Chair of Drilling Engineering and Well Completion

Master Thesis

Factory Drilling: A Lean Manufacturing Approach to Drilling Operations

Written by:
William Duffy, BSc
m1135497

Advisor:
Univ.-Prof. Dipl.-Ing. Dr.mont. Gerhard Thonhauser

Leoben, 21.06.2016

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Kurzfassung

Techniken zur Effizienzsteigerung werden in der Bohrindustrie erfolgreich eingesetzt um die Bohrkosten zu reduzieren. Leider werden sie dennoch von Bohrkontraktoren vernachlässigt, obwohl deren Hauptziel die Steigerung des Umsatzes ist. Wenn Operatoren Chancen zur Verbesserung nicht wahrnehmen, können Ineffizienzen bei Bohroperationen überhandnehmen. Einige Firmen produzieren beispielsweise die billigstmögliche Ausrüstung um die Kosten pro Bohrung zu reduzieren. Andere wiederum gehen so weit und legen ihre Bohrungen unterhalb der Mindeststandards aus, wenn sie das Gefühl haben, dass der Qualitätsverlust das Risiko und die gesparten Ausgaben rechtfertigt. Ineffizienzen und minderwertige Auslegung versuchen jedoch so gut wie in allen Fällen eine Erhöhung der Bohrungskosten, entweder sofort, in Form von langsamem Bohrfortschritt oder später im Lebenszyklus der Bohrung, wenn die minderwertige Ausstattung versagt und teure Sondenbehandlungs- und Reparaturarbeiten notwendig sind.

Das „Lean Manufacturing“ Konzept hat sich in vielen Industrien durchgesetzt um die Effizienz zu optimieren und die Kosten zu senken. Vereinfacht gesagt, wird bei dieser Methode unnützer Ballast in der Produktion beseitigt, während der Wert für den Kunden maximiert wird. Die Öl- und Gasindustrie stellt hier keine Ausnahme dar, da auch hier mit diesem Konzept Lieferung und Kosten optimiert werden, sei es bei Bohrungen im Fall von Operatoren oder bei Werkzeugen und Ausrüstung im Fall von Servicefirmen. Auch das Bohren selbst kann durch dieses Verfahren optimiert werden, indem Ineffizienzen beseitigt, die notwendigen Ressourcen reduziert, Kosten minimiert und die Qualität beibehalten werden.

In Anerkennung der Tatsache, dass die Wirtschaftlichkeit von Projekten weltweit gesteigert werden muss, hat sich eine der führenden Öl- und Gasfirmen dazu entschlossen eine Kampagne zu starten um in sämtlichen Gebieten und Funktionen die Effizienz zu steigern und Kosten zu reduzieren um die finanziellen Ziele zu erreichen. Diese Arbeit betrachtet, wie eine der Bohrmannschaften im Unternehmen die Konzepte des „Lean Manufacturing“ übernommen hat und effektiv sowohl die Kosten als ich die Zeit reduziert hat um eine Bohrung fertigzustellen.

Abstract

Drilling efficiency optimization techniques are proven at reducing well costs. Unfortunately, they are often neglected by operators, even when their primary focus is to maximize revenue. Inefficiencies can inundate drilling campaigns, usually as a result of operator's being blind to opportunity. To achieve well cost reductions, some operators will procure the cheapest available equipment. Others will go as far as designing their wells below minimum standards if they feel that the sacrifice in quality and specification is worth the risk and money saved. Inefficiencies and sub-standard designs almost always cause increased well costs, either right away, as the case is with slow drilling in typical day rate contract , or later on in the well life cycle, when costly work overs and remedial operations are required when the substandard equipment fails.

Lean manufacturing has been accepted across a wide array of industries as the most proven method for optimizing efficiency and reducing operating cost. In essence, Lean is the elimination of waste while maximizing value to the customer. The oil and gas industry is no exception as Lean has been successfully used for improving product delivery and cost, whether its wells in the case of operators or tools and equipment in the case of service providers. Drilling, a component of the overall well construction process, can be optimized through Lean concepts by removing inefficiencies, reducing required resources, minimizing costs and maintaining product quality.

In recognition of the need for improving project economics world-wide, a major international oil and gas company instated a campaign to improve efficiency and reduce costs across all areas and function groups to help meet financial goals. This paper reviews how one of the company's drilling teams adopted Lean methodologies and effectively reduced the costs and days to drill wells in North Dakota in an infill development drilling campaign without sacrificing quality standards.

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1. Introduction

Reducing drilling days through efficiency improvements is an effective method for achieving well cost savings in a standard Rig Operating Rate scenario with spread rates in the $90,000/day range. On average, the time to drill an onshore well is comprised of 35-50% on-bottom drilling time, with the rest of the time being consumed by flat time operations. Flat time operations are any activities that do not result in the hole being deepened but are required to drill the well, and should not be confused with undesirable Non-Productive Time (NPT). This implies that over half of the overall drilling time is taken up by non-drilling activities. Within the drilling process are embedded inefficiencies, that when eliminated will reduce the amount of time required to deliver wells to the next internal customer of the overall well construction process.

A tremendous amount of focus in the industry has been devoted to improving penetration rates with little attention to flat time operations that book-end any on-bottom drilling time. As on-bottom drilling time is reduced through technological advances and improved drilling practices, the total percentage of flat time operations becomes a larger component of the overall time to drill a well. Improving flat time operations should be as high of a priority as on-bottom drilling.

One approach to improving the drilling process is through implementation of Lean concepts. Lean essentially is a critical review of a process with the goal of recognizing and eliminating non-value adding activities known as “Waste”, while maximizing value to the customer. In this situation, drilling is the process under review, with the well as the manufactured product and the completions group as the customer. The steps to drill a well in a development infill scenario should be, for the most part, fully repeatable and readily optimized similar to assembly line production in a factory. Though this should be the case, variability runs rampant in most drilling campaigns. It is not uncommon for two rigs with identical configurations, drilling in similar geologies, and following the same procedure, to drill their wells in different manners and in varying amounts of time.

The first step towards efficiency optimization should be the elimination of variability, ensuring that all rigs perform the drilling process the same. Once this is achieved, a reduction in standard deviation and average drilling days will be realized. The following and forever ongoing steps should then be striving for process optimization through the quest and elimination of embedded process waste. Perfection is never fully achieved but should always remain as the ultimate goal.

1.1. Scope of Thesis

Lean has been used across a wide array of industries to improve product delivery both from an efficiency and cost perspective. This thesis reviews the applicability of Lean to the oil and gas industry, in particular the drilling process of the overall well construction process. The paper is written in third person but is an account of my experiences working for an operator, whose identity will be kept private, and our journey with Lean and the pursuit of drilling process perfection.

2. Literature Review

Lean Drilling – Introducing the Application of Automotive Lean Manufacturing Techniques to Well Construction (de Wardt 1994)

Lean methodologies developed in the automotive industry can be applied to drilling operations to successfully improve efficiency and cost. Lean production combines the advantages of craft production and mass production while avoiding the high cost of the former and rigidity of the latter. Because of the highly customized design in many well construction processes, drilling is most analogous to craft production. In some areas of operations, a large scale of repetition of similar wells has allowed for standardization and mass production to be achieved after enduring a typical learning curve in the early phases of developing a new area.

Developing a close relationship with suppliers, to the level of partnerships or alliances, is essential to the implementation of Lean. Relying on a supplier's knowledge and skill set permits a reduction in time through the offline assembly of products required for the primary process, and the efficient use of specialized tools. This reliance removes some of the detailed engineering, design and execution management from the owner/operator of the well. Suppliers are viewed as integral to the entire production process and incorporated into all phases of the product from design, execution and lastly to evaluation.

Similar to the automotive industry in the incorporation of technology, directional drilling and the drilling of horizontal wells has allowed for production increases at lower cost per barrel. Further improvements must come through organizational improvements through Lean production methods. What the automotive industry incorporated was breaking the entire process into sub assembly components which constitute logical and efficiently combined elements of the final product. Lean production has evolved the relationships of each manufacturer of a process to achieve significantly increased efficiency and quality in the overall process.

Implementing Lean Manufacturing Principles in New Well Construction (Charles, Deutman, and Gold 2012)

Aera Energy LLC based out of California is in an intensive drilling program manufacturing 1000+ producers and water/steam injectors per year. Due to the high level of activity involving around 800 contractors, logistics can be quite complex and rife with inefficiencies. Realizing the need to improve their operational efficiency, Aera set out on an improvement journey starting in 2001 surveying multiple industries for the most effective way of achieving their desired improvements. The management team settled on Lean principles to meet their goals.

Some of the problems that Aera identified were large, hard to manage projects, very long-lead planning times prior to spud and difficulty implementing the major steps in the process – building facilities, drilling, well completion and well hook-up. This lead to major congestion issues in the field.

Aera created a Development Team to make use of continuous flow process to level load the work and eliminate waste. The Development Team is broken into two sub-groups, the Design Team and the Implementation Team, who have specific responsibilities working through “gates” with well-defined deliverables. The Development Team integrated the various functions required for the Well Construction Process, i.e. reservoir, geology, drilling, and operations. Aera found that reducing the waste in processes, continuous improvements, using a pull system, level loading production, mapping the value stream, finding and fixing problems and transparency through visual controls were the Lean tools most applicable to their improvement efforts.

Part of the Lean transition required a cultural change and also a modification of the conventional manufacturing concept that instead of the product moving past stationary workers, the workers moved past a stationary product. There was also the need to establish alliances with suppliers that could be trusted and would take part in the continuous improvement efforts on their own.

For the project to be successful, Aera recognized that leadership commitment, discipline and persistence, trust between Aera and their suppliers and excellent information management and technology were paramount.

Application of Lean Six Sigma in Oilfield Operations (Buell and Turnipseed 2003)

Lean Six Sigma and International Standardization Organization (ISO) systems can be used in conjunction with each to create sustainable, continuous improvement in upstream operations. Lean Six Sigma is marriage of Six Sigma, a process-improvement methodology that focuses on delivering products at a lower cost, with improved quality and reduced cycle time by reducing process variation, and Lean, a process-improvement methodology that focuses on removing non-value-added activity and aligning production with customer requirements. Historically Lean advocates recognized Six Sigma as a tool that supported Lean and Six Sigma advocates recognized Lean as a tool for reducing cycle time and inventories, but the two approaches were also viewed as competing with each other. Only within the last few years were the two methods merged into a single process-improvement methodology: Lean Six Sigma. ISO is used for controlling operating procedures, assessing the capability of quality systems, sustaining continuous improvement, and managing records and documents.

Six Sigma makes use of mathematical equations to measure variability and are as follows:

Process Capability Potential

$$\mathbf{C_p = (USL - LSL)/6\sigma} \qquad \textbf{Equation 1}$$

Process Capability

$$\mathbf{C_{pk} = \text{minimum of } [(USL - xbar)/3\sigma \text{ or } (xbar-LSL)/3\sigma]} \qquad \textbf{Equation 2}$$

Sigma Level

$$\mathbf{\sigma_{level} = \text{minimum of } [(USL-xbar)/\sigma \text{ or } (xbar-LSL)/\sigma\ ]} \qquad \textbf{Equation 3}$$

Quality is improved through increasing the σ_{level} and reducing the number of process steps. Lean Six sigma works both dimensions to accomplish quality improvement.

A fusion of Lean Six Sigma and ISO was used for a series of improvement projects in North America and Asia. An example of the projects was improvement to Rod-Pump Repair through reducing the number of pump designs, a reduction in inventory, reducing the number of pump storage locations, new dedicated pump delivery service, more insert pump designs, an audited ISO 9001 quality system to improve the rating of pump repair shops, and optimized settings of the internal pump clearance to maximize pump run life.

Overall 11 projects in North American oil fields, resulting in a net benefit of $500,000 per project, and 16 projects in Southeast Asian oil fields, resulting in a net benefit of $1,000,000, were successfully completed.

Application of Lean Principles to Accelerate Project Development (Tønnessen et al. 2015)

In effort to reduce the total amount of development time for smaller fields in offshore Norway, Lean principles were used to "Fast Track" the process from beginning to end. Since the discoveries of major field with complex designs are decreasing, an improved, faster and less expensive approach is required to develop the smaller fields. A team was assembled that used the following to achieve their improvement goals.

- Standardization
- Collaboration
- Streamlined process
- Change Management

Through their efforts, the total time required to develop a project reduced from 5.3 days down to just over 3 days.

Through standardization, the team was able to reduce the number of complex, customized designs that required long lead times to a few designs that could be widely used. A well design was chosen based on a basis of design with standardized design options that were selected on the following constraints

- Maximum well pressures, temperatures and depths
- Casing programs
- Well completion options

If a well could not be designed based on the criteria, it did not qualify for Fast Track

Through collaboration the team was able to accelerate the long lead time that was normally required for planning. One example is the directional plan development that would require multiple weeks of back and forth emails between the directional planner and the geologist to agree on a design. This was improved through a meeting with the lead engineer, the well planner and the subsurface specialist to agree with a plan in only a few hours.

The streamlined process improvement made revisions to the way a project was planned such as whether a well met the Fast Track criteria. The initial decision gate 0 would already have established whether a project met the conditions or not. Once a project was selected as Fast Track, then well planning could start instead of waiting for project sanctioning and performing the tasks in sequence.

