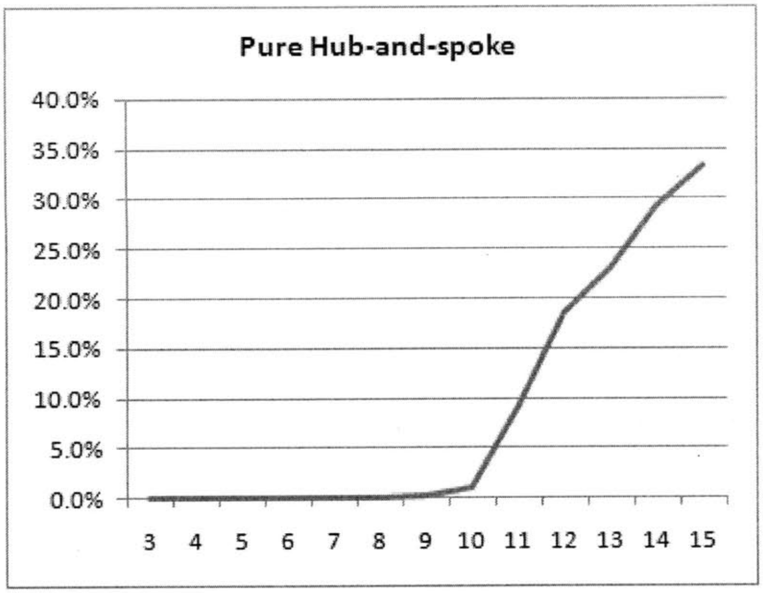


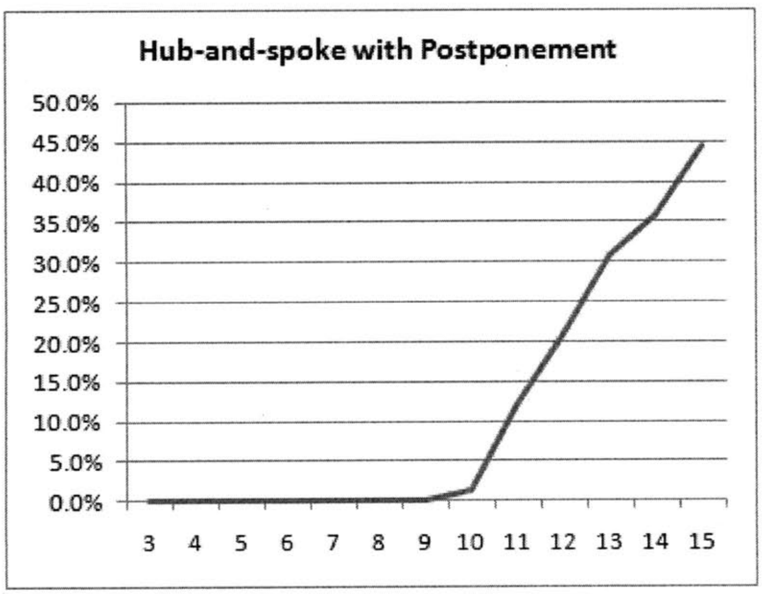


Both charts: Horizontal axis –number of tools demanded per day, vertical axis – average service level

It is clear that as daily demand goes above 8 units per day, the service levels start to deteriorate. As average demand breaches the repair and maintenance capacity of the system, service levels drop very quickly, since AAA is not able to meet such demand. **The key insight**: the postponement system holds at a level close to 100% for around one unit of demand more than the pure hub-and-spoke system; the implication is that the postponement system may be more robust in a situation when demand approaches capacity.

Lost Sales





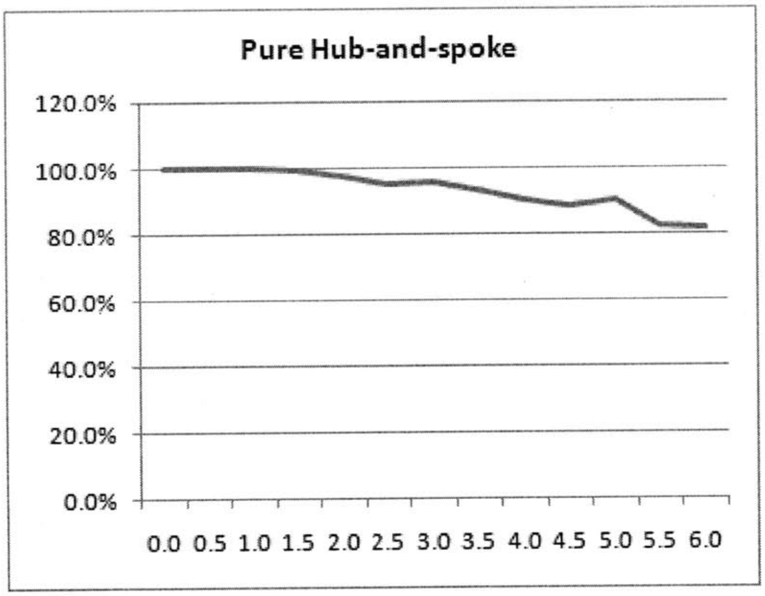
Both charts: horizontal axis – number of tools demanded per day, vertical axis – percentage of lost sales

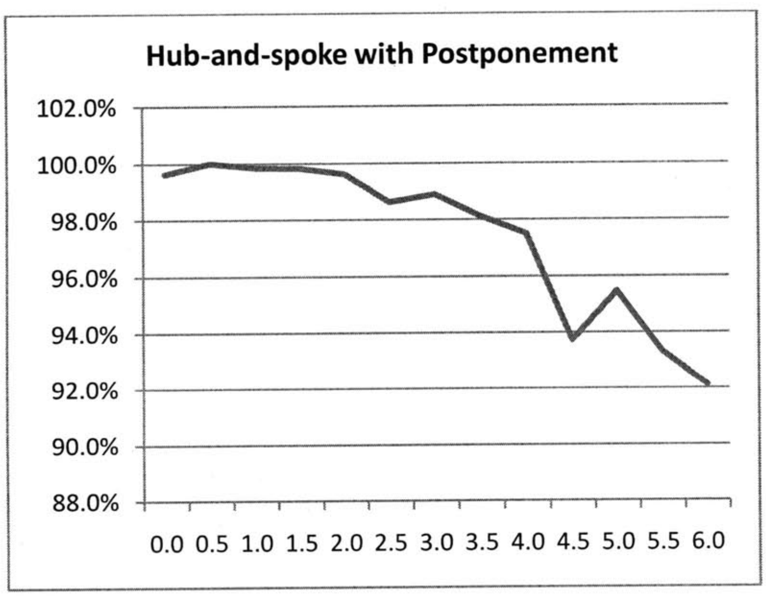
Unsurprisingly, lost sales under both configurations start to pick up as the system reaches capacity and then rises steadily.

6.2 Standard Deviation of Daily Demand

Base case = 3

Average On-time Delivery





Both charts: horizontal axis – standard deviation of daily demand, vertical axis – average service level

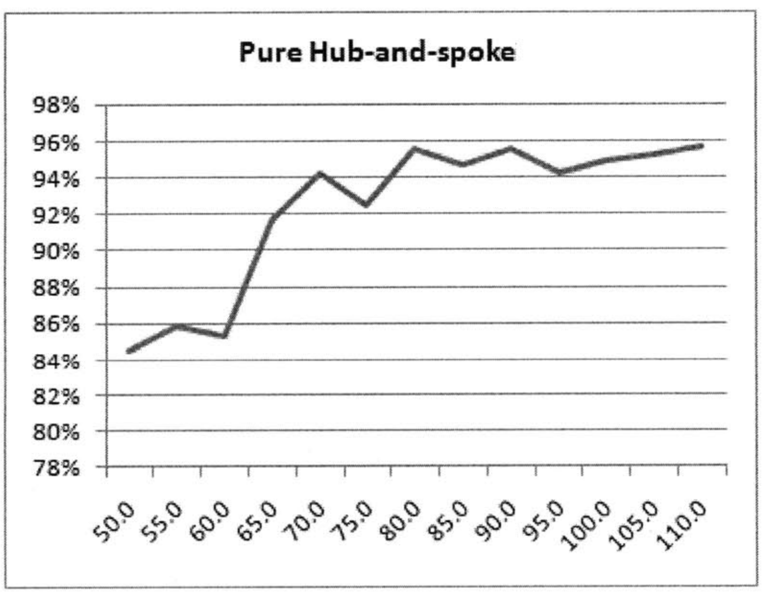
As the standard deviation of demand increases, both network configurations show deteriorating performance; however, increasing variability has a much larger effect on the pure hub-and-spoke system. The drop in on-time deliveries produced by the hub-and-spoke system is almost twice as large as it is for the postponement setup. **Key finding**: late tool differentiation enables the postponement system to deal with volatility in demand in a much more effective manner.

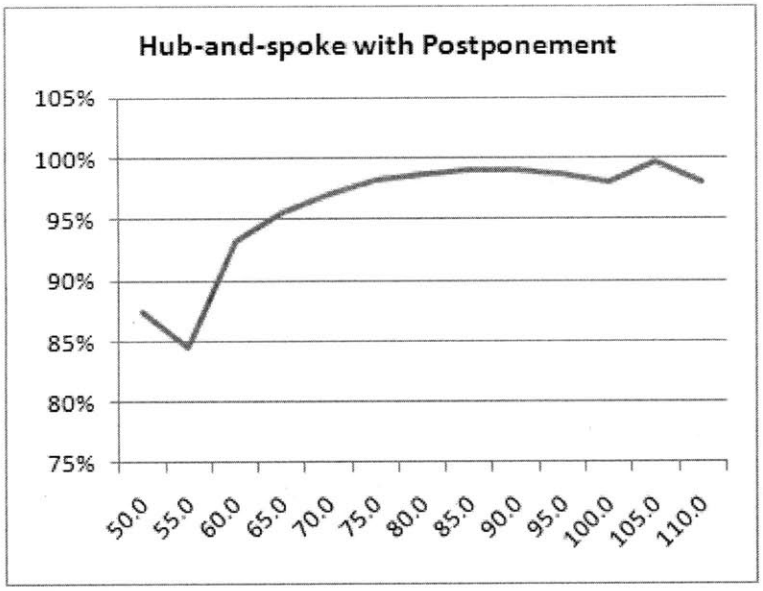
6.3 Number of Tools Available

Base case = 95

As the number of MD tools carried on AAA's books is varied between 50 and 110, the following results are generated:

Average On-time Delivery

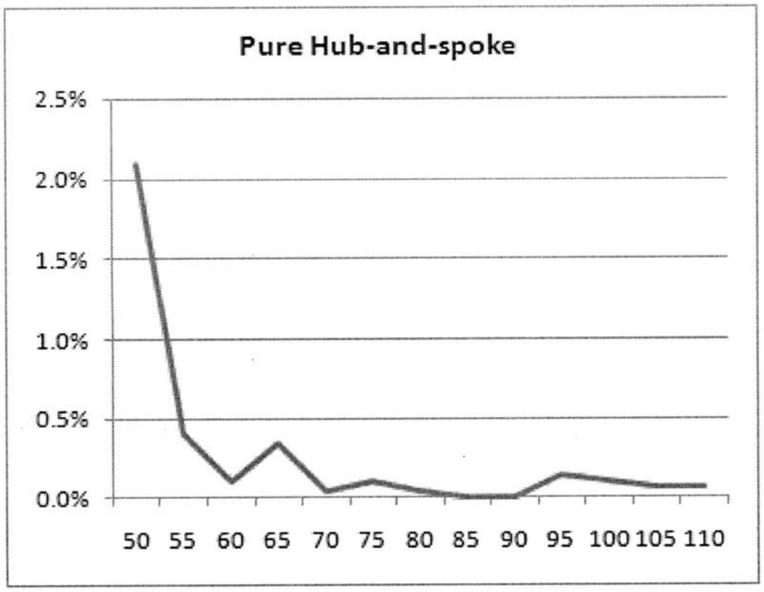


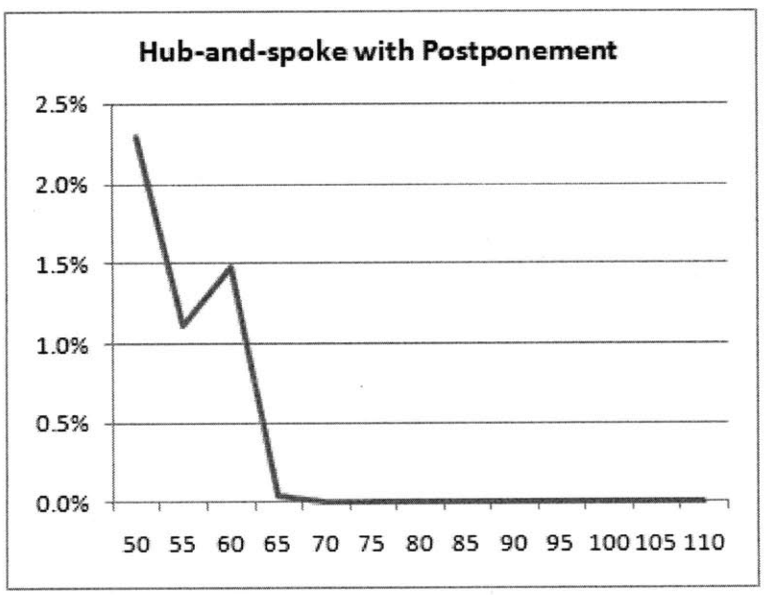


Both charts: horizontal axis – total number of tools on AAA books, vertical axis – average service level

Again, it appears that, as the inventory of tools is increased, the postponement configuration approaches higher service levels earlier, and it more stable as inventory grows. Also, it appears to provide a higher level of on-time deliveries at lower inventory levels.

Lost Sales





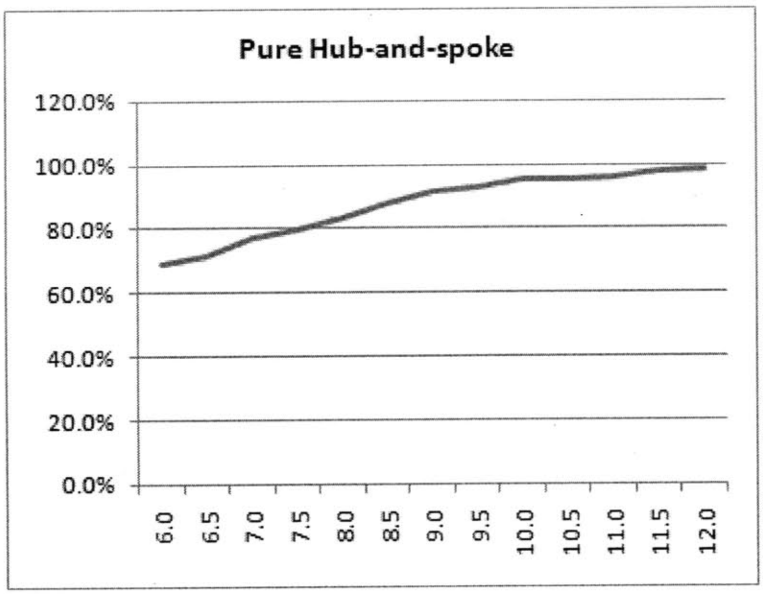
Both charts: horizontal axis – total number of tools on AAA books, vertical axis – percentage of lost sales

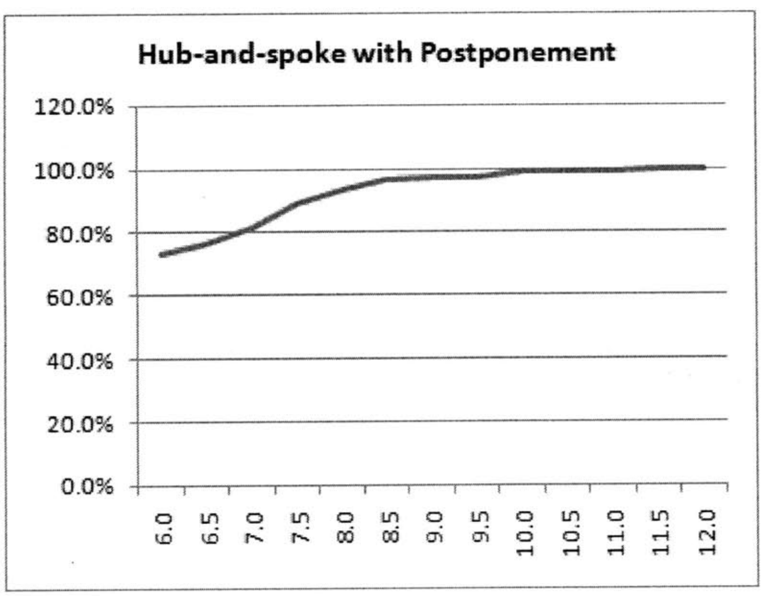
Both configurations show similar levels of lost sales as inventory levels change; however, once the inventory level reaches sufficient levels, the lost sales percentage is consistently at zero with postponement, whereas it exhibits some variability with pure hub-and-spoke.