Change Management was required to insure success of the Fast Track process change since this would require adoption of new ways of planning. The team needed to be comprised of individuals that would embrace the change and adapt quickly. The individuals needed to be able to provide the necessary value to the project and engage in regular Fast Track Workshops for planning. Involvement from Management was also required to identify KPIs that would track the success of the project.

3. Lean Manufacturing

Lean is the relentless pursuit of perfection through the elimination of waste. Lean maximizes value to the customer through process and resources optimization. Lean has become regarded as one of the most effective process improvement methods.

3.1. Background of Lean

The Lean principles in place today evolved over the latter half of the twentieth century starting in the early 1950’s in Japan. Lean manufacturing married the efficiency of mass production with the attention to detail and quality of craft production. One of the most famous and successful early initiatives for mass production that contributed the development of Lean, came from Henry Ford when he developed flow production for automobiles. Flow production made use of a combination of interchangeable parts and assembly line conveyance passing the production components past stationary workers to quickly manufacture automobiles (Lean Enterprise Institute 2016a). The process was established to fully incorporate repetition within stations through standardized work and designed-for-purpose tools and machinery that could be operated by minimally skilled employees and go/no-go gauges. Ford’s desire was to manufacture the Model T, his most successful vehicle for the masses in the early 1900’s, at fast rates and affordable prices through his “flow production” manufacturing process. His automobile became so popular domestically in the US that he opened a manufacturing plant in the UK and made the Model T available for Europe.

After a while, the public grew bored with the standardized design of the Ford’s vehicles yearning for variety. Unfortunately for Ford, customization was very difficult, expensive and time consuming to achieve as the fit for purpose machinery used for manufacturing his automobiles could not easily be changed over. Customers desiring change could only resort to craft car manufacturers which meant longer wait times for the specialized production and much higher prices.

In response to the public’s desire for variety, other automobile manufacturers offered customization such as GM who offered yearly “hang-on features” which could be installed to existing body designs to sustain customer interest (Womack, Jones, and Roos 1990a). Although, the public was pleased with the alternatives, the new design changes meant that the other car manufacturing companies lagged in through put times compared to Ford since extra processing was involved. In effort to become more efficient, the companies invested heavily in the latest most expensive machines that would increase the production rates at specific stations but often led to the buildup of inventories in between stations as one out-paced the other. These machines also were often difficult to set up and change out parts. Should an error in the manufactured parts occur, instead of stopping the assembly line to address the issue, the error would remain throughout the manufacturing process and be fixed on the back end. This led the need of additional resources to fix problems afterwards and often resulted in a loss in quality.

While the US pioneered and was fully embracing mass production achieving maturation with time, Japan lagged behind the rest of the automotive industry. Understanding the general public's desire for variety but also recognizing that there were considerable inefficiencies in mass manufacturing processes that already existed, Kiichiro Toyoda, Taiichi Ohno and others at Toyota focused their attention on the entire automobile manufacturing process instead of the performance of individual machines and their utilization. The need for optimizing resources was driven by a shortage of resources, both human and supplies post World War II. Toyota concluded that by right-sizing machines for the actual volume needed, introducing self-monitoring machines to ensure quality, lining the machines up in process sequence, pioneering quick setups so each machine could make small volumes of many part numbers, and having each process step notify the previous step of its current needs for materials, it would be possible to obtain low cost, high variety, high quality, and very rapid throughput times to respond to changing customer desires (Lean Enterprise Institute 2016a). This shift became known as the Toyota Production System (TPS).

The Toyota Production System was based on two main concepts that formed the pillars of the operation **(Fig. 1)**. The first was built-in quality which came through automation with a human touch, known as Jidoka in Japanese. Toyota implemented a requirement that should an error in a manufactured part occur, the entire production line would be stopped and the error resolved before manufacturing could resume. This philosophy focused on delivering high quality products to the customer with the customers' needs as the main driver. The second pillar was Just-In-Time (JIT) manufacturing which is an inventory management philosophy where parts would only be manufactured on an as needed basis, eliminating the unnecessary and wasteful build-up of inventory. Downstream partners would pull parts from upstream partners only when the part was required. In conjunction with the pillars, Ohno recognized the importance of buy-in from everyone involved in the manufacturing process for continuous improvement and that without the human component, the operation would be unsuccessful. Employees needed to feel empowered and have a desire to strive for perfection for improvements to be achieved. TPS is maintained and improved through iterations of standardized work and kaizen.

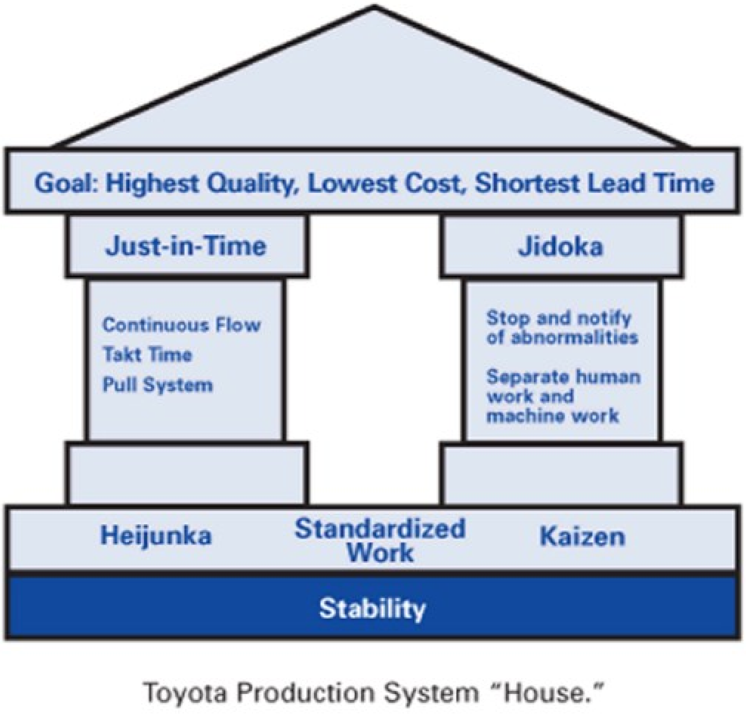


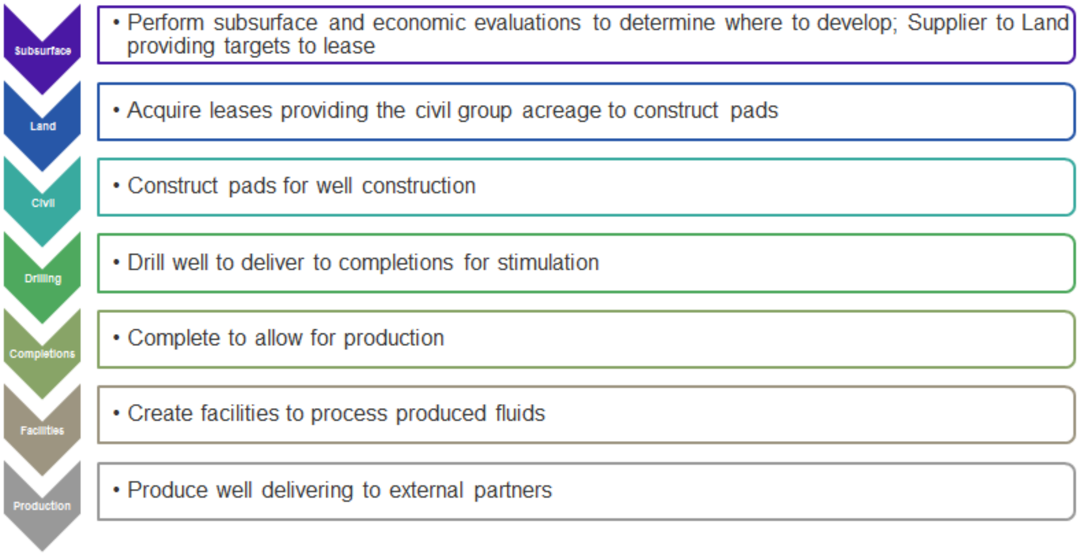
Fig. 1 - Toyota production system "House" (Lean Enterprise Institute 2016b).

In the book *The Machine that Changed the World* (Womack, Jones, and Roos 1990b) the author performs an in depth review of TPS and its success which he refers to as Lean production. The ultimate goal of Lean, is striving for perfection through the elimination of process waste, known as Muda in Japanese. Countless companies have since adopted Lean methodologies, spanning virtually all industries to an extent, to improve their processes, whether manufacturing a product or providing a service, to enhance efficiency and increase revenue. Examples of Lean in other industries are the medical field as demonstrated by Virginia Mason Medical Center in Seattle, Washington where they used lean to improve patient care processes (Miller 2015), the military with the manufacturing of defense equipment (Cook and John 2001) and World Wide Postal Services reducing processing costs while improving on-time deliveries (Miller 2005).

3.2. Lean in the Oil & Gas Industry

Lean improvement methodologies have yet to gain much traction in the Oil & Gas industry and seem to be lagging behind many other industries. Though this is the case, Lean is beginning to gain in popularity due to the need to reduce well costs with the current state of heavily depressed oil prices. Operators that are weathering the proverbial "Storm" the best are looking for ways to do more with less without sacrificing quality. If quality is neglected on the front end during the well construction process, the productive life of the well may be cut short or incur costly work overs to fix problems that should never occurred with proper design. Lean has successfully been used to varying degrees to assist some operators and service providers to maintain positive economics while other companies are shutting their doors.

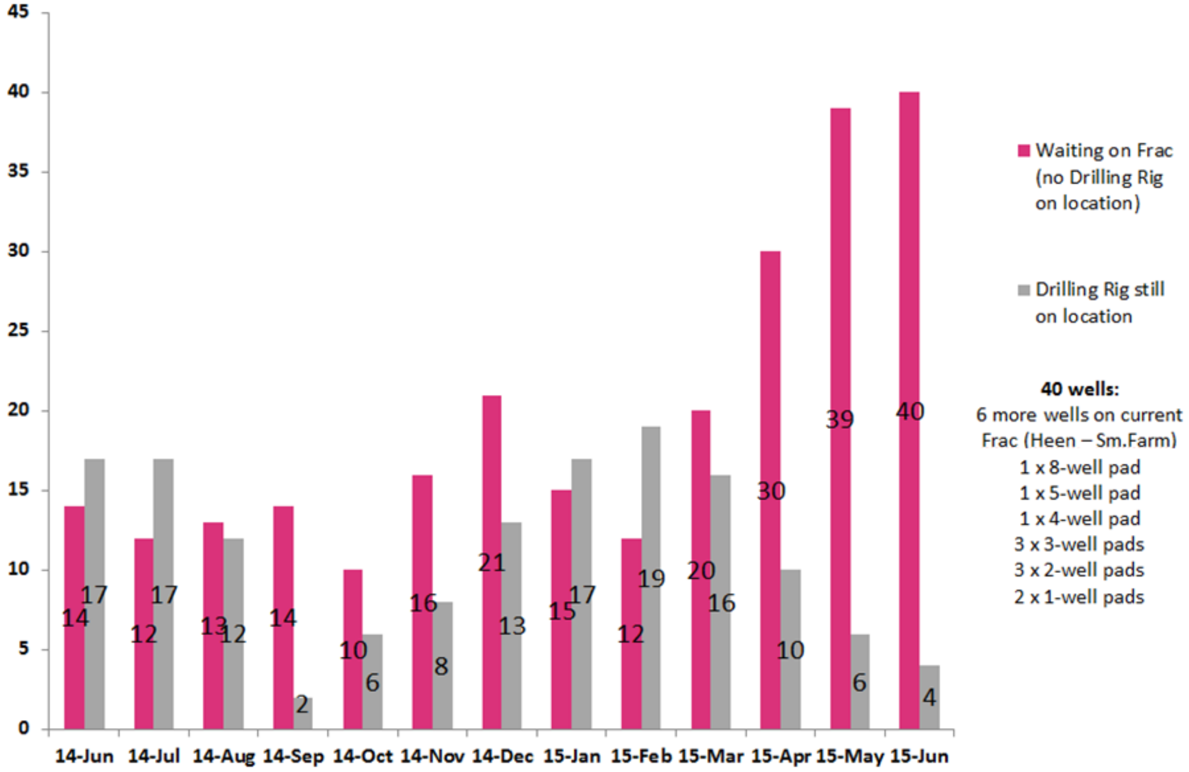
For operators Lean can be used to improve well delivery through reducing cycle time. Cycle time is the total amount of time required to deliver a well from planning all the way through first production which is the holistic view of the well delivery process. The well cycle time has several internal customers/suppliers. **Fig. 1** shows a breakdown of the entire well life cycle from planning within the Subsurface group to production of the well.



- Perform subsurface and economic evaluations to determine where to develop; Supplier to Land providing targets to lease
- Acquire leases providing the civil group acreage to construct pads
- Construct pads for well construction
- Drill well to deliver to completions for stimulation
- Complete to allow for production
- Create facilities to process produced fluids
- Produce well delivering to external partners

Fig. 2 - Well early life cycle.

Should one function group outpace another, then a costly buildup of inventory can cause a misalignment in capital expenditures to revenue. One example is an imbalance of drilling delivery to the completions delivery. Since the drilling process is easily repeatable compared to completions, which may undergo regular revisions to design since the ultimate productivity of a well can be heavily influenced by minor design changes in a complex multivariate scenario, efficiency improvements often cause excessive inventories to compound beyond what the completions group can handle. If this occurs the only way to correct the imbalance is to either reduce drilling activity by rig reduction, barring a loss of efficiency, or incorporation of additional frack fleets. **Fig. 2** is an example of an operator’s well inventory that was building between the drilling group and the completions group.



40 wells:
6 more wells on current Frac (Heen – Sm.Farm)
1 x 8-well pad
1 x 5-well pad
1 x 4-well pad
3 x 3-well pads
3 x 2-well pads
2 x 1-well pads

Fig. 3 - Well inventory for operator in the Williston Basin.

The grey bars represent wells that were drilled but had yet to be released to completions since the rig was still on the pad batch drilling the remaining wells. The magenta bars are wells that had been released by drilling with the rig moved off the pad ready for stimulation operations. The buildup of inventory due to drilling outpacing completions caused the well cycle time to increase beyond acceptable limits as defined by management. Later on in the year, the operator released several rigs which allowed for the inventory of wells to be reduced to appropriate levels.

Wells in the state of “Drilling rig still on location” is an example of one of the drawbacks associated with batch-and-queue manufacturing in a multi-well pad scenario and the prolongation of cycle time. Batch-and-queue is manufacturing a large batch of a single part to reduce the frequency of changing out equipment. The cost and efficiency savings associated with drilling multiple wells per pad and reducing the number of rig moves outweighs the temporary buildup of inventory.

Aera Energy LLC, based out of California, is an example of a company that incorporated Lean to improve the delivery of their wells. Their operations consist of drilling and completing over 1,000 producers and steam/water injectors per year. With such an active schedule, Aera often found that logistics could be quite difficult to coordinate with over 800 service providers involved in their operation. Some of the problems that Aera identified were large, hard to manage projects, very long-lead planning times prior to spud and difficulty implementing the major steps in the process – building facilities, drilling, well completion and well hook-up (Charles, Deutman, and Gold 2012).

To improve the well construction process, Aera assembled a development team that consisted of members from subsurface, drilling and operations. Their goal was to find waste in processes, level load the operation, perform value stream mapping, move away from batch-and-queue and "push", which means to move a product to a customer without a request, to a "pull" system, manufacturing a product on an as needed basis, and implement continuous improvement. The team also made use of visual tools to provide transparency to problems that needed addressing address.

Through the incorporation of Lean, Aera was able to make substantial improvements to well delivery. At the time the article was written, the Lean implementation program was in its tenth year which highlights the fact that the Lean journey takes time and is not an overnight sensation. As waste from their process was eliminated over the decade, new opportunities would become visible which has allowed Aera to maintain a state of continuous improvement. Their efforts have resulted in the consistent release of 1,000 wells per year while maintaining price stability despite oil price volatility. The company also achieved a reduction in Total Recordable Injury Rate despite the high count of contractors.

Another company with operations offshore Norway successfully used Lean to reduce the development of a new project from 5.2 years down to 3. Through the establishment of a selection process, a field that met specific conditions could be "Fast Tracked" to reduce the amount of time required for development. The Fast Track team made use of Value Stream Mapping, starting from discovery to production, to determine each step and associated lead time of the development process and then targeted opportunities for improvement that became visible.

Service providers to the Oil and Gas industry have also made use of Lean to improve delivery of services and products. Tools and equipment used for the well construction process fall closer in line with the typical model of a product manufacturing factory from which Lean evolved. A customer, in this case an operator, places an order for a product, such as a drill bit, which goes through the manufacturing process starting from raw material, passed along from station to station as it is assembled until a final product emerges.

Since operators often make same day requests for a product, service providers must maintain an appropriate inventory of products to prevent costly delays to the well construction process. Proper planning and projections of customer demand are essential to balance out the production of new tools without building of unnecessary inventories.

Sakhardande (2011) surveyed multiple oil and gas equipment producers and service providers and found the following Lean tools most widely applicable to process improvements.

- Kanban – A pull system to manufacture parts only on an as needed basis
- 5S – Used for organization and neatness within work stations or factories
- Poka – Yoke – Mistake proofing or building checks into a process to reduce mistakes
- TPM (Total Productive Maintenance) – A maintenance program used to keep equipment in top condition
- Kaizen – Continuous improvement

- Cellular Manufacturing – Arranging stations in logical order for streamlined production
- SMED (Single-Minute Exchange of Dies) – Used for quickly setting up or changing out equipment
- Value Stream Mapping – A map used to identify the steps and associated time of a process and embedded waste
- Leveled Production – A method for leveling the production of an order over a period by evenly distributing the daily production volume across the total number of days in the period
- Standard Work – A benchmarking tool for tracking employee delivery
- Jidoka – Automation of machinery with a human touch
- Seven Quality Tools – Graphical tools that are used to troubleshoot issues related to delivery and quality

Based on the results from Sakhardande survey, 5S, TPM, Kaizen and the 7 Quality Tools were the lean concepts most widely used in the service industry.

4. Application of Lean to Achieve Drilling Process Improvements

The application of lean concepts to improve drilling operations is not new with one of the earliest documented cases dating back to 1994, a short 4 years after the release of Womack's (1990b) first lean publication. This work was performed by John de Wardt where he used lean techniques to assist British Petroleum (BP) in the construction and management of wells in their Andrew project (De Wardt & Company, Inc. 2016). De Wardt developed a tool box of lean concepts that he could apply to drilling and completion operations which he called Lean Drilling^{TM}. Since 1994, de Wardt has applied Lean Drilling^{TM} to assist a number of oil and gas companies worldwide in achieving step change improvements followed by establishing continuous improvement methods that the operators can carry on sustainably without continuous consultation.

Over the years after the establishment of Lean Drilling^{TM}, other consulting companies have emerged that specialize in using lean to assist operators in improving drilling operations. The majority of these companies rely on in-depth knowledge and understanding of oil and gas operations plus lean improvement concepts to provide a marketable service. Though these companies may be lean experts, operators can adopt lean concepts independently without any formal training.

In 2013, an oil & gas producer with operations in North America set out on a campaign to improve their drilling efficiency through the use of lean concepts. Their goal was to reduce the amount of time and cost to drill their wells without sacrificing quality. The remainder of this thesis focuses on one of the operator's drilling team's journey applying lean, to achieve improvements without the assistance of a consulting company.

4.1. Drilling Operations in the Williston Basin

The company's operations discussed in this thesis are in the Williston Basin, located in North Dakota, and consists of drilling and completing horizontal wells targeting the Bakken and the Three Forks formations. Well True Vertical Depths (TVD) range from 10,100' to as deep as 11,300' with Measured

Depths (MD) in the +/-20,000' range. Well designs consist of 9-5/8" surface casing with shoe depths at +/- 2,000', a 7" intermediate casing string installed from surface to the landing point of the curve and a production liner installed from target depth of the well to 150' above the Kick Off Point (KOP) of the curve, hung off in the intermediate casing.

The drilling process starts with a turnkey contracted small capacity, truck mounted rig, often referred to as the "spudder rig", which drills the surface hole and installs the surface casing offline, prior to the primary rig moving onto the well. Since the contract is on a turnkey rate, if any problems are encountered while drilling the surface hole causing operational delays, the operator is sheltered from a price escalation associated with a typical day rate contract. This is an example of lean relying on an external supplier to provide a quality, pre-drilled surface hole off the critical path. Once the surface hole is complete, the spudder rig moves off the pad and the primary rig is then mobilized to the well and resumes drilling operations starting with the intermediate hole which extends from the surface shoe to the landing point of the curve. After the intermediate section had been drilled and cased off, the production hole is drilled horizontally to the Target Depth (TD) of the well after which a liner is installed with the hanger assembly set in the intermediate casing.

In North Dakota, it is common practice to drill multiple wells per pad together as a batch. This allows for a reduction in rig moves, which are costly in both time and money, to only one mobilization/de-mobilization per pad. The move costs can then be evenly split between all wells. In addition, drilling multiple wells per pad reduces the civil costs on a per well basis. The costs associated with constructing the pad can be evenly distributed to all wells instead of charged solely against one as is the case in a single well scenario.

Batch drilling starts with the intermediate sections drilled in sequential order until the last intermediate hole is drilled and cased off, at which point the rig continues drilling the production hole on that well. Before the production hole can be drilled though, the 5" drill string used for the 8-3/4" hole section must be laid down and the 4" drill string picked up for the 6" production hole. In addition, the synthetic based mud used to drill the intermediate hole must be pumped out of the tanks, which are then cleaned and filled with brine, the drilling fluid used for the lateral. Once completed, the remaining wells' production sections are drilled in reverse order. Although lean preaches that batch-and-queue is less efficient than "continuous flow", the time and cost associated with swapping out drill strings and drilling fluids tips the scale in favor of batch drilling. Well inventories undergoing batch drilling are kept low with the typical count limited to four. The internal customer, the completions group, also conducts their operations in batches fracking alternating stages across all wells in sequence, known as a Zipper Frac.

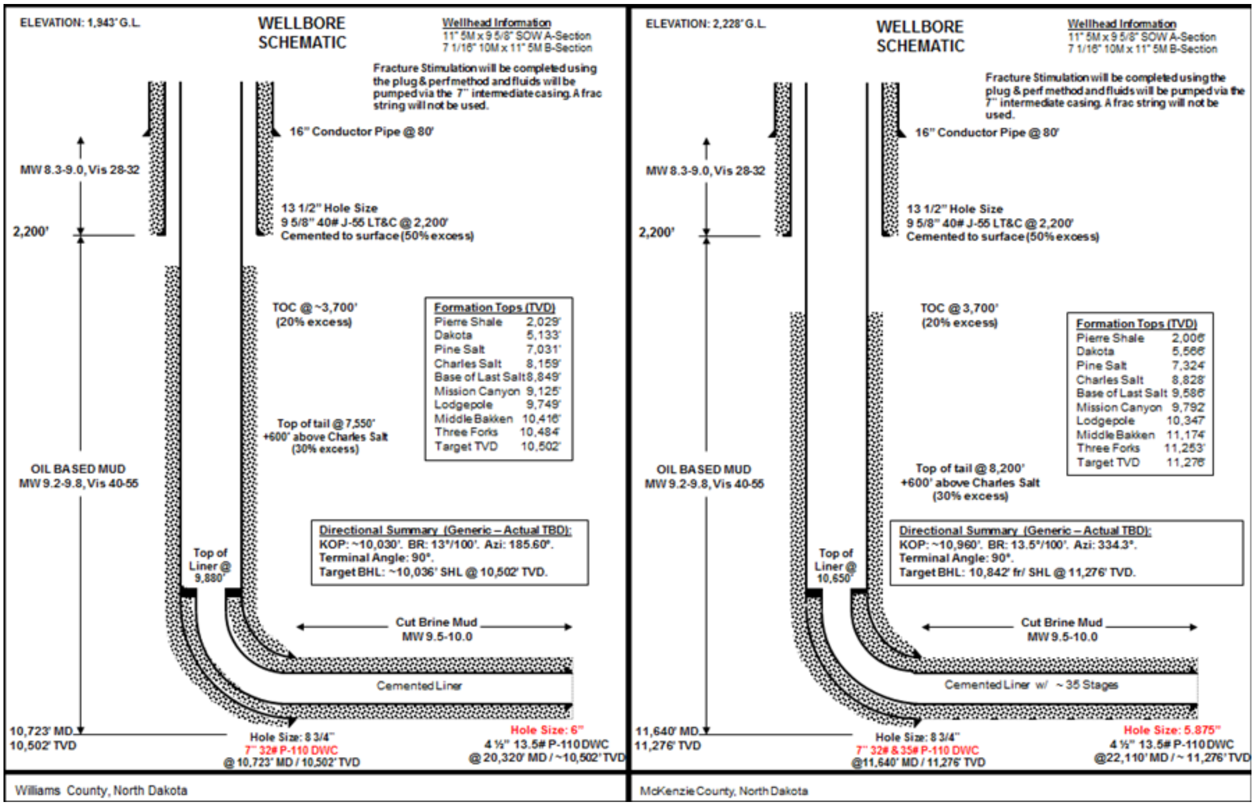


Fig. 4 - Wellbore diagrams of Bakken/Three Forks wells; standard casing design - left; enhanced casing design - right

The casing programs in the Williston Basin vary slightly based on location in the field due to geological differences. The design shown in **Fig. 4** on the left is used throughout the majority of the field. The enhanced casing design on the right in **Fig. 4** is used in an area where the salts are thicker and more ductile. Heavier casing with higher collapse resistance is required to counteract the loads exerted by the squeezing salts. Since the heavier casing has a reduced inner diameter, the production hole must be drilled with a 5-7/8" bit instead of the standard 6" used in the rest of the field. The differences in design have negligible impacts on drilling performance.

Operators in the Williston Basin target the middle dolomitic portion of the Bakken formation, which is sandwiched between upper and lower Bakken shale members, and the Three Forks, a primarily dolomitic formation mixed with mudstone and bituminous shale (Amicone 2014), is located just below the Lower Bakken Shale, **Fig 5**. In contrast to the Three Forks, the Bakken production laterals are easy to drill with one BHA in less than 100 hours. The Three Forks, on the other hand, is much tougher on downhole equipment. Bits have a tendency to core out often requiring replacement trips to reach TD. Embedded within the Three Forks are hard stringers that can cause sudden BHA deflections that, if uncontrolled in the upwards direction, can result in a Lower Bakken shale strike. Once the shale has been exposed, the well must be sidetracked due to wellbore instability and the risk of the BHA becoming stuck. The Three Forks is usually drilled in 125 to 150 hours barring any major setbacks.