6.4 Repair, Maintenance, Assembly and Configuration Capacity

Base case = 10

Average on-time deliveries

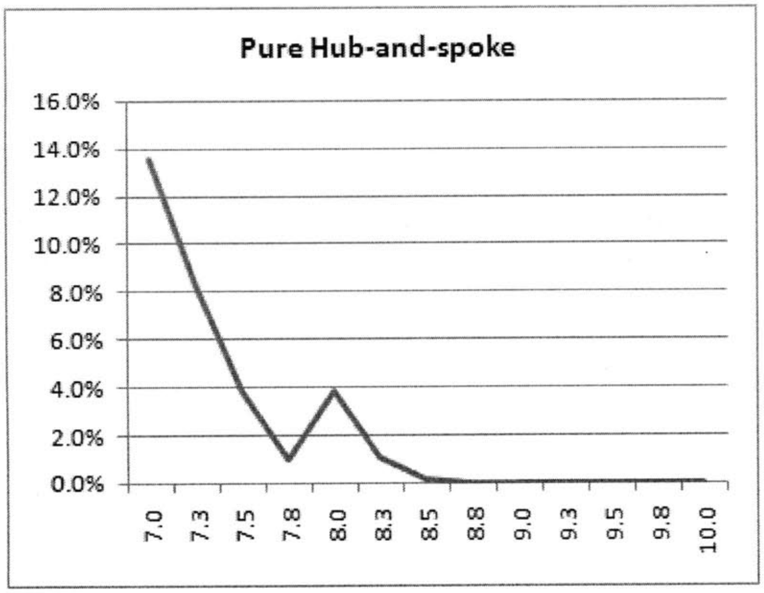


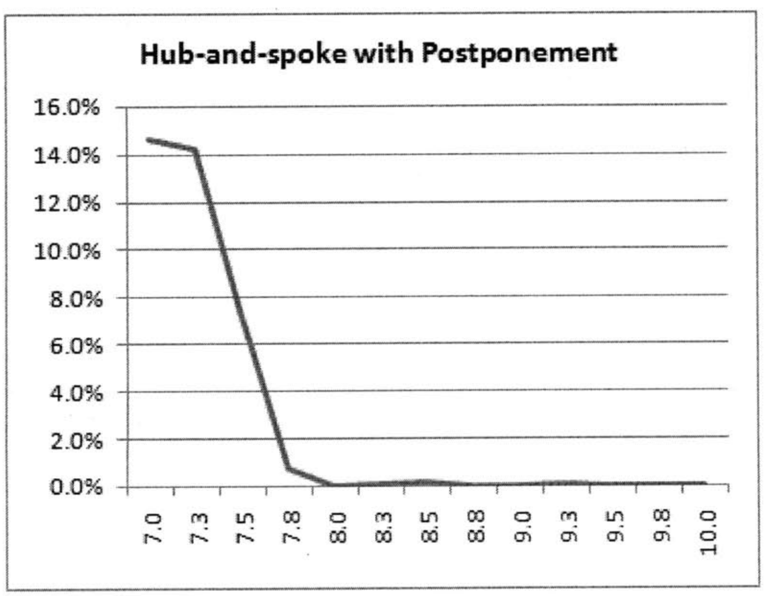


Both charts: horizontal axis – maintenance daily capacity, vertical axis – average service level

As throughput capacity approaches the level of daily demand and exceeds it, the postponement setup reaches 95%+ service levels faster and consistently stays above those levels.

Lost Sales





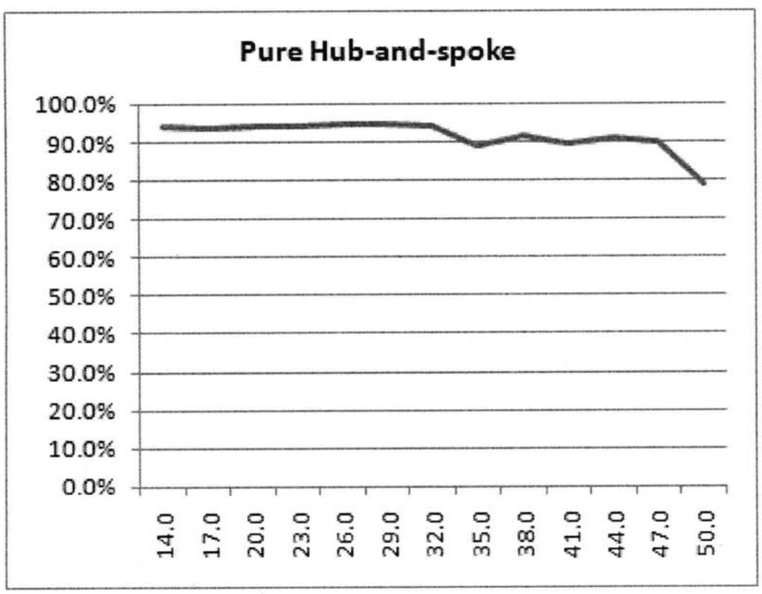
Both charts: horizontal axis – maintenance daily capacity, vertical axis – percentage of lost sales

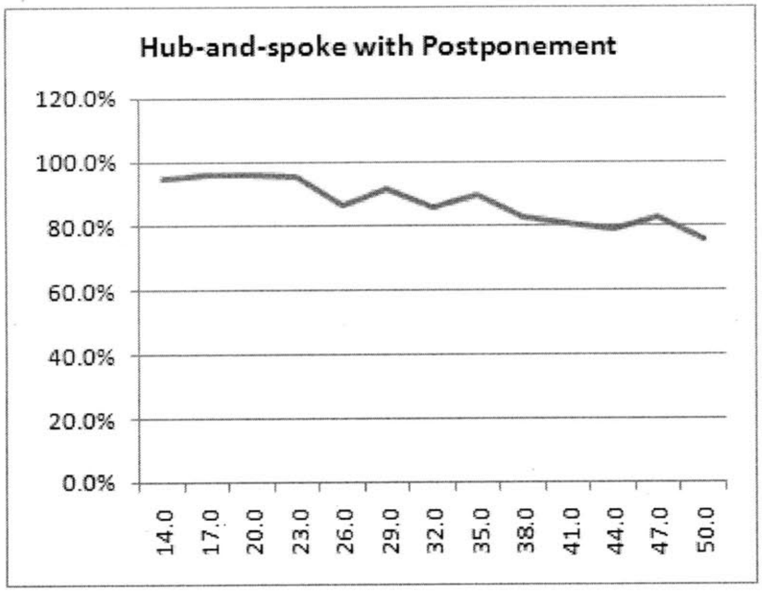
Similar sensitivities are exhibited in this situation as well: the postponement setup hits zero lost sales at a lower level of available capacity and has less volatility overall.

6.5 Idle Time at Rig

Average on-time deliveries

The effect of increasing rigging up and overall standby times from 14 to 50 hours does not materially affect service levels if there is sufficient inventory and processing capacity. However, if AAA finds itself in a situation where its inventory levels are low relative to demand levels, these variables start to matter. Looking at a situation with base case demand of 8 units per day, but only 55 tools in inventory, the following results:

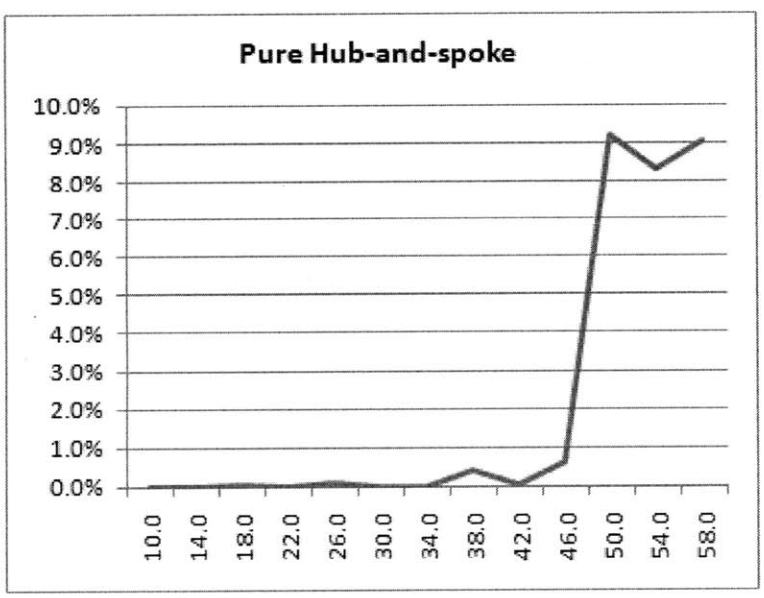


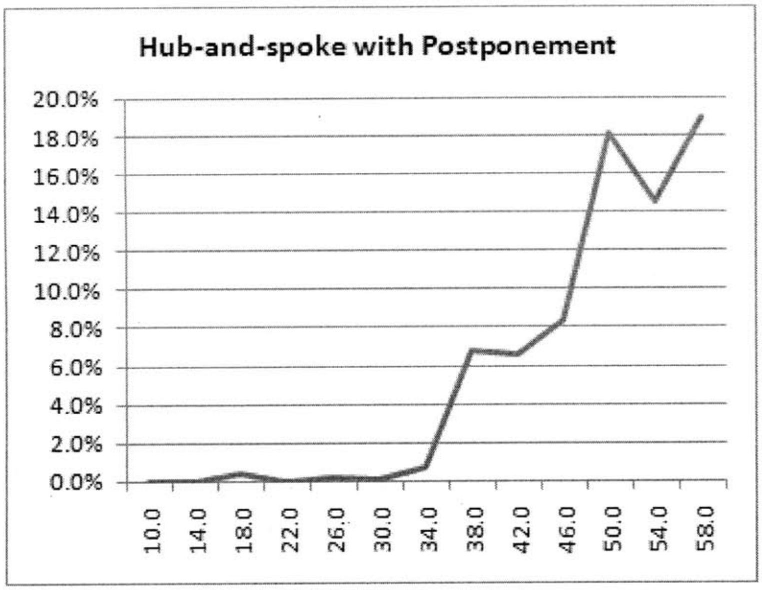


Both charts: horizontal axis – idle time at rig, vertical axis – average service level

There is quite a bit of variability in these results, but both charts show clear evidence of a downward trend in on-time deliveries as standby times increase.