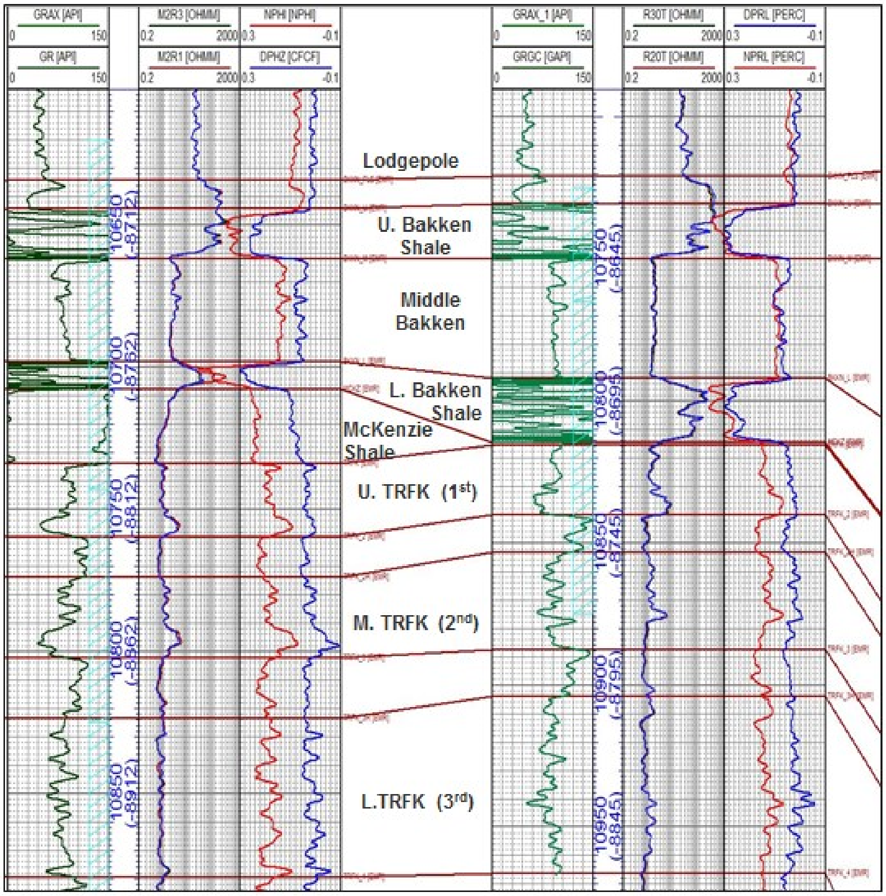


Fig. 5 - Type log showing the Bakken and Three Forks formations.

To preserve bit life in the abrasive Three Forks, the mud motor speeds are reduced compared to the standard Bakken Bottom Hole Assembly (BHA). Bits are also designed to be less aggressive with increased cutter densities, higher back rake angles and the addition of back-up cutters.

Besides the difference in casing weights, production hole sizes and the drillability of the Bakken vs the Three Forks, the process for drilling wells in the Williston Basin can be standardized. In general, the need for customized designs is rare if ever required in a standard operating year. Occasionally a geological anomaly or downhole equipment failure will require deviation from the standard drilling process or casing design.

When operators first started drilling horizontal Bakken and Three Forks wells, casing designs and drilling processes varied significantly usually customized based on uncertainties that exist when learning to drill in a new area. Because of the frequently changing designs, the well manufacturing process closely resembled craft production while going through the initial learning curve phase. At this stage in development, drilling operations in North Dakota more closely resemble mass manufacturing due to the repeatability in the process and standard well design. Process optimization is now the remaining goal which can be facilitated through lean implementation.

4.2. Defining a Quality Product

The drilling process is one component of the overall well construction process which has the goal of delivering oil and gas to an external customer at the lowest cost possible. The drilling team is an internal supplier of a drilled and cased off wellbore to the completions group who have the responsibility of stimulating the well to enable flow of oil and gas in tight reservoirs. The drilling team must consistently deliver quality wells, on time, with the internal customer's needs met. To the operator, the value of a well is defined through the following criteria.

General Criteria

- Successfully drill well to permitted target depth remaining within the Authorization for Expenditure (AFE) budgeted amount.
- Drill lateral 100% within the target window as defined by geology to maximize reservoir contact.
- Provide wellbore isolation from ground water
- Withstand future pressure loads associated with completions and production operations
- Serve as a conduit for produced fluids and as protective housing for the installation of tubing and associated artificial lift equipment

Bakken/Three Forks Specific Design Criteria

- Dogleg severities limited to less than 1° per 100' in the vertical portion of the well to reduce sidewall loading which can cause
    - severe intermediate casing wall wear while drilling the lateral resulting in a de-rating of the burst capacity,
    - the mandatory installation of a tie-back if the de-rated burst capacity of the intermediate casing does not provide enough safety factor for stimulation pressures,
    - increased tubing/rod wear once well is on rod lift
- The completions group must be able to open sleeves installed at the toe of the production liner to permit the pumping down of the first set of wireline conveyed perforating guns

If the drilling group manufactures a well with any of the design criteria not met, well economics are usually impacted either through impaired production or costly work overs troubleshooting problems. It is critical that constant communication between the supplier, the drilling group, and the immediate internal customer, the completions group, and the further down the line internal customer, the production group, is maintained to identify problems that may require modification of the design or process to prevent the issues from reoccurring.

4.3. Lean Through Collaboration

In 2013, the operator held a collaborative workshop, which they called a Well Time and Cost Reduction Workshop (WTRCW), where the performed an in depth review of their drilling process. This was their first exposure to lean in which they applied SMED to evaluate opportunity for improvement. Two years later the operator reconvened for another WTCRW which built on the first workshop but incorporated additional lean concepts.

4.3.1. Well Time and Cost Reduction Workshop I: SMED

The first lean evaluation of the operator's drilling operations was conducted during a WTCRW held in July 2013 where the process was mapped and evaluated for improvement opportunities by applying concepts from SMED. SMED was developed by Shigeo Shingo to improve the change out time of dies in Toyota's metal stamping machines. Toyota recognized that one of the main problems with mass manufacturing's ability to easily offer variety stemmed from the metal stamping machines which use upper and lower dies to shape sheet metal into car components, such as fenders. The dies were heavy as well as difficult and time consuming to change out and could only be performed by specialists. To reduce the productivity loss associated with the changing out of dies, large batches were manufactured and change outs were limited.

Through SMED, Toyota was able to quickly change out dies, minimizing downtime, allowing for small batches and easy incorporation of variety in stamped metal components. The essence of the SMED system is to convert as many changeover steps as possible to "external" (performed while the equipment is running), and to simplify and streamline the remaining steps that are "internal" (performed while the equipment is stopped) (Vorne 2016). The Single-Minute component of SMED means that the equipment should be changed out in single digit minutes, i.e. less than 10 minutes.

In the workshop a modified version of SMED was adopted where instead of switching out equipment, each step of the drilling process was evaluated for what could be performed externally and what could be simplified and streamlined. Moving steps externally were referred to as being performed "in parallel". For the simplification and streamline part of SMED, steps were evaluated for what could be shortened or eliminated. **Fig. 6** is a visual representation of the SMED improvement process. As can be seen, if properly applied, the time and steps associated with a process can be dramatically reduced.

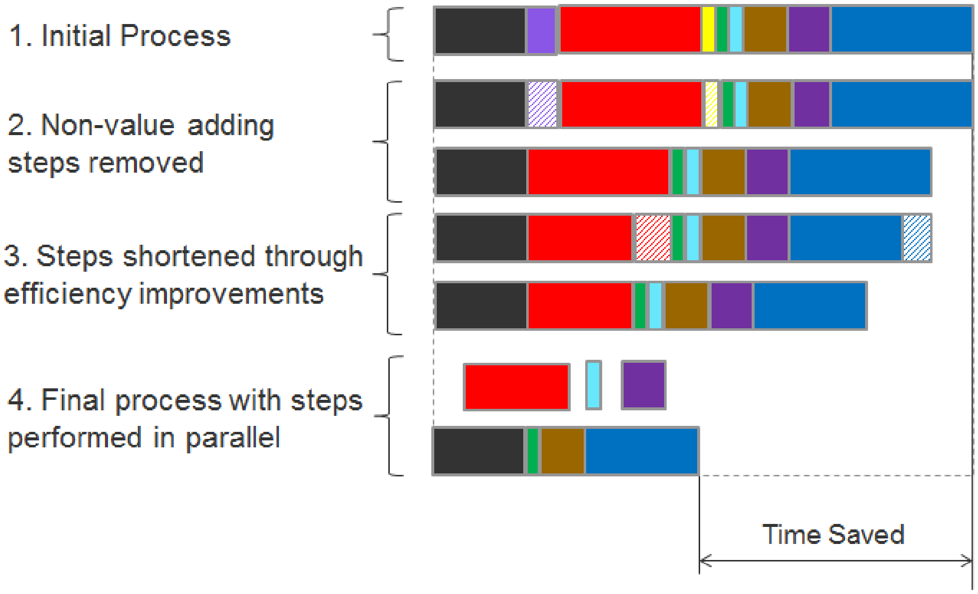


Fig. 6 - Visual representation of the SMED.

4.3.1.1. SMED Evaluation of Workshop Data

In the workshop, each step of the drilling process was documented in sequential order and evaluated for what could be shortened, performed in parallel (externally) or eliminated altogether. For reference, an associated average and best demonstrated performance (BDP) time was also listed for the steps. The BDP time served merely as a benchmark but not as the ultimate limit for opportunity since the SMED process rendered some of the operations and their associated times obsolete.

While collecting data for the workshop, it was recognized that the daily drilling reports used for the analysis were inundated in inconsistencies and errors voiding countless data points for inclusion in the evaluation. This highlighted a severe need for improvements to the data quality captured in the daily reports. Operations can't be managed if they are correctly measured.

In the workshop, participants were encouraged to suggest any ideas that came to mind regardless of how far-reaching they may seem. The SMED evaluation revealed obvious waste on several occasions and a few times led to the question of "How was this overlooked?" In contrast to the easily recognized opportunities, several other steps in the drilling process went through prolonged debates whether proposed changes would truly provide value or would impose unnecessary safety risks. One example was the picking up of 4" drill pipe and making up stands in the mouse hole while drilling the intermediate section eliminating having to perform the steps after running the casing. After much discussion, it was determined that due to the increased safety risk associated with the simultaneous operations of handling the drill pipe and drilling ahead, it would not be added to the improvement list.

Phase	Drilling Process	Well Depth, ft	BDP Time, hrs	Average Time, hrs	Challenge Elements - Ideas
		9900	**79.5**	**120.5**	
Intermediate Vertical	Drill and survey 8-3/4" Intermediate hole to KOP	9900	72	110	Develop consistent, optimized drilling parameters (and contingency parameters) particularly in the salt Evaluate bit design to reduce number of bit runs Decision tree regarding bit trip requirements Evaluate use of rotary steerable system Investigate use of a stabilized 1.1 deg motor assembly
	Circulate hole clean and pump fresh fresh water pill/Pump slug/TOOH with to P/U curve assembly	9900	6.5	9.5	Evaluate stabilized assembly Eliminate fresh water circ.
	L/D Vertical BHA	9900	1	1	
		10750	**35.5**	**57.5**	
Intermediate Curve	P/U and M/U 8-3/4" Curve PDC and adj bend	10750	8	10	Drill the curve with casing
	Drill and survey curve to landing point	10750	16	30	Tom's study to revise the BHA
	Circ B/U and conduct short trip to KOP	10750	3.5	6.5	Put shouldered connections on 7" and add CRT to be able to wash casing to bottom. Evaluate use of auto-fill float equip.
	Circ B/U until hole is clean and trip out L/D DP and BHA	10750	8	11	
		10750	**37.5**	**50.5**	
Intermediate Casing	Pull wear bushing/Hold Safety meeting with Casing crew/Rig up	10750	1.5	3	
	M/U shoe track/P/U 7" 32# P-110 LTC casing to the end of curve	10750	10	14	Buck up shoe and collar off location
	Ciculate and condition hole while preparing to cement casing	10750	1	3	
	PJSM w/ cementing crew/rig up cementing equipment/Pump spacer/cement slurry/displace fluid until plug is bumped/Check	10750	6	6	
	Verify casing is landed and back out landing joint and L/D/cleaning mud tanks and filling w/ brine	10750	2.5	4	
	P/U and M/U lateral BHA 1.5 bend MM/Stab/MWD/Stab/Monel	10750	1.5	2	
	Trip in hole P/U 4" DP	10750	12.5	16	PU and stand back of the 4" DP (3-4,000'). Pre-strap 4" DP before running 7" Evaluate move 90' mousehole to be able to torque up pipe
	Pressure test csg/Tag Cement and drill out shoe track and 10' of formation	10750	2	2	Bump plug and test casing
	Perform F.I.T	10760	0.5	0.5	

Table 1 - Snapshot of drilling process documentation used for WTCRW

Process Steps Eliminated - Some of the process steps that were determined to be non-value adding were eliminated and resulted in significant efficiency improvements associate with the time savings. Some examples identified in the workshop are the following.

- Circulating freshwater after reaching the landing point of the curve to washout salts to prevent BHA hang up through Charles Salt
  - Pumping freshwater would washout the salts to a point that caused problems with hole enlargement and cement integrity
- Short trip lateral assembly at TD
  - Deemed not necessary since casing could be ran without encountering any issues hanging up
- Reaming after drilling down each stand
  - Reaming caused wasteful processing of the wellbore since the circulating flow rates were high enough and the mud properties properly balanced to adequately remove cuttings.

Process Steps Performed in Parallel/Offline - Some of the process steps were found could be performed offline simultaneously to an operation on the critical path. Some examples are the following.

- Pre-drilling surfaces hole with a turnkey contracted spudder rig
  - Drilling the surface hole with the primary rig on a day rate contract could result in cost escalations if a problem is encountered causing operational delays
- Strapping, calipering and making up of BHA components offline. Some of the BHA components came pre-assembled prior to delivery to the rig
  - Waiting until it was time to pick up the BHA to strap and caliper the components wasted time and could easily be performed offline.
- Displacing the mud from a water based to an oil based system during drilling out of the shoe track
  - Prior to the improvement, the rig would wait until the hole was fully displaced before drilling out the shoe track
- Buck up casing float equipment at the shop before being shipped to the rig
  - Making up float equipment is easily handled with a bucking machine in the shop and eliminates the time associated with bucking it up at the rig.

Process Steps Shortened - Some of the operations were found could be improved through standardization. Some examples are as follows.

- Standardized salt drilling procedure
  - Each drill site supervisor had their own method for drilling a 1000’ thick salt section that would cause the BHA to become stuck if drilled too aggressively. After reviewing the electronically recorded drilling data of several rigs, the rig that drilled the salts the most efficiently was recognized and their method became the standard.
- Standardized nippling up Blow Out Preventers (BOPs) and testing procedure

    - The process for nippling up the BOPs varied from rig to rig with some less efficient than others. A BOP task force was assembled and standardized the way the BOPs would be nippled up and tested
- Standardize Weight-to-Weight connections
    - Standardizing the weight-to-weight connection process was recognized as a significant efficiency improvement opportunity due to the high count of connections performed during the drilling of a well.

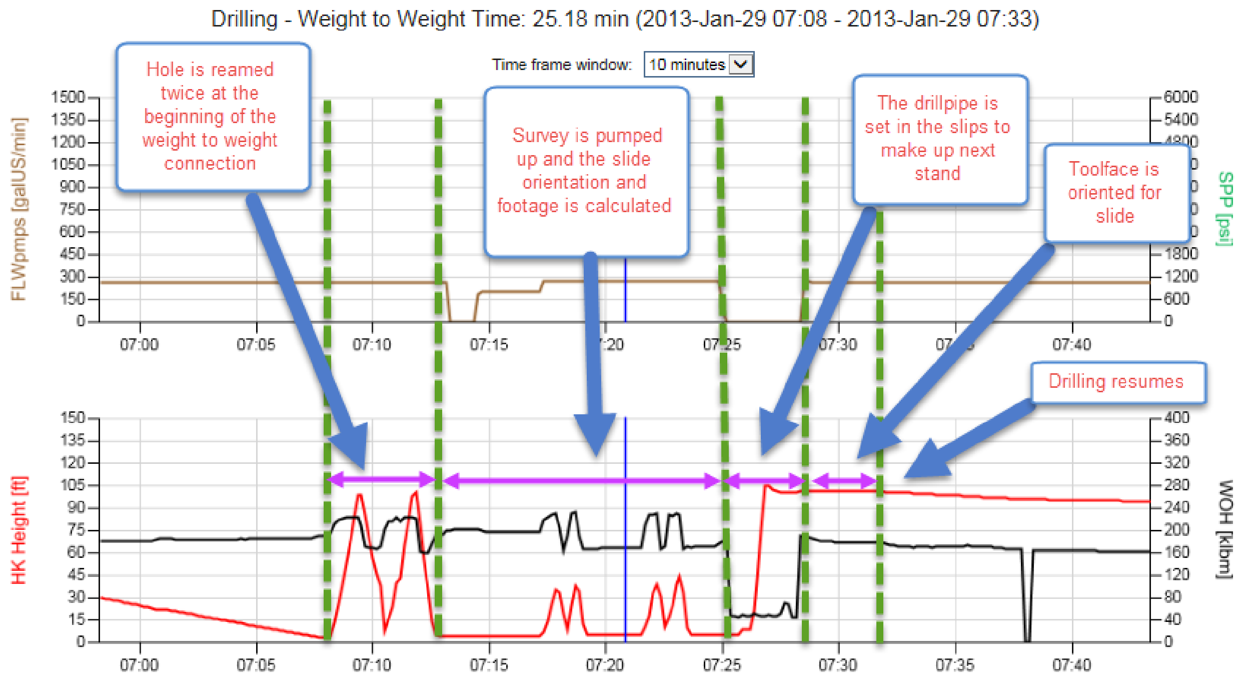
4.3.1.2. Changing for the Better

The incorporation of improvement findings had mixed results with some proving out to be immediately achievable and successful, some not being feasible and others delayed because of being met with resistance from field personnel since it required a mindset change to “we’ve always done it that way.” This highlighted the necessity for a cultural change and establishing buy-in from all levels involved in the lean initiatives. It quickly became apparent, that without buy-in from the field personnel, from the drill site supervisor down to the rig crews, improvement changes would not be successful.

Some of the changes found to be controversial were at one point necessary during the early exploratory/appraisal stages of drilling horizontal wells in the Bakken and Three Forks formations. The extra precautionary steps being challenged improved success rates of well delivery. Later on, once the development/infill drilling stage was reached and the drilling process had matured, many of extra measures for ensuring well delivery were no longer valid. Abandoning old practices caused a great deal of discomfort for the drill site supervisors that feared change.

One of the most debated changes became eliminating reaming after drilling down of each stand. Several of the drill site supervisors had at one point in their careers experienced stuck pipe associated with inadequate hole cleaning. Their negative experiences usually dated back to the days when rigs were power limited and sufficient flow rates for proper cuttings removal could be problematic. Reaming after each stand resulted in considerable amounts of time lost over-processing the wellbore when multiplied times the number of connections required for drilling a well.

Fig. 7 shows a typical weight-to-weight connection prior to the workshop. A weight-to-weight connection is the total amount of time spent making up the next stand of drill pipe starting when the bit is picked up off bottom lasting until it is back on bottom drilling. During the connection, time is lost to reaming the wellbore, pumping up of the Measurement While Drilling (MWD) survey, determination of the next slide orientation and length based on the calculated wellbore trajectory, and then orienting the bit tool face for sliding in the desired direction.



Drilling - Weight to Weight Time: 25.18 min (2013-Jan-29 07:08 - 2013-Jan-29 07:33)

Hole is reamed twice at the beginning of the weight to weight connection

Survey is pumped up and the slide orientation and footage is calculated

The drillpipe is set in the slips to make up next stand

Toolface is oriented for slide

Drilling resumes

Fig. 7- Weight-to-weight connection with reaming and survey issues.

The following are the detailed components of the connection shown in **Fig. 7**.

Weight-to-Slip

Component 1: The hole is reamed up and down twice after drilling the stand down at the start of the connection. (Total duration 4.52 min)

Component 2: A turbine powered MWD is activated and records the inclination and azimuth orientation of the survey tool located 72’ from the bit, followed by circulating up of the survey which conveys the results of the survey through mud pulses. Results from the survey are used to calculate whether a trajectory correction slide is required. If a slide is required, a toolface orientation and slide length are calculated based on the yield of the bent housing motor. If the proper flowrate sequence is not followed to activate the turbine and MWD, the process has to be repeated, which is the case in the example above. (Total duration 12.53 min)

Slip-to-Slip

Component 3: The drill pipe is set in the slips to make up the next stand for drilling the next 90’. (Total duration 2.97 min)

Slip-to-Weight

Component 4: The drill pipe is lifted out of the slips and, as was determined from the results of the MWD survey, the tool face is oriented for a directional slide before the bit is set back on bottom. (Total duration 5.08 min)

The connection in **Fig. 7** is inundated with process waste. An immediate reduction in time of 4.5 minutes is achievable through eliminating component 1, reaming at the start of the connection. **Fig. 8** is an example of a connection from the same well where the MWD survey was successfully transmitted to surface on the first attempt only requiring 4.96 minutes to complete. Based on this information, there is 7.57 minutes of waste associated with reshooting the survey in the first connection. This highlighted the need for the directional company to standardize their surveying method, one of the action items from the WTCRW.

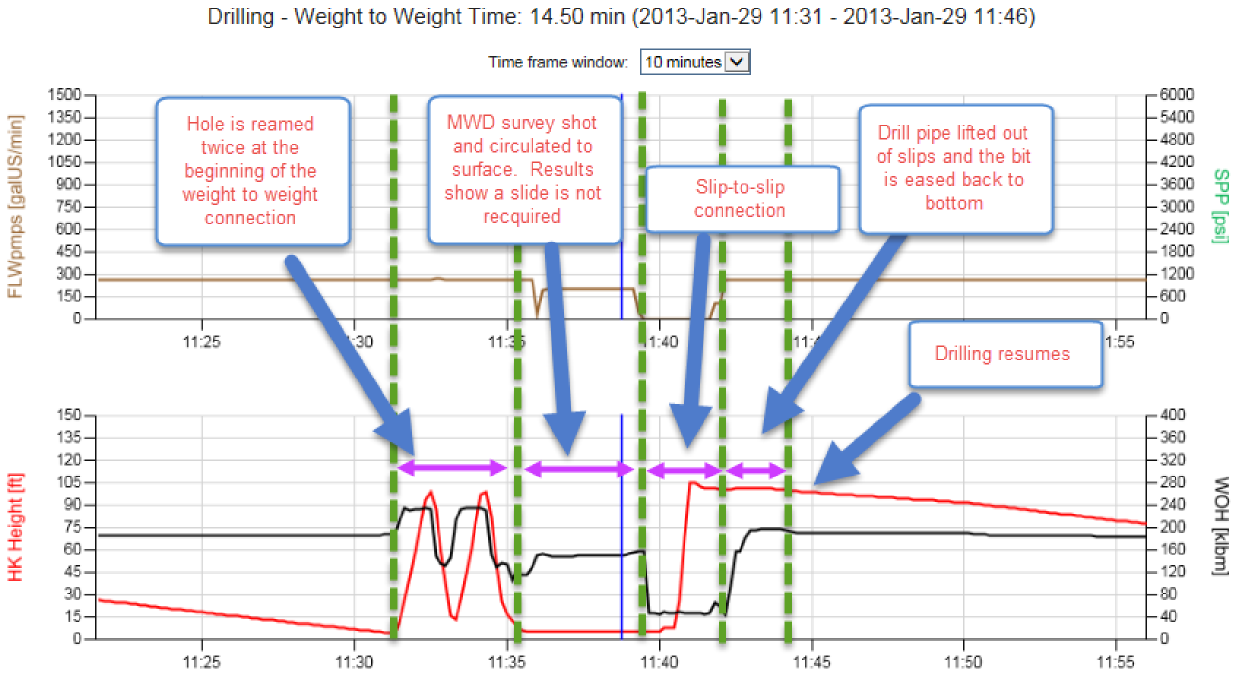


Fig. 8 - Example of a weight-to-weight connection with reaming and no survey issues.

A few of the rigs in the fleet immediately made adjustments to their weight-to-weight connection process resulting in the elimination of waste. For the other rigs that chose not to abandon their old practices, they soon were being outperformed receiving negative attention from management.

Since the WTCRW in 2013 and the initial recognition for the need to improve weight-to-weight connections, continuous improvement has resulted in a dramatic reduction in connection time. **Fig. 9** is an example of a typical connection from 2016. When comparing the problem free connection from 2013 **(Fig. 8)** to the connection shown below, a savings of 10.22 minutes has been accomplished. In a standard 10,000' Bakken/Three Forks lateral with 110 connections, a 10.22 minute savings reduces the overall time for connections by 18.74 hours.

Some of the additional changes to the weight-to-weight connections that have permitted the continuous improvement are the following:

- Flow off MWDs that are powered by battery. Eliminated the need to activate the turbine powered MWD through a flow sequence. Surveys can be taken during the slip-to-slip segment.

- Directional drillers are required to remain on the rig floor at all times and be ready to calculate slide lengths and tool face orientation immediately. In 2013, directional drillers would often remain in their trailers and only walk up to the rig floor once the surveys had been successfully circulated to surface causing unnecessary delays.
- Drillers were coached to use a stationary object on the opposite side of the rig floor as a visual reference to align the drill pipe tool joints at the proper height for setting in the slips. If the tool joint was too high or low, the iron roughneck could not be properly engaged to make up or break out the connection.
- The placement of items used for connections and the positioning of the rig crews were adjusted to improve flow of movement for stabbing the next stand of drill pipe and threading it to the drill string in the hole.