Lost Sales





Both charts: horizontal axis – idle time at rig, vertical axis – percentage of lost sales

Lost sales percentage increases at a rapid rate for both network setups as tools spend more non-value added time at the rig.

7 ANALYSIS OF PROJECTED LOGISTICS SPEND

Besides service levels, the second key performance metric is the amount of total logistics spend. The company's objective is to minimize the deployment costs while maintaining high service levels. Therefore, this part of the analysis investigates the costs of running both network configurations – pure hub-and-spoke and hub-and-spoke with postponement – and quantifies cost savings associated with each network setup.

To create a point of comparison, a hypothetical "base case" annual logistics spend is established by calculating how expensive it would be to service all drilling sites out of CO only. This scenario effectively removes the option of having OK as a hub, and forces all orders to go point-to-point from CO. This option can be thought of as an upper bound on logistics expenses. The total annual costs of shipping using the two networks with a hub are compared to this base case scenario, and a level of "savings" is established (e.g. if it costs $10MM per year to ship with the base case and $8MM under one of the hub-and-spoke setups, then the savings are 20%).

Continuing with the set of demand and resource/capacity availability assumptions of Section 5, the annual logistics costs are generated:

Outputs			
	Pure Hub-and-spoke	**Hub-and-spoke with Postponement**	**100% Point-to-point out of CO**
Average on-time deliveries	94%	99%	
Lowest level of time deliveries	93%	96%	
Percentage of Lost Sales	0.00%	0.00%	
Logistics Spend	**8,219,462**	**6,381,335**	**9,556,323**
Savings Vs Point-to-point	**14%**	**33%**	

Compared to the base case cost of $9.6MM per year, the pure hub-and-spoke system generates savings of 14% (vs. the Point-to-point setup), while the postponement option brings the cost down by 33%. These estimates are based on one run of the model, hence they will vary somewhat from run to run; the Scenario Analysis part of the thesis presents more stable averages of 40 runs. **Key insight:** due to that fact that all planned orders and most call outs under the postponement option go through the hub, this network configuration produces the lowest cost of logistic deployment. In dollar terms, the postponement option results in a logistics spend that it $3.2MM lower than the base case, and $1.3MM lower than that with the pure hub-and-spoke configuration.

In terms of absolute levels of logistics costs, the two network configurations deliver the following simulated performance as demand is varied between 4 and 16 tools per day:

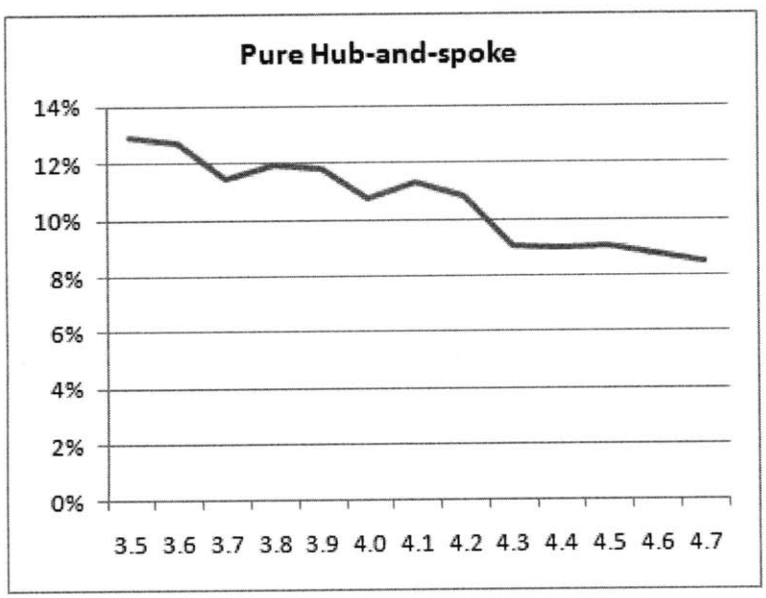
TPD	Point-to-point	Hub-and-spoke	Postponement	Difference (H&S - Post.)	Difference (P2P - Post.)
4	$4,830,965	$4,670,326	$3,576,806	**$1,093,520**	**$1,254,159**
5	$6,088,426	$5,453,183	$4,289,922	**$1,163,261**	**$1,798,504**
6	$7,136,451	$6,288,911	$5,069,079	**$1,219,831**	**$2,067,372**
7	$7,938,040	$7,191,751	$5,739,833	**$1,451,918**	**$2,198,208**
8	$9,402,970	$8,189,529	$6,354,760	**$1,834,769**	**$3,048,209**
9	$10,547,054	$9,268,067	$7,071,392	**$2,196,675**	**$3,475,661**
10	$11,684,431	$10,136,097	$7,738,965	**$2,397,132**	**$3,945,466**
11	$11,758,705	$10,199,042	$7,830,750	**$2,368,292**	**$3,927,955**
12	$11,911,501	$10,355,312	$7,920,436	**$2,434,877**	**$3,991,065**
13	$12,095,731	$10,258,212	$7,888,436	**$2,369,776**	**$4,207,295**
14	$12,221,363	$10,527,372	$7,983,882	**$2,543,490**	**$4,237,480**
15	$12,296,734	$10,551,309	$8,030,069	**$2,521,240**	**$4,266,665**
16	$12,395,931	$10,674,525	$8,072,794	**$2,601,730**	**$4,323,137**

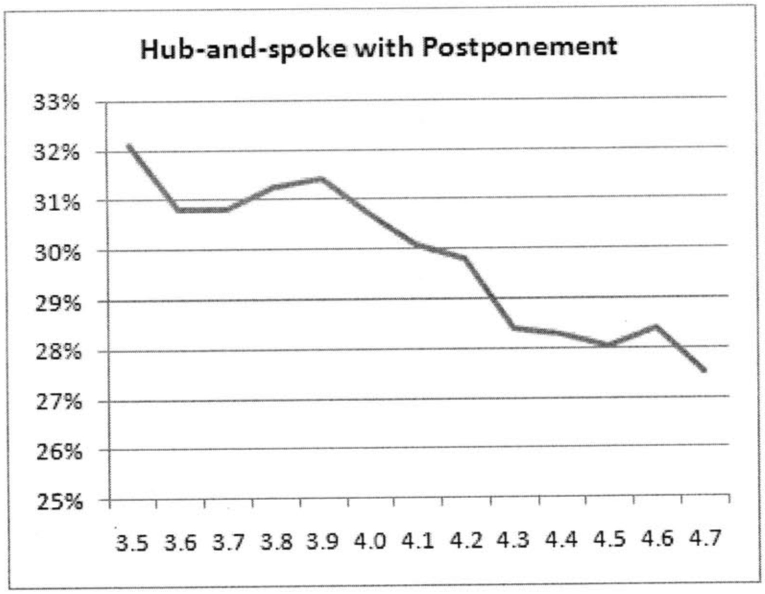
Depending on demand level, the postponement setup is between $1.1MM and $2.6MM less expensive to run annually in terms of logistic deployment, compared to the pure hub-and-spoke configuration. Also, the postponement setup is $1.2MM to $4.3MM less expensive logistically then the point-to-point configuration.

However, there are several elements that affect both the absolute levels of logistics costs, and the relative savings between the two alternative configurations: cost per mile of the milk run service, hot shot rate markup and average number of tools per shipment. These variables have some uncertainty over their final values (e.g. rates not fully negotiated), and/or AAA has a certain level of control over them (e.g. average shipment size). The cost effects of changing these variables within their conceivable ranges are presented next.

7.1 Cost of Daily Milk Run Service between the Hubs

According to our research, the cost of the milk run operation per mile may range between $3.5 and $4.7, with the backhaul rate (OK to CO) equal to 50% of that. The following charts indicate the levels of savings (relative to the point-to-point setup) vs. the per mile cost of milk run.



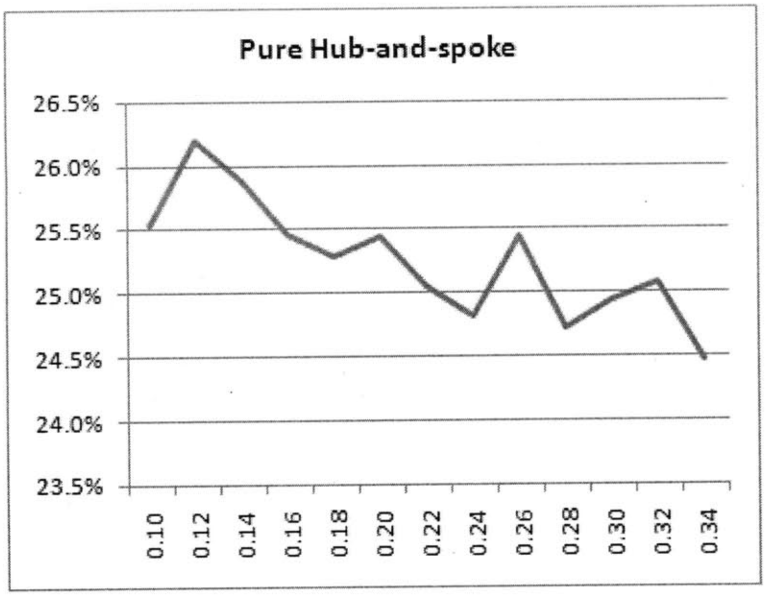


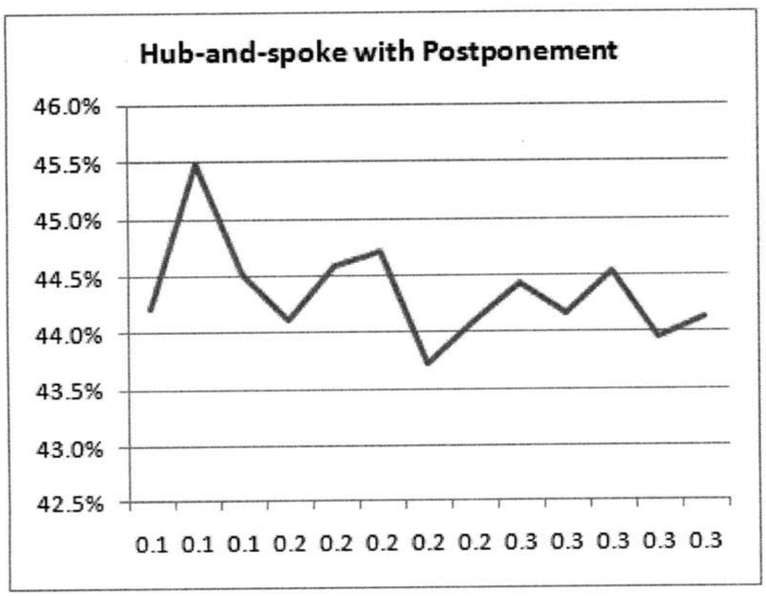
Both charts: horizontal axis – cost per mile of milk run service, vertical axis – savings relative to hypothetical point-to-point configuration

As expected, increasing the milk run rate from $3.5 per mile to $4.7 reduces the possible savings under the hub-and-spoke configuration by around 5%, and by around 6% for the postponement setup. **Key insight:** since the postponement setup has more tools flowing through the milk run service and lower overall shipping costs, an increase in the somewhat fixed cost of a daily milk run causes a larger percentage increase in the overall logics spend, and, therefore, a lower level of savings relative to the base case without milk runs.

7.2 Hot Shot Rate

The current rate markup for hot shot deliveries paid by the company is $0.1 per mile (in addition to base rate). This rate is lower than the prevailing market rate for such services, and there is a meaningful probability that the hot shot rate will increase in the future. In order to understand what impact a rate increase up to $0.3 per mile can have on the amount of savings, the following sensitivity analysis is performed:



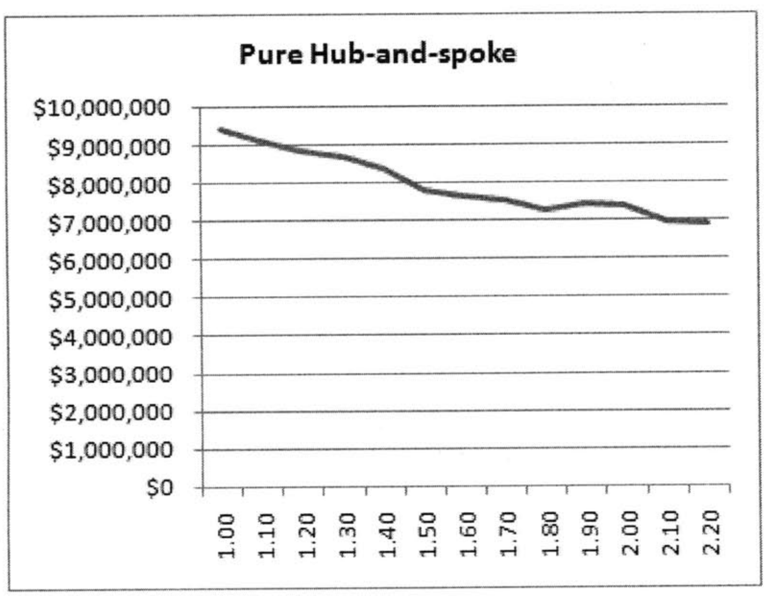


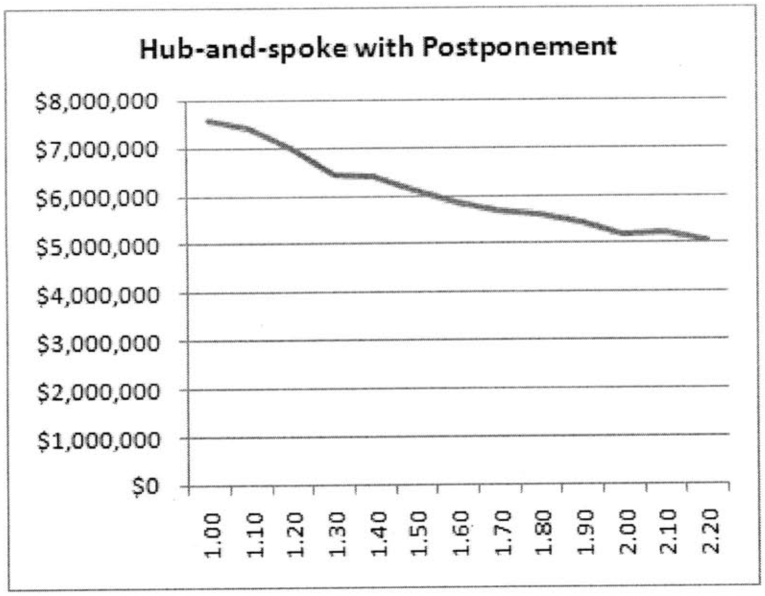
Both charts: horizontal axis – additional cost per mile of hot shot service, vertical axis – savings relative to hypothetical point-to-point configuration

Key insight: Since the amount of the hot shot markup is relatively low compared to regular rates (between $1.67 and $4 per mile), it is not a major driver of savings under any hub-and-spoke configuration. One insight can be gleaned from the analysis above: the postponement configuration appears to be less affected by an increasing hot shot rate, since it relies less on expedited deliveries (compared to the point-to-point and the pure hub-and-spoke setups).

7.3 Total Logistics Spend vs. Average Planned Shipment Size

The average shipment size for deliveries to the field, meaning how many tools are put onto a delivery truck to one of the basins, is under AAA's control to a certain extent. If the logistics department can coordinate transportation in batches for some planned orders, money can be saved. It is more challenging to do so for call out orders since such orders are extremely time sensitive and need to be shipped out as soon as tools are configured. Increasing planned orders shipment size from 1 unit to 2.2 leads to the following decrease in the overall level of annual logistics spend for AAA:





Both charts: horizontal axis – average planned shipment size, vertical axis – annual logistics spend

It is clear that a substantial amount of money – around $2MM – can potentially be saved by aggregating deliveries of planned orders.