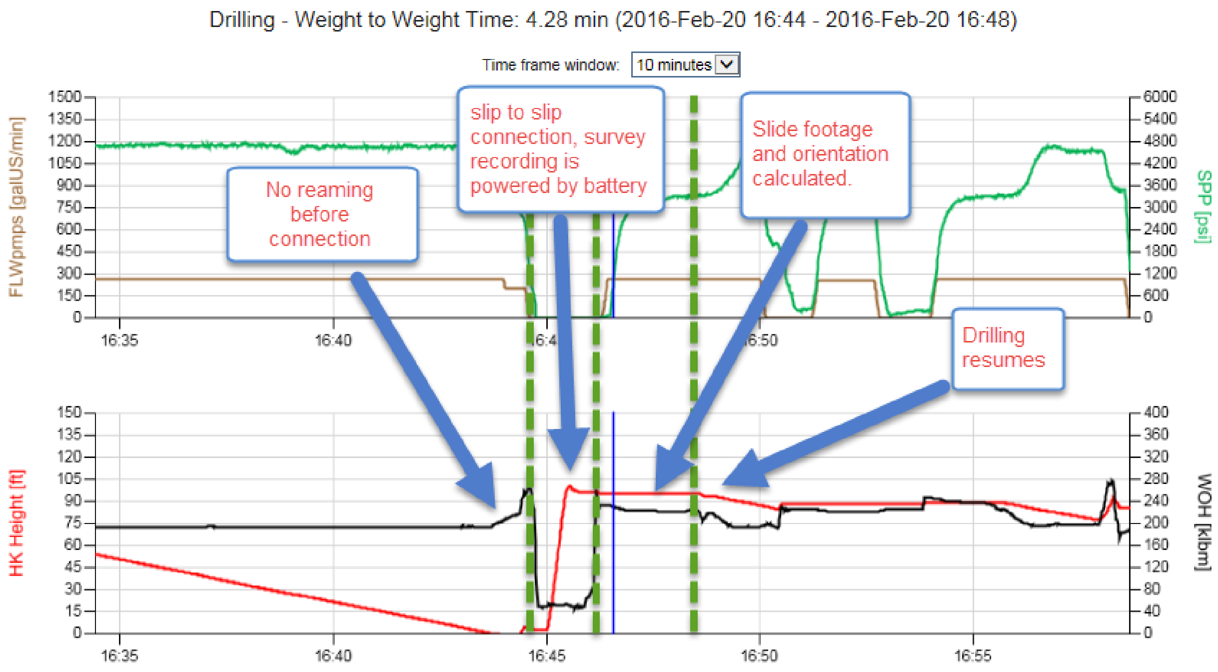


Fig. 9 - Example of a weight-to-weight connection in 2016

4.3.1.3. Tracking Efficiency Improvements

The measuring and tracking of performance improvements became an essential component to facilitating the workshop changes and visualizing the impact. Through the establishment of Key Performance Indicators (KPIs) rig crews could benchmark their level of performance. Before the establishment of the KPIs, the rig personnel operated in a state of unknown. They had no reference points to which they could compare their performance. As an analogy, it is similar to playing a sport without a scoreboard or tracking statistics. Everyone is left guessing as to how well they are performing but assumptions are usually made that each respective team is the best.

In the early phase of rolling out the changes, a wide spread in performance developed as the rigs that were open to change quickly showed the impact on performance the improvement findings made possible, where those that resisted the changes had performance levels remain flat. Instead of taking the stance that we'll simply replace any reluctant personnel, the operator treated the personnel as irreplaceable valuable resources and chose to work with them in educating the importance of what was being requested. The operator used the KPIs to show the rigs where they stood in the rankings and what was achievable. This was where the alpha mentality, which so often exists in the oil field, assisted in achieving buy-in, as the rigs now had performance scoreboards and did not want to be the weakest performers. Once this breakthrough was achieved, the gaps in performance narrowed and the overall average for drilling days reduced.

The data used to create the KPIs came from two independent sources. The first source was the daily drilling activity reporting software database, which was used to perform the SMED analysis. The recording and tracking of operations through the reporting software requires manual selection of activity codes and hand typing descriptions of the operations and associated start and stop times. Because of the human error, data quality can be an issue. Operations are frequently miscoded and the hand typed descriptions sparse in detail. Time rounding is done liberally skewing the true duration of an activity. Attempting to perform a duration analysis on too fine of a level will lead to erroneous results. One example is the time required to install a wellhead wear bushing. A query of the database results in 30 minutes to perform the task in almost every case. In reality, a wear bushing can be installed in under 10 minutes. The time is rounded up by 20 minutes. This highlights the caution that should be exercised when performing a KPI analysis on too fine of a scale when the source is the daily reporting database. The daily drilling reports should only be used for broader KPIs such as spud to release times.

The second data source used for KPI tracking is provided by a third party drilling performance monitoring company which provides to-the-second levels of detail of drilling operations. The company makes use of state detection algorithms to breakdown electronically recorded drilling data into their respective operations which is then stored in a database and accessible for statistical analyses. The electronically recorded data is fed by sensors located throughout the rig. Because the data is recorded automatically, human error and rounding error is removed from the measurements. The weight-to-weight connections discussed earlier are an example of a sensor derived KPI. **Fig. 10** shows the average yearly production hole weight-to-weight connection times for all connections made by the operator's rig fleet generated through the performance monitoring company's service. It can be seen that continuous improvement has been achieved year over year.

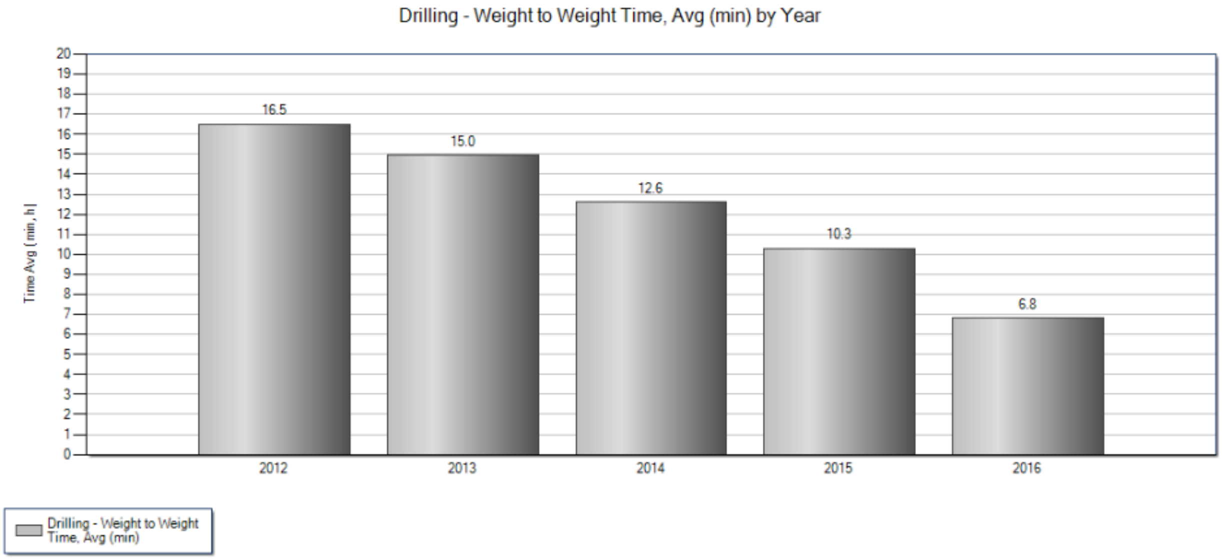


Fig. 10 - Average production hole weight-to-weight connection times by year.

4.3.1.4. The Importance of Data Quality

On-bottom drilling efficiency is another KPI that can be tracked through the performance monitoring services with a high level of accuracy but only comprises 35%-45% of the total drilling process time for an average performing rig. The other 55%-65% consists of flat time operations some of which have associated sensors, e.g. making connections, tripping pipe, running casing, and the rest which cannot be recorded through sensors and only can be tracked through observational recording, e.g. nippling up BOPs, cleaning of mud tanks and rigging up of equipment. Tracking the performance of the latter operations is limited to the quality of what is logged in the reports.

At the time the WTCRW in 2013 was held, the operator was using a basic reporting software that limited the classification of operations to a single level. Grouping by hole phase or dividing a main process into individual components was not an option unless conducted manually on the backend. **Table 2** is an example of the operational breakdown of running casing generated in the reporting software. As can be seen, “Casing and/or Cementing” is the main grouped process that is being captured which is comprised of rigging up the casing crew, running the casing, rigging up of the cement crew, cementing the casing and finally rigging down of the crews. A quick multi-well query to analyze the time for only cementing operations is not possible. The reporting software also did not allow for the designation of non-productive time. Only after reading the report below, would it become apparent that there is embedded NPT during the installation of casing, which are waiting on equipment and services and changing out failed equipment.

Date	StartTime	EndTime	Hours	IADCDescription	Remarks
10/5/2013	6:30:00 PM	8:00:00 PM	1.5	12 - Casing and/or Cementing	PJSM rig up casing tools.
10/5/2013	8:00:00 PM	10:00:00 PM	2	21 - Other	Wait on torque turn. (lay down DP).
10/5/2013	10:00:00 PM	10:30:00 PM	0.5	12 - Casing and/or Cementing	Rig up torque turn.
10/5/2013	10:30:00 PM	6:00:00 AM	7.5	12 - Casing and/or Cementing	Run 7" casing.
10/6/2013	6:00:00 AM	10:00:00 AM	4	12 - Casing and/or Cementing	Run 7" casing.
10/6/2013	10:00:00 AM	11:00:00 AM	1	12 - Casing and/or Cementing	Power tongs failed, change out to back up set, rig torque turn back up.
10/6/2013	11:00:00 AM	2:30:00 PM	3.5	12 - Casing and/or Cementing	Run 7" casing, Run 112 Jt's (4,900.96') 7" 29# DWC Casing M/U Torque 25K, M/U Rpm 12 High 4 Rpm Low, Shoe 2.3' Set @ 4,918.14' Float Collar 1.635 Set @ 4,823.82', 1 Semi-Ridged Centralizers Per Joint in Curve & 1 Bow Spring Centralizer Every 3rd Joint F/ KOP T/ 300' From 9 5/8 Shoe.
10/6/2013	2:30:00 PM	11:00:00 PM	8.5	21 - Other	Circ. And wait on Cementers.
10/6/2013	11:00:00 PM	2:00:00 AM	3	12 - Casing and/or Cementing	PJSM, rig up cementers, cement 7". 20 bbls invert-flush at 10.0 ppg, 20 bbls invert spacer at 10.0 ppg, 70 bbls brine spacer + 0.2 gal/bbl ACW-4, 305 sks0:1:0 G + additives at 15.8 ppg.179 bbls fresh water displacement.
10/6/2013	2:00:00 AM	2:30:00 AM	0.5	12 - Casing and/or Cementing	Rig down Cementers

Table 2 - Example of daily drilling report generated in old reporting software.

In 2014 the operator made the decision to change the reporting software to a more advanced alternative. This was done out of recognition that the old software simply was inadequate for proper analyses of performance.

The new software allowed for four levels of classification of operations which are the following

- Activity Phase – Classifies operations based on hole section (surface, intermediate, production) and by main operational process (moving, rigging up, drilling, casing). Groups certain activities similar to the old report software such as casing and cementing activities
- Activity Code – Classifies the Activity Phase on a finer level, e.g. Casing and Cementing become their own codes
- Activity Sub-Code – Operations are broken down to the finest level that specifies what is happening within the two higher levels of classification, e.g. "Run Casing" or "Pull Casing"
- Activity Classification – Classifies an activity as "productive" or "non-productive".

DATE_REPORT	ACTIVITY_PHASE	ACTIVITY_ CODE	ACTIVITY_ SUBCODE	TIME_FROM	TIME_TO	ACTIVITY_MEMO	ACTIVITY_ CLASS	ACTIVITY_ DURATIO
1/14/2016	21INRC	RU		1/14/2016 11:00	1/14/2016 12:00	PJSM and R/U CRT and casing equipment.	P	1
1/14/2016	21INRC	Casing	Run Csg	1/14/2016 12:00	1/14/2016 14:00	PJSM and made up 2 joint shoe track of 9-5/8", 47 ppf, P-110, BTC Casing with pre bucked on	P	2
1/14/2016	21INRC	Other		1/14/2016 14:00	1/14/2016 15:00	Level mast	PN	1
1/14/2016	21INRC	Casing	Run Csg	1/14/2016 15:00	1/15/2016 0:00	Run 9-5/8" 47 ppf, P-110, BTC casing from 178' to 7,750'. Filling every 25 joints ran and the ave	P	9
1/15/2016	21INRC	Casing	Run Csg	1/15/2016 0:00	1/15/2016 2:00	Ran 9-5/8" 47 ppf, P-110, BTC casing from 7,750' to 9,471'. Filling every 25 joints ran and the a	P	2
1/15/2016	21INRC	Casing	Run Csg	1/15/2016 2:00	1/15/2016 2:30	P/U Cameron 9-5/8" hanger and running tool. Wash down from 9,471' and landed hanger wi	P	0.5
1/15/2016	21INRC	Circ & Cond		1/15/2016 2:30	1/15/2016 3:30	Halliburton and rig crew to review cement operations. Rigged up Halliburton cement lines, load cement head with top and bottom plugs and witnessed by DSM.	P	1
1/15/2016	21INRC	Cement	Primary	1/15/2016 3:30	1/15/2016 7:30	Install cement head and pressure test line to 8,000 Psi. Good test. Mix and pump cement for (Intermediate) casing as follows: Pumped 30 bbls FW spacer – 8.33 Ppg @ 4.5 bpm and 320 psi. Dropped bottom plug. Mix and pump lead cement 469 bbls – 13.0 ppg – 7.0 bpm at 585 psi. Mix and pump tail cement 80 bbls - 16.2 ppg at 6.4 bpm, 609 psi. Dropped top plug. Pumped 690 bbls of 12.5 ppg SBM displacement at 8.0 bpm, slowing down to 3 bpm on the last 10 bbls displaced. Final circulating pressure was 600 PSI. Bumped plug and increased pressure to 1100 PSI. Bumped plug on calculated displacement of 690 bbls. Held 5 min then pressured to 6,500 psi. Held and charted casing pressure test for 30 mins. Bled back 16 bbls, and verified floats	P	4
1/15/2016	21INRC	Other		1/15/2016 7:30	1/15/2016 8:30	Flush lines, backed out and laid down landing joint.	P	1
1/15/2016	21INRC	RD		1/15/2016 8:30	1/15/2016 9:30	PJSM and rigged down CRT and casing equipment. Cleaning tanks and well deck.	P	1

Table 3 - Example of daily drilling report generated in the new software.