8 SCENARIO ANALYSIS

Building on insights developed in the previous two sections, three distinct end user demand scenarios are now explored:

1. Base case demand – 8 units per day, standard deviation of 4
2. Low demand – 6 units per day, standard deviation of 3
3. High demand – 14 units per day, standard deviation of 5

The objectives are to:

1. Understand what combination of resources controlled by AAA, such as tool inventory levels and capacity, can support sufficiently high levels of on-time deliveries and no lost sales under the two network configurations
2. Calculate the likely amount of annual logistics spend for each demand scenario under the two network setups

While the model allows the user to change any of the 18 inputs, the analysis in this section is limited to dynamically changing two major determinants of the delivery network efficiency and effectiveness – tool inventory levels and maintenance capacity in the system. The model is run 40 times and the results are averaged to make them statistically stable. The goal is to come up with a combination of system inventory level and maintenance capacity that will result in AAA being able to consistently ship out 95%+ of all orders on-time. For modeling purposes, this is equivalent to keeping the average level of on-time deliveries metric above 95%.

The following is a list of modeling assumptions for this section, with the inputs to be varied highlighted:

Inputs	
Demand, tools per day	8
Standard Deviation of Daily Demand	4
Number of MD on Books	95
DFP	3%
Failed	3%
CO maintenance Capacity, tools per day	12
OK Final Configuration Capacity, tools per day (for Postponement Only)	12
Standby Time on Site Average, hours	42
Standby Time Standard Deviation	12
Waiting for Pickup time average, hours	42
Waiting for Pickup time standard deviation	12
Cost of Milk Run, dollars per mile	3.5
Hot Shot Rate Markup, dollars per mile	0.20
Average Shipment Size - Planned	1.38
Average Shipment Size - Call Out	1.11
Minimum Inventory level for Rockies, % of total (for Postponement only)	10%
# of days in backlog to start expediting planned shipments	2
Randomization of returns (for demand level > 6 per day)	Yes

Running the model with different combinations of these inputs yields the following results matrix:

	Inventory	Capacity	Logistics Spend ($MM/year)	P2P Logistics Spend ($MM/year)
Base Case				
Hub-and-spoke	**90**	**13**	**8.3**	**9.6**
Postponement	**85**	**12**	**6.5**	**9.6**
Low Demand				
Hub-and-spoke	**70**	**11**	**6.2**	**7.2**
Postponement	**65**	**10**	**5.1**	**7.2**
High Demand				
Hub-and-spoke	**150**	**21**	**13.4**	**16.4**
Postponement	**140**	**19**	**10.2**	**16.4**

Several key insights can be gleaned from these results:

1. The postponement configuration requires less tool inventory to deliver a desired service levels, and this difference grows as the level of demand goes up. The ability to postpone tool differentiation allows the company to run a leaner operation.
2. The repair and maintenance capacity required to maintain a certain service level is lower as well; the difference increases as demand goes up. It must be noted that, for the postponement operation, this level of capacity must be maintained at both CO and OK, which of course entails certain costs.
3. The postponement configuration enables larger savings on the logistics front, and the amount saved (as a percentage of the hypothetical point-to-point logistics cost) grows as demand goes up. Also, the amount saved relative to the pure hub-and-spoke operation goes up as demand increases.

In addition, a rough rule of thumb for the postponement setup can be developed based on this analysis:

- In order to consistently maintain on-time deliveries of above 95%, the company would need to maintain an inventory level of functioning tools equal to 11 times its average daily demand, and the maintenance capacity of the system of the average daily demand plus one standard deviation of such demand. The levels of inventory and maintenance capacity are somewhat higher with the pure hub-and-spoke network.

For a more refined analysis of the relationship between other inputs and the performance of the company network, the user should use the model. The model is designed to run on any recent version of Microsoft Excel and does not require any special add-ins.

9 CONCLUSIONS AND RECOMMENDATIONS

As mentioned previously, it is only economic to use a hub-and-spoke distribution method if demand consistently exceeds 4 tools per day. When this is the case, the analysis performed suggests that the hub-and-spoke with postponement network setup is superior to the pure hub-and-spoke configurations in several key areas:

1. It appears to deliver a higher level of service with a fixed set of available resources (e.g. inventory and maintenance center capacity). Specifically, the level of tool inventory that needs to be maintained is between 5 and 10 units lower, and the required daily maintenance capacity is between 1 and 2 units lower.
2. It is more robust; as either demand increases or available resources decrease, the network delivers a higher level of service.
3. It is better able to deal with increased demand volatility
4. It generates significant cost savings on the logistics front, around $1.8MM in the base case scenario (relative to the pure hub-and-spoke network setup).

While running a postponement operation in OK clearly delivers value to AAA in terms of service levels and logistic deployment, it must also be considered that there are costs associated with maintaining final assembly and configuration capacity in OK. While this type of cost data is proprietary and is not disclosed, the model created as a part of this thesis allows AAA to enter the assumptions for demand and resource availability and immediately see what the simulated service levels and logistics costs are. An informed decision as to which network setup is preferable can then be made by comparing costs and benefits of a postponement operation. In general, insights generated by the model will enable the user to allocate the budget in a way that brings the most value to the organization.