Analyzing drilling the data became much more comprehensible through multi-leveled classifications. Efficiency gaps and waste could be honed in on much quicker through simple queries. Similar to the previous software though, quality was essential and any errors in reporting could cause erroneous interpretations of results. The engineer should perform the final quality check for what is logged at the rig on a daily basis.

4.3.1.5. Results From Workshop I

The year following the workshop was spent working with the field personnel educating them over the reasons for the changes and why their buy-in was crucial for success. **Fig. 11** shows the largest scale KPI used to track operational performance, Spud-to-Release time, which starts the moment the well is spudded and lasts until the rig is released. In the situation of pre-setting the surface casing, since the task is performed offline, the spud date and time starts after a successful Formation Integrity Test has been completed at the start of the intermediate hole section. In the chart below, it can be observed that immediate time savings were realized in the month after the workshop attributable to temporary acceptance of “easy win” changes. In the months following August, a loss in efficiency was experienced which resulted from some rigs abandoning the changes that had so successfully worked. This highlighted the need to provide the rigs the KPIs on a regular basis to visually show the impact changes had on performance. The remainder of the year was spent breaking down the resistance barriers associated with the more controversial changes. It wasn’t until a few months short of a year before widespread acceptance of the improvement initiatives was achieved.

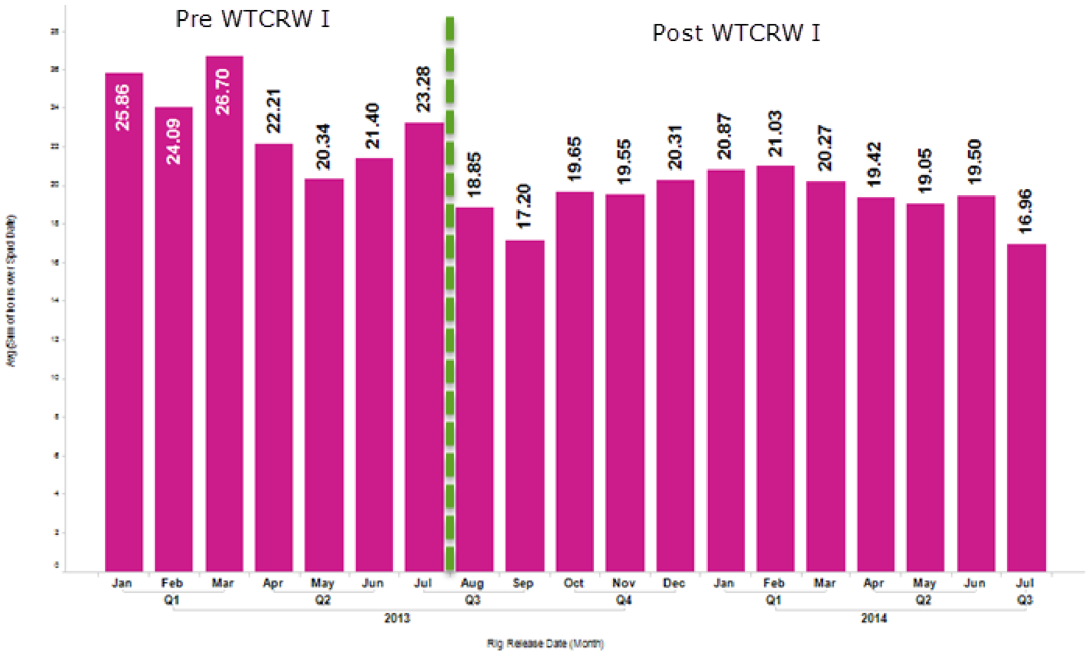


Fig. 11 - Average spud to release days by month.

4.3.1.6. Lessons Learned from WTCRW I

The first workshop proved to be successful but not without challenges. The main lessons learned were the following.

- Buy-in was essential
- Buy-in takes time
- Data quality was severely lacking and needed to be improved
- KPIs needed to be tracked and provided to the rig
- Once KPI data was made available to the rigs, performance improved as the rig crews had a reference benchmark and a desire to be the best

4.3.2. Well Time and Cost Reduction Workshop II - New Push for Lean

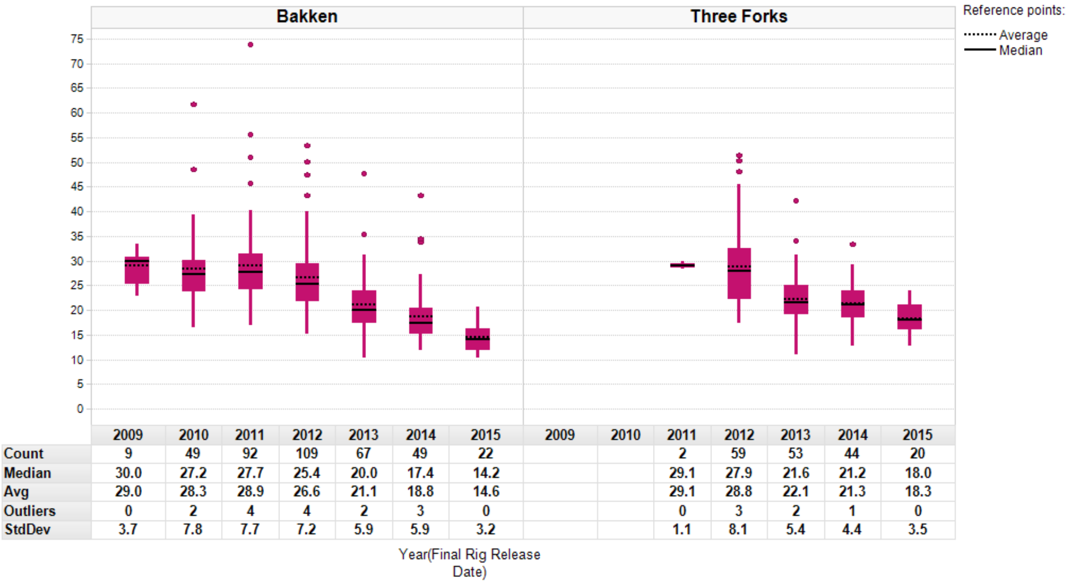
In the summer of 2015, two years after the first WTCRW, oil prices had fallen by 50% and the need to further reduce costs was imperative. By this time, most of the low hanging fruit had been picked and to achieve further continuous improvements the operator decided to reconvene as a cross functional group and hold another workshop, this time reaching deeper into the Lean toolbox.

4.3.2.1. Factory Drilling

In the new workshop the operator set their focus on achieving a “Factory Drilling” mode of operating or in other words, standardizing the delivery of quality wells in the shortest amount of time possible in a streamlined fashion with zero process variability. The manufacturing process of a well should be fully repeatable with a standard deviation of zero. The ultimate goal of the factory is to strive for perfection through continuous improvement.

4.3.2.2. Process Variability

Fig. 12 is a Box and Whiskers plot of drilling Spud-to-Release days dating back to the first year the operator began in the Williston Basin, broken out by formation. The tightening of the boxes and shortening of the vertical line lengths portrays a reduction in the average and standard deviation of drilling days through continuous improvement. The reduction in the standard deviation has been a result of eliminating process variability. The lowest point of all of the lines expanding below the boxes represents lost opportunity time and are examples of what is achievable.



	Bakken 2009	Bakken 2010	Bakken 2011	Bakken 2012	Bakken 2013	Bakken 2014	Bakken 2015	Three Forks 2009	Three Forks 2010	Three Forks 2011	Three Forks 2012	Three Forks 2013	Three Forks 2014	Three Forks 2015
Count	9	49	92	109	67	49	22			2	59	53	44	20
Median	30.0	27.2	27.7	25.4	20.0	17.4	14.2			29.1	27.9	21.6	21.2	18.0
Avg	29.0	28.3	28.9	26.6	21.1	18.8	14.6			29.1	28.8	22.1	21.3	18.3
Outliers	0	2	4	4	2	3	0			0	3	2	1	0
StdDev	3.7	7.8	7.7	7.2	5.9	5.9	3.2			1.1	8.1	5.4	4.4	3.5

Fig. 12 - Spud to release Box and Whiskers plot.

Drilling variability can exist in a number of ways preventing a factory operation and can be broken into three main categories, Process Variability, Equipment Variability and Geologic Variability. Below are examples of variability in all three categories that are frequently found in a standard drilling campaign.

Process Variability

- A rig stops relying on the standardized drilling procedure as they believe they have the plan committed to memory
- A rig decides to drill off the procedure because they believe their way is better
- A rig cuts corners to achieve improvements to their drilling statistics usually at the sacrifice of quality or safety
- A rig does not follow a preventative maintenance program and experiences frequent failures resulting in downtime or diminished capacities

Equipment Variability

- Rigs have varying equipment design ratings, e.g. mud pump pressure ratings, draw works power ratings, etc.
- Rigs have different equipment layouts
- Rigs have excessive unused equipment or are missing equipment

Geologic Variability

- Geological anomalies cause drilling issues, e.g. wellbore instability, lost circulation, excessive hard stringers causing BHA deflections
- Formation markers not correlating with geo-steering comparisons to offset control wells

Each example stated above can result in inconsistent drilling durations. Through proper design and process, the influences of the variables on drilling delivery can be minimized.

When analyzing the standard deviation, an indicator of the degree of variability, the lower end of time durations should be evaluated for sustainability. If determined that the lower times are repeatable and sustainable without cutting corners or exposing the crews to increased safety risk, then these can be set as the performance targets.

4.3.2.3. Lean Evaluation of Workshop Data

Different from the first workshop, focus was shifted from only looking at the overall averages of all of rigs combined to comparing them on a side by side basis. Performing the analysis by grouping all of the rigs together hid underperformers. Also instead of evaluating each individual step as a single focal point in the drilling process, activities were grouped together into logical cells based on common goals, e.g. the pre-spud phase which is comprised of the sub-assemblies of nippling up the blowout preventers, making up and tripping in the bottom hole assembly and drilling out the shoe track of the surface casing as shown in **Fig. 13** below in the 20PRES phase.