10 Appendix

Exhibit 1. Pure-hub-and-spoke Model Inventory Cycle

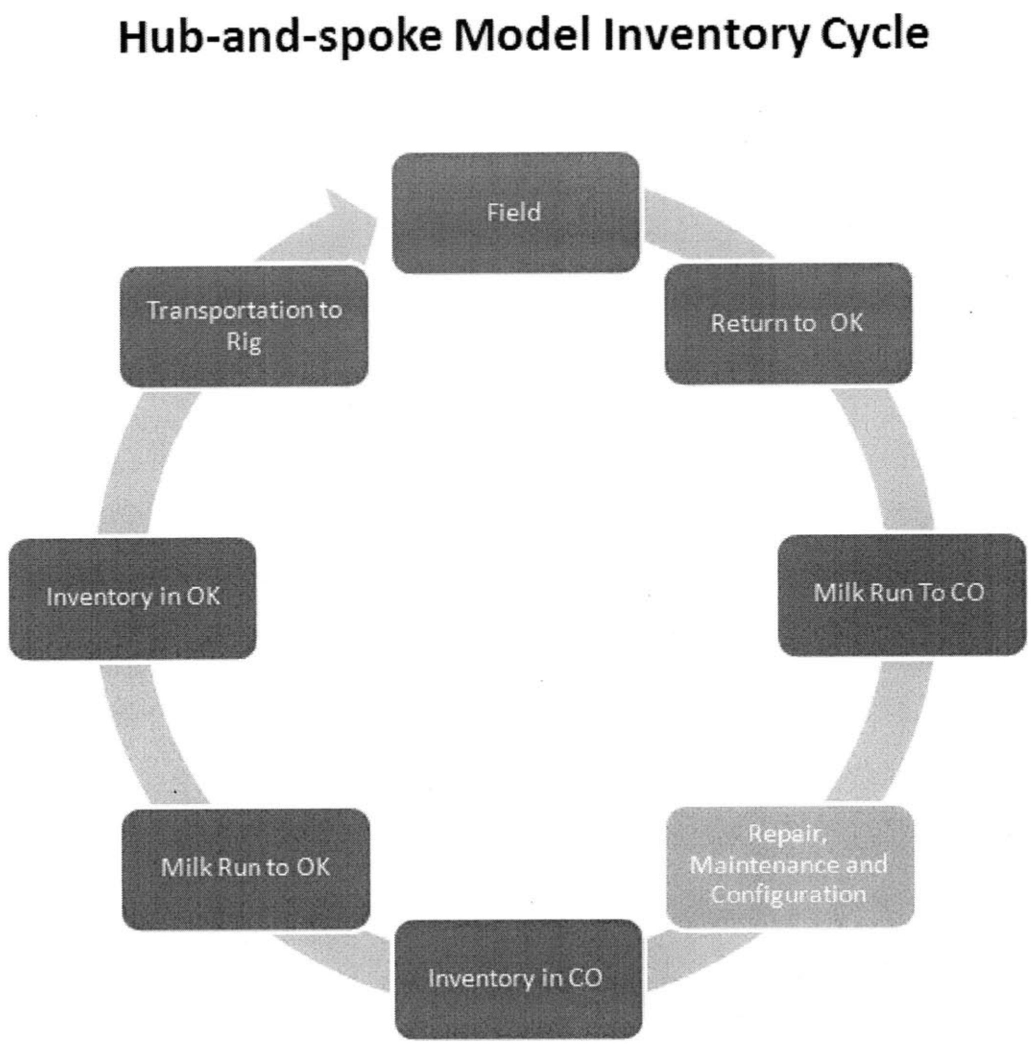


Exhibit 2. Hub-and-spoke with Postponement Inventory Cycle

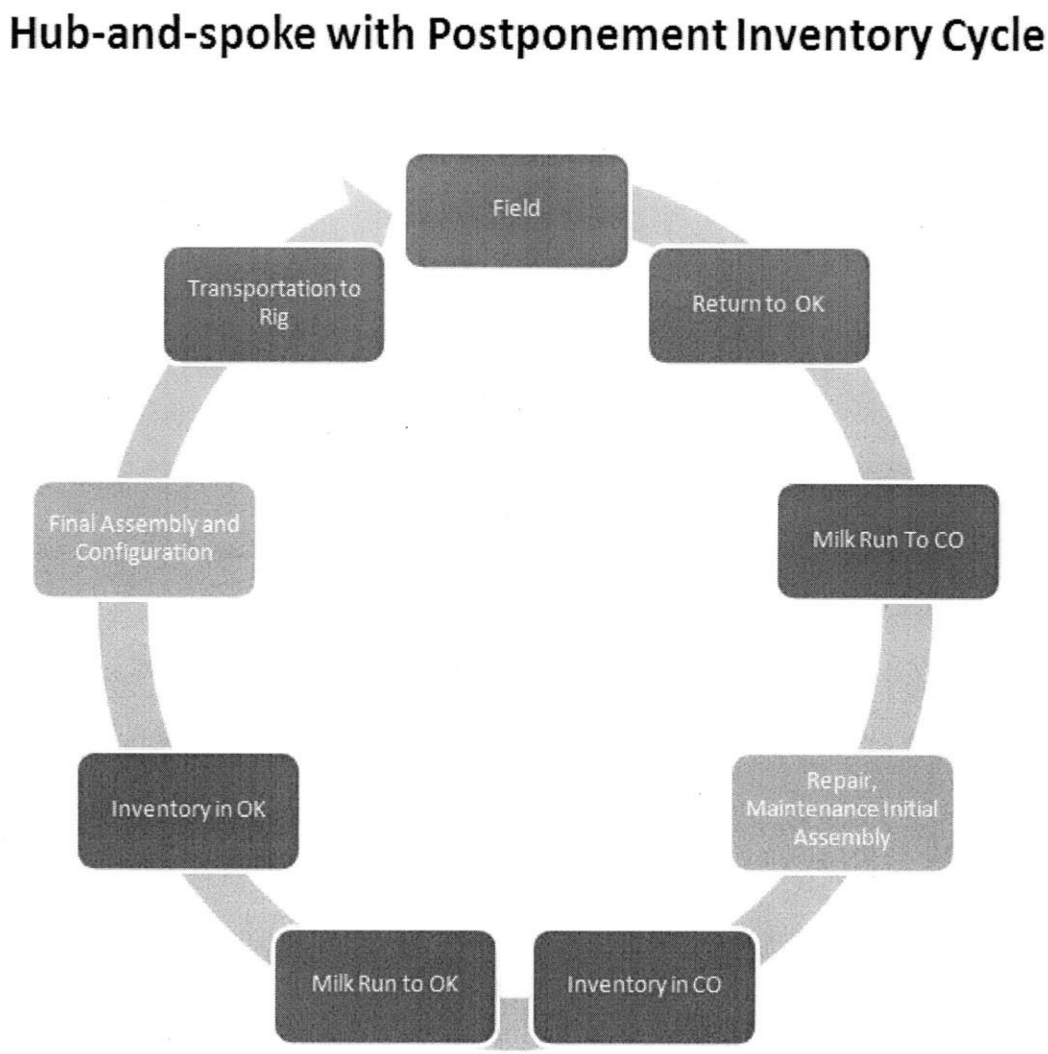


Exhibit 3. Hub-and-spoke System Inventory Worksheet

	PD on Books	DFP	Failed	Available	Beg. Inv.	Tools In	Dirty Tools Available	Planned Demand	Call-out Demand	Can Fill CO out of Inv	Config Capacity	Config Done	Ship Out	Delayed Shipments	End. Inv.
1	95	3%	3%	89	89	-	-	9	3	3	10	10	10	2	79
2	95	3%	3%	89	79	-	-	6	3	3	10	10	10	1	69
3	95	3%	3%	89	69	-	-	4	2	2	10	7	7	-	62
4	95	3%	3%	89	62	-	-	6	3	3	10	9	9	-	53
5	95	3%	3%	89	53	-	-	10	4	4	10	10	10	4	43
6	95	3%	3%	89	43	-	-	5	2	2	10	10	10	1	33
7	95	3%	3%	89	33	-	-	6	3	3	10	10	10	-	23
8	95	3%	3%	89	23	10	10	7	3	3	10	10	10	-	23
9	95	3%	3%	89	23	10	10	5	2	2	10	7	7	-	26
10	95	3%	3%	89	26	7	7	1	-	-	10	1	1	-	32
11	95	3%	3%	89	32	9	9	1	1	1	10	2	2	-	39
12	95	3%	3%	89	39	10	10	2	1	1	10	3	3	-	46
13	95	3%	3%	89	46	10	10	8	3	3	10	10	10	1	46
14	95	3%	3%	89	46	10	10	3	1	1	10	5	5	-	51
15	95	3%	3%	89	51	10	10	6	3	3	10	9	9	-	52
16	95	3%	3%	89	52	7	7	1	1	1	10	2	2	-	57
17	95	3%	3%	89	57	1	1	8	3	3	10	10	10	1	48
18	95	3%	3%	89	48	2	2	5	2	2	10	8	8	-	42
19	95	3%	3%	89	42	3	3	9	3	3	10	10	10	2	35
20	95	3%	3%	89	35	10	10	2	1	1	10	5	5	-	40
21	95	3%	3%	89	40	5	5	-	-	-	10	-	-	-	45
22	95	3%	3%	89	45	9	9	8	3	3	10	10	10	1	44
23	95	3%	3%	89	44	2	2	5	2	2	10	8	8	-	38
24	95	3%	3%	89	38	10	10	11	4	4	10	10	10	5	38
25	95	3%	3%	89	38	8	8	-	-	-	10	5	5	-	41
26	95	3%	3%	89	41	10	10	1	1	1	10	2	2	-	49
27	95	3%	3%	89	49	5	5	9	4	4	10	10	10	3	44
28	95	3%	3%	89	44	-	-	1	-	-	10	4	4	-	40
29	95	3%	3%	89	40	10	10	11	4	4	10	10	10	5	40
30	95	3%	3%	89	40	8	8	3	1	1	10	9	9	-	39
31	95	3%	3%	89	39	10	10	4	1	1	10	5	5	-	44
32	95	3%	3%	89	44	5	5	4	2	2	10	6	6	-	43
33	95	3%	3%	89	43	2	2	4	2	2	10	6	6	-	39
34	95	3%	3%	89	39	10	10	4	2	2	10	6	6	-	43
35	95	3%	3%	89	43	4	4	9	3	3	10	10	10	2	37
36	95	3%	3%	89	37	10	10	3	1	1	10	6	6	-	41
37	95	3%	3%	89	41	9	9	6	2	2	10	8	8	-	42
38	95	3%	3%	89	42	5	5	4	1	1	10	5	5	-	42
39	95	3%	3%	89	42	6	6	9	3	3	10	10	10	2	38

Exhibit 4. Shipping Rates from Drilling Sites to AAA Service Facilities

TL-OD-MINI-FLOAT			OK			CO		
State			Miles	Rate	Linehaul	Miles	Rate	Linehaul
CA			1345.7	$2.88	$3,875.62	1046	$2.88	$3,012.48
TX			427.9	$1.95	$834.40	662.5	$1.95	$1,291.88
TX			464.4	$1.95	$905.58	1139.5	$1.95	$2,222.03
AR			313.5	$1.95	$611.33	937.3	$1.95	$1,827.73
WV			1111.9	$2.88	$3,202.27	1454.2	$2.88	$4,188.10
ND			1296.6	$2.88	$3,734.21	692.9	$2.88	$1,995.55
OK			0	$1.95	$0.00	684.8	$1.95	$1,335.36
CO			685.9	$1.67	$1,145.45	0	$1.67	$0.00

TL-OD-Mini-Float
Max Load Capacity
15,000 lbs
Max Load Dimensions
40L X 8W X 8H

Exhibit 5. Snapshot of the Dashboard Worksheet

Inputs	
Demand, tools per day	**8**
Standard Deviation of Daily Demand	**4**
Number of MD on Books	**95**
DFP	**3%**
Failed	**3%**
CO maintenance Capacity, tools per day	**12**
OK Final Configuration Capacity, tools per day (for Postponement Only)	**12**
Standby Time on Site Average, hours	**42**
Standby Time Standard Deviation	**12**
Waiting for Pickup time average, hours	**42**
Waiting for Pickup time standard deviation	**12**
Cost of Milk Run, dollars per mile	**3.5**
Hot Shot Rate Markup, dollars per mile	**0.20**
Average Shipment Size - Planned	**1.38**
Average Shipment Size - Call Out	**1.11**
Minimum Inventory level for Rockies, % of total (for Postponement only)	**10%**
# of days in backlog to start expediting planned shipments	**2**
Randomization of returns (for demand level > 6 per day)	**Yes**

Outputs		
	Pure Hub-and-spoke	**Hub-and-spoke with Postponement**
Average on-time deliveries	**95%**	**99%**
Lowest level of on-time deliveries	**94%**	**95%**
Percentage of Lost Sales	**0.00%**	**0.00%**
Logistics Spend	**7,993,865**	**6,282,489**
Savings Vs Point-to-point	**13%**	**32%**

Exhibit 6. Hub-and-spoke with Postponement Inventory Worksheet

	1					2											3										
	Tools on Books	DFP	Failed	Rockies Inventory	Available	Beg. Inv.	Tools In	Mtc. Caoacity	Mtc. Not Done	Tools Done	Rockies Planned	Rockies Call Out	Rockies Filled	Rockies Not Filled	Tools to OK	End. Inv.	Beg. Inv.	Tools In	Tools from CO	Planned Demand	Call-out Demand	Can Fill CO out of Inv	Config Capacity	Config Done	Ship Out	Delayed Shipments	End. Inv.
1	95	3%	3%	10%	89	69	-	10	59	10	1	-	1	-	9	59	20.00	-	-	2	1	1	10	3	3	-	17
2	95	3%	3%	10%	89	59	1	10	50	10	2	-	2	-	8	50	17.00	-	9	2	2	2	10	4	4	-	22
3	95	3%	3%	10%	89	50	2	10	42	10	2	-	2	-	8	42	22.00	-	8	2	2	2	10	4	4	-	26
4	95	3%	3%	10%	89	42	2	10	34	10	-	1	1	-	9	34	26.00	-	8	12	4	4	10	10	10	6	24
5	95	3%	3%	10%	89	34	1	10	25	10	3	1	4	-	6	25	24.00	-	9	1	1	1	10	8	8	-	25
6	95	3%	3%	10%	89	25	4	10	19	10	-	-	-	-	10	19	25.00	-	6	4	2	2	10	6	6	-	25
7	95	3%	3%	10%	89	19	-	10	9	10	-	-	-	-	10	9	25.00	-	10	4	1	1	10	5	5	-	30
8	95	3%	3%	10%	89	9	-	10	-	3	1	-	1	-	2	6	30.00	3	10	5	3	3	10	8	8	-	32
9	95	3%	3%	10%	89	6	4	10	-	3	1	-	1	-	2	7	32.00	6	2	6	3	3	10	9	9	-	25
10	95	3%	3%	10%	89	7	7	10	4	7	2	-	2	-	5	7	25.00	7	2	8	4	4	10	10	10	2	17
11	95	3%	3%	10%	89	7	9	10	6	9	1	-	1	-	8	7	17.00	11	5	3	1	1	10	6	6	-	16
12	95	3%	3%	10%	89	7	12	10	9	10	1	-	1	-	9	9	16.00	8	8	1	1	1	10	2	2	-	22
13	95	3%	3%	10%	89	9	9	10	8	10	2	-	2	-	8	8	22.00	6	9	2	1	1	10	3	3	-	28
14	95	3%	3%	10%	89	8	8	10	6	9	-	-	-	-	9	7	28.00	3	8	3	1	1	10	4	4	-	32
15	95	3%	3%	10%	89	7	3	10	-	3	-	-	-	-	3	7	32.00	8	9	6	2	2	10	8	8	-	33
16	95	3%	3%	10%	89	7	8	10	5	8	1	-	1	-	7	7	33.00	9	3	2	1	1	10	3	3	-	33
17	95	3%	3%	10%	89	7	10	10	7	10	-	1	1	-	9	7	33.00	11	7	4	1	1	10	5	5	-	35
18	95	3%	3%	10%	89	7	12	10	9	10	2	-	2	-	8	9	35.00	5	9	7	3	3	10	10	10	-	34
19	95	3%	3%	10%	89	9	7	10	6	9	2	2	4	-	5	7	34.00	-	8	6	1	1	10	7	7	-	35
20	95	3%	3%	10%	89	7	4	10	1	4	1	-	1	-	3	7	35.00	4	5	3	1	1	10	4	4	-	36
21	95	3%	3%	10%	89	7	5	10	2	5	3	-	3	-	2	7	36.00	5	3	4	3	3	10	7	7	-	32
22	95	3%	3%	10%	89	7	8	10	5	8	2	-	2	-	6	7	32.00	6	2	1	1	1	10	2	2	-	32
23	95	3%	3%	10%	89	7	8	10	5	8	-	-	-	-	8	7	32.00	6	6	3	1	1	10	4	4	-	34
24	95	3%	3%	10%	89	7	6	10	3	6	-	-	-	-	6	7	34.00	7	8	-	-	-	10	-	-	-	42
25	95	3%	3%	10%	89	7	7	10	4	7	2	-	2	-	5	7	42.00	11	6	5	3	3	10	8	8	-	40
26	95	3%	3%	10%	89	7	13	10	10	10	2	1	3	-	7	10	40.00	4	5	3	1	1	10	4	4	-	41
27	95	3%	3%	10%	89	10	7	10	7	10	4	-	4	-	6	7	41.00	9	7	9	5	5	10	10	10	4	38
28	95	3%	3%	10%	89	7	13	10	10	10	3	1	4	-	6	10	38.00	6	6	3	1	1	10	8	8	-	36
29	95	3%	3%	10%	89	10	10	10	10	10	2	-	2	-	8	10	36.00	1	6	8	4	4	10	10	10	2	32
30	95	3%	3%	10%	89	10	3	10	3	6	3	-	3	-	3	7	32.00	6	8	4	3	3	10	9	9	-	31
31	95	3%	3%	10%	89	7	9	10	6	9	1	-	1	-	8	7	31.00	1	3	2	1	1	10	3	3	-	31
32	95	3%	3%	10%	89	7	2	10	-	2	1	-	1	-	1	7	31.00	6	8	4	2	2	10	6	6	-	33
33	95	3%	3%	10%	89	7	7	10	4	7	2	1	3	-	4	7	33.00	5	1	7	2	2	10	9	9	-	25
34	95	3%	3%	10%	89	7	8	10	5	8	2	-	2	-	6	7	25.00	8	4	2	1	1	10	3	3	-	26
35	95	3%	3%	10%	89	7	10	10	7	10	1	-	1	-	9	7	26.00	11	6	1	1	1	10	2	2	-	30
36	95	3%	3%	10%	89	7	12	10	9	10	1	1	2	-	8	9	30.00	10	9	3	1	1	10	4	4	-	35
37	95	3%	3%	10%	89	9	12	10	11	10	1	1	2	-	8	11	35.00	6	8	1	-	-	10	1	1	-	42
38	95	3%	3%	10%	89	11	8	10	9	10	-	-	-	-	10	9	42.00	4	8	1	1	1	10	2	2	-	48
39	95	3%	3%	10%	89	9	4	10	3	6	-	1	1	-	5	7	48.00	8	10	6	2	2	10	8	8	-	50

Exhibit 7. Explanation of Line-by-Line Inventory Flow Logic for the Postponement Network Configuration

Please refer to the first line of Exhibit 6. The model does the following:

1. It takes the total number of tools on books and subtracts the DFP and Failed percentages to arrive at the number of tools actually available for drilling – 89 tools are Available; this number initializes the combined inventory at OK and CO. Rockies Inventory, an input, establishes the minimum level of inventory to maintain in CO.

2. With 69 tools staged in CO, the model adds any tools that may have come in from either OK or the field (Tools In), after which it compares the on-hand inventory with available maintenance capacity and determines how many tools will be processed (Tools Done). This number is the lowest of what's available in inventory and the maintenance capacity constraint (Mtc. Capacity). Then, the model takes the simulated demand levels (Rockies Planned and Rockies Call Out) and determines if there is sufficient inventory on hand to fill such demand. Rockies Filled shows how many units are shipped out to Rockies – 1 in this case – and the last calculation determines how many tools are available for shipping to OK via a milk run (Tools to OK), 9 in this case. Lastly, the Ending Inventory is calculated by taking account of what came in and what came out of the CO facility on that day.

3. The tools that are shipped to OK are assumed to arrive the next day, so the 9 tools that left CO on day 1 will arrive in OK on day two (Tools from CO). This number is added to Beginning Inventory to determine how many tools are available for final configuration. The Tools In column shows how many tools return from the field on that day; this number is assumed to be moved to CO via a milk run, with tools arriving in CO one day later. Planned Demand and Call Out Demand columns contain simulated demand levels for the OK-serviced basins. The model than compares the demand levels with the available inventory and capacity levels and determines how many units can be configured and shipped out (Ship Out). If more units are demanded that can be processed, the model records a delayed shipment (Delayed Shipments) and carries this backlog to the next period. Lastly, the Ending Inventory at OK is computed.

Having completed an analysis of stocks and flows of inventory in this fashion, the model moves on to the next time period and proceeds according to the same logic.