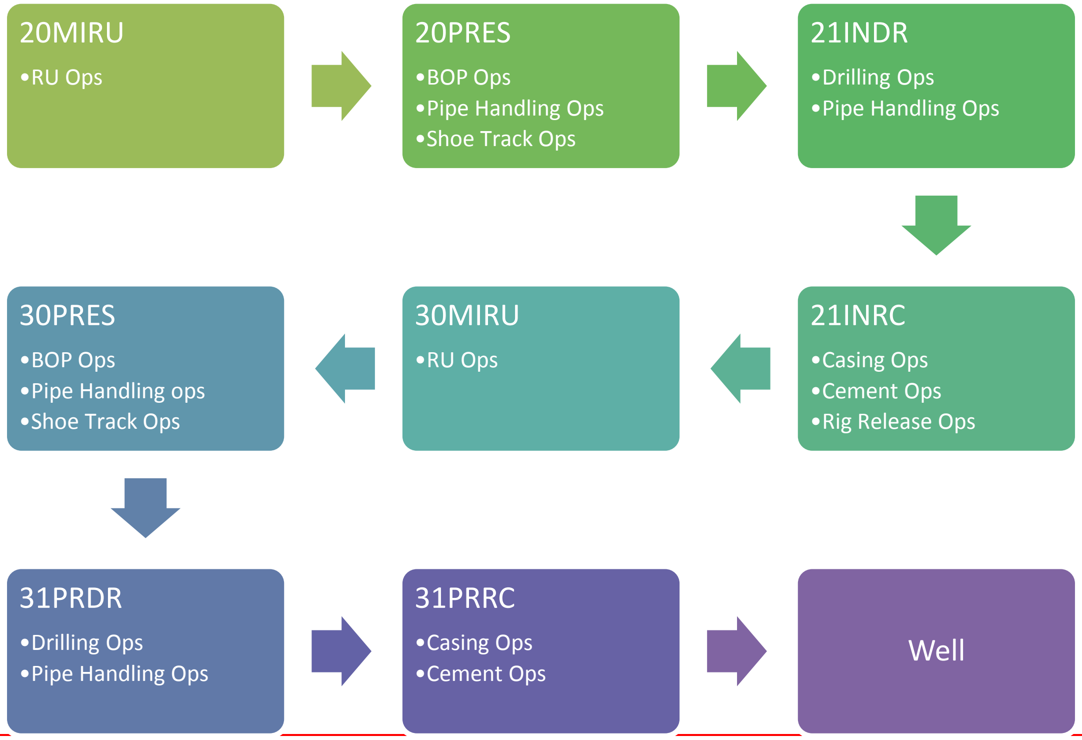
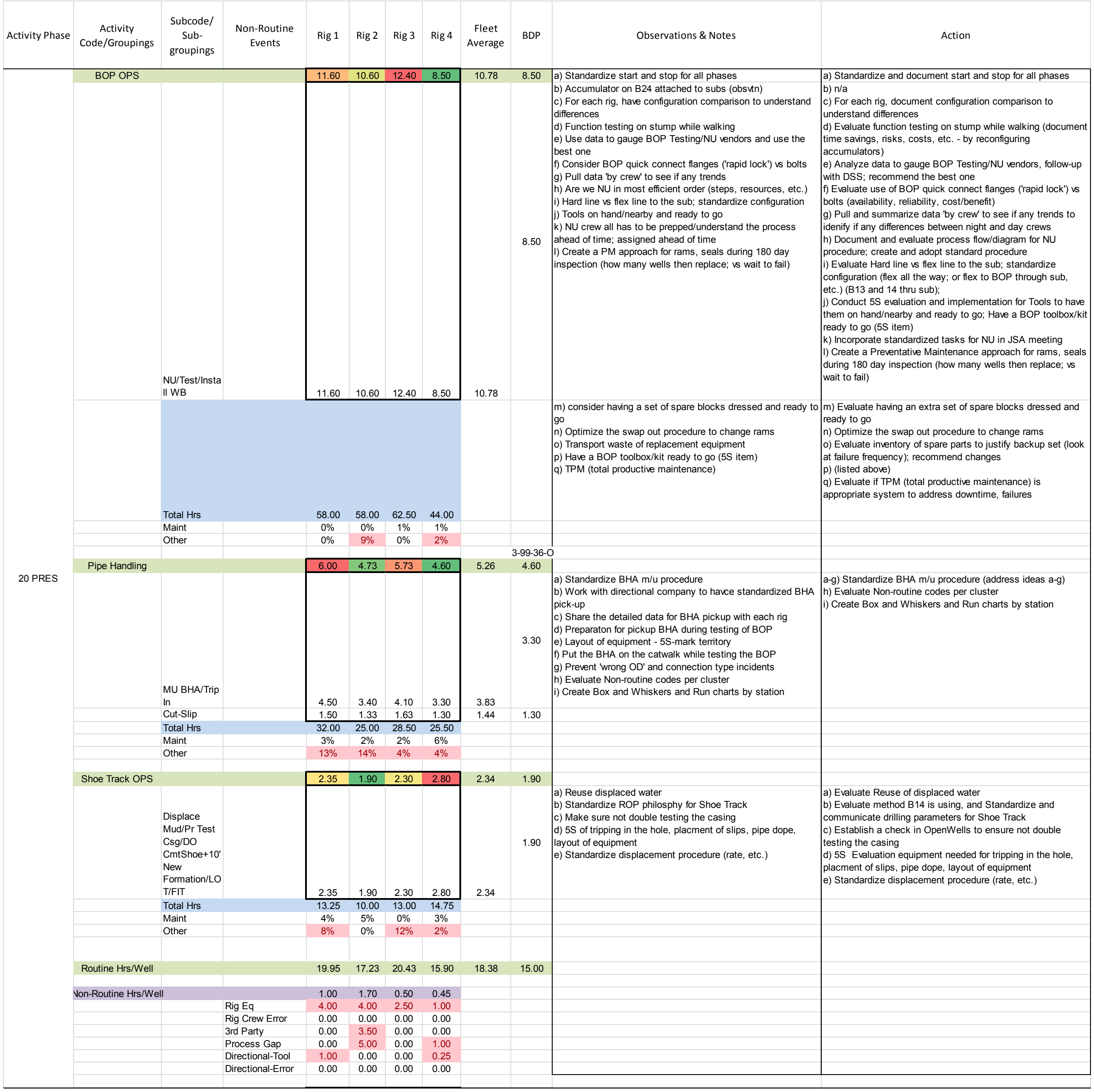


Fig. 13 - Cellular groupings of drilling sub-assemblies.

Also different from the first workshop, instead of solely relying on SMED to evaluate the drilling process, other Lean concepts were incorporated into the analysis. Table 4 shows an example of the evaluation that was performed and the solutions that were discussed to improve efficiency. As can be seen, the time associated with each sub-assembly varied significantly from rig to rig. The workshop revealed that not one rig dominated across the board in all areas. The comparison made it possible to recognize which rig performed the best in a particular sub-assembly which could then be used to observe what was working so well and replicate the best practices fleet wide.



Activity Phase	Activity Code/Groupings	Subcode/ Sub-groupings	Non-Routine Events	Rig 1	Rig 2	Rig 3	Rig 4	Fleet Average	BDP	Observations & Notes	Action
20 PRES	BOP OPS			11.60	10.60	12.40	8.50	10.78	8.50	a) Standardize start and stop for all phases	a) Standardize and document start and stop for all phases
		NU/Test/Install WB		11.60	10.60	12.40	8.50	10.78	8.50	b) Accumulator on B24 attached to subs (obsvtn) c) For each rig, have configuration comparison to understand differences d) Function testing on stump while walking e) Use data to gauge BOP Testing/NU vendors and use the best one f) Consider BOP quick connect flanges ('rapid lock') vs bolts g) Pull data 'by crew' to see if any trends h) Are we NU in most efficient order (steps, resources, etc.) i) Hard line vs flex line to the sub; standardize configuration j) Tools on hand/nearby and ready to go k) NU crew all has to be prepped/understand the process ahead of time; assigned ahead of time l) Create a PM approach for rams, seals during 180 day inspection (how many wells then replace; vs wait to fail)	b) n/a c) For each rig, document configuration comparison to understand differences d) Evaluate function testing on stump while walking (document time savings, risks, costs, etc. - by reconfiguring accumulators) e) Analyze data to gauge BOP Testing/NU vendors, follow-up with DSS; recommend the best one f) Evaluate use of BOP quick connect flanges ('rapid lock') vs bolts (availability, reliability, cost/benefit) g) Pull and summarize data 'by crew' to see if any trends to idenify if any differences between night and day crews h) Document and evaluate process flow/diagram for NU procedure; create and adopt standard procedure i) Evaluate Hard line vs flex line to the sub; standardize configuration (flex all the way; or flex to BOP through sub, etc.) (B13 and 14 thru sub); j) Conduct 5S evaluation and implementation for Tools to have them on hand/nearby and ready to go; Have a BOP toolbox/kit ready to go (5S item) k) Incorporate standardized tasks for NU in JSA meeting l) Create a Preventative Maintenance approach for rams, seals during 180 day inspection (how many wells then replace; vs wait to fail)
		Total Hrs		58.00	58.00	62.50	44.00			m) consider having a set of spare blocks dressed and ready to go n) Optimize the swap out procedure to change rams o) Transport waste of replacement equipment p) Have a BOP toolbox/kit ready to go (5S item) q) TPM (total productive maintenance)	m) Evaluate having an extra set of spare blocks dressed and ready to go n) Optimize the swap out procedure to change rams o) Evaluate inventory of spare parts to justify backup set (look at failure frequency); recommend changes p) (listed above) q) Evaluate if TPM (total productive maintenance) is appropriate system to address downtime, failures
		Maint		0%	0%	1%	1%				
		Other		0%	9%	0%	2%				
									3-99-36-O		
	Pipe Handling			6.00	4.73	5.73	4.60	5.26	4.60		
		MU BHA/Trip In		4.50	3.40	4.10	3.30	3.83	3.30	a) Standardize BHA m/u procedure b) Work with directional company to havce standardized BHA pick-up c) Share the detailed data for BHA pickup with each rig d) Preparaton for pickup BHA during testing of BOP e) Layout of equipment - 5S-mark territory f) Put the BHA on the catwalk while testing the BOP g) Prevent 'wrong OD' and connection type incidents h) Evaluate Non-routine codes per cluster i) Create Box and Whiskers and Run charts by station	a-g) Standardize BHA m/u procedure (address ideas a-g) h) Evaluate Non-routine codes per cluster i) Create Box and Whiskers and Run charts by station
		Cut-Slip		1.50	1.33	1.63	1.30	1.44	1.30		
		Total Hrs		32.00	25.00	28.50	25.50				
		Maint		3%	2%	2%	6%				
		Other		13%	14%	4%	4%				
	Shoe Track OPS			2.35	1.90	2.30	2.80	2.34	1.90		
		Displace Mud/Pr Test Csg/DO CmtShoe+10' New Formation/LOT/FIT		2.35	1.90	2.30	2.80	2.34	1.90	a) Reuse displaced water b) Standardize ROP philosphy for Shoe Track c) Make sure not double testing the casing d) 5S of tripping in the hole, placment of slips, pipe dope, layout of equipment e) Standardize displacement procedure (rate, etc.)	a) Evaluate Reuse of displaced water b) Evaluate method B14 is using, and Standardize and communicate drilling parameters for Shoe Track c) Establish a check in OpenWells to ensure not double testing the casing d) 5S Evaluation equipment needed for tripping in the hole, placment of slips, pipe dope, layout of equipment e) Standardize displacement procedure (rate, etc.)
		Total Hrs		13.25	10.00	13.00	14.75				
		Maint		4%	5%	0%	3%				
		Other		8%	0%	12%	2%				
	Routine Hrs/Well			19.95	17.23	20.43	15.90	18.38	15.00		
	Non-Routine Hrs/Well			1.00	1.70	0.50	0.45				
			Rig Eq	4.00	4.00	2.50	1.00				
			Rig Crew Error	0.00	0.00	0.00	0.00				
			3rd Party	0.00	3.50	0.00	0.00				
			Process Gap	0.00	5.00	0.00	1.00				
			Directional-Tool	1.00	0.00	0.00	0.25				
			Directional-Error	0.00	0.00	0.00	0.00				

Table 4 - WTCRW lean analysis worksheet.

The average times associated with each sub-assembly do not include times associated with non-routine events, or in other words, any activities that are not written into the standard operating procedure. These events were seen as waste and the total time summed up and listed as “Other”. The purpose of removing the non-routine events from the standard operations was to level the playing field and evaluate how a rig performs under normal operating conditions. The waste evaluation would be separate component of the workshop.

One of the most compelling differences between the first workshop and the second was achieving buy-in at the field level. The supervisors and crews had grown accustomed to change over the previous few years. Achieving buy-in was no longer a barrier to success.

Each phase of the drilling process shown in **Fig. 13** is treated as an internal supplier to the subsequent cell, i.e. each step requires delivery of the well, at progressing stages of assembly. What is left off in **Fig. 13** is the surface section as the job of drilling and installing casing is performed off-line by a small fit for purpose rig, on a turnkey contract. This is an example of an external supplier delivering a quality product, a cased off surface hole, to a customer, the primary rig, who relies on the expertise of the supplier. The spudder rig has multiple sub-assemblies, which are essentially sub-sub-assemblies to the overall drilling process, that are included in the turnkey pricing for drilling the hole, installing and cementing the casing and installing the wellhead. These sub-assemblies are directional drilling, for providing a directional nudge in the surface hole, cuttings disposal services for trucking off cuttings to approved disposal sites, a cement provider who cements the casing and finally installation of a wellhead. This is an example of interdependencies as discussed by de Wardt (1994).

The surface wellbore must meet the standards required by the following phases of the drilling process which is the primary rig being able to nipple up BOPs on the wellhead to establish well control and perform an FIT indicating quality cement. Before that can occur, the rig must rely on a rig mover to mobilize the rig onto location, assemble the rig with the use of cranes and center the rotary table over the wellbore the first sub-assembly for the primary rig.

Breaking the drilling process into logical cells, or sub-assemblies, allows for simplified management of the groups for performance. If too fine of a level is made the data quality becomes an issue. The total time required to perform the grouped sub-assemblies and number of error occurrences, reveals areas where improvement is needed. **Fig. 14** shows the assembly comparison of the 20PRES or the pre-spud phase broken into the sub-assembly components of BOP ops, Pipe Handling Ops and Shoe Track Ops. The amount of variability is evident on an individual rig basis but also on a comparative basis with the other rigs. The main offender of duration variability for the pre-spud phase are the BOP ops. This warranted a deeper dive investigation into what the root of the variance was which required direct observation at the rig site which embodies the Lean philosophy of Gemba (the real place) meaning that to be able to thoroughly understand an issue, one must leave the office and spend time on the plant floor or, in the case of the drilling, the well site.

Problems that were observed on the weakest rig recognized in the workshop were the following:

- Underutilization of resources – Instead of dividing the rig crew to handle various tasks associated with nippling up the BOPs and testing, several of the workers remained in a group to take on individual tasks in sequence. An example that was observed was five guys making up a single hammer union on the choke line. Three of the guys were standing by watching while one guy held the pipe up and the fifth guy hammered the connection. This is a one person job when planned properly.

- Disorganized equipment and the inability to find the right tools for the job.
- Time lost retrieving tools that were stored in a tool box on the other side of the rig
- Differences in the way the choke and kill line were routed out of the sub structure
- BOP components that wouldn't test requiring time consuming replacement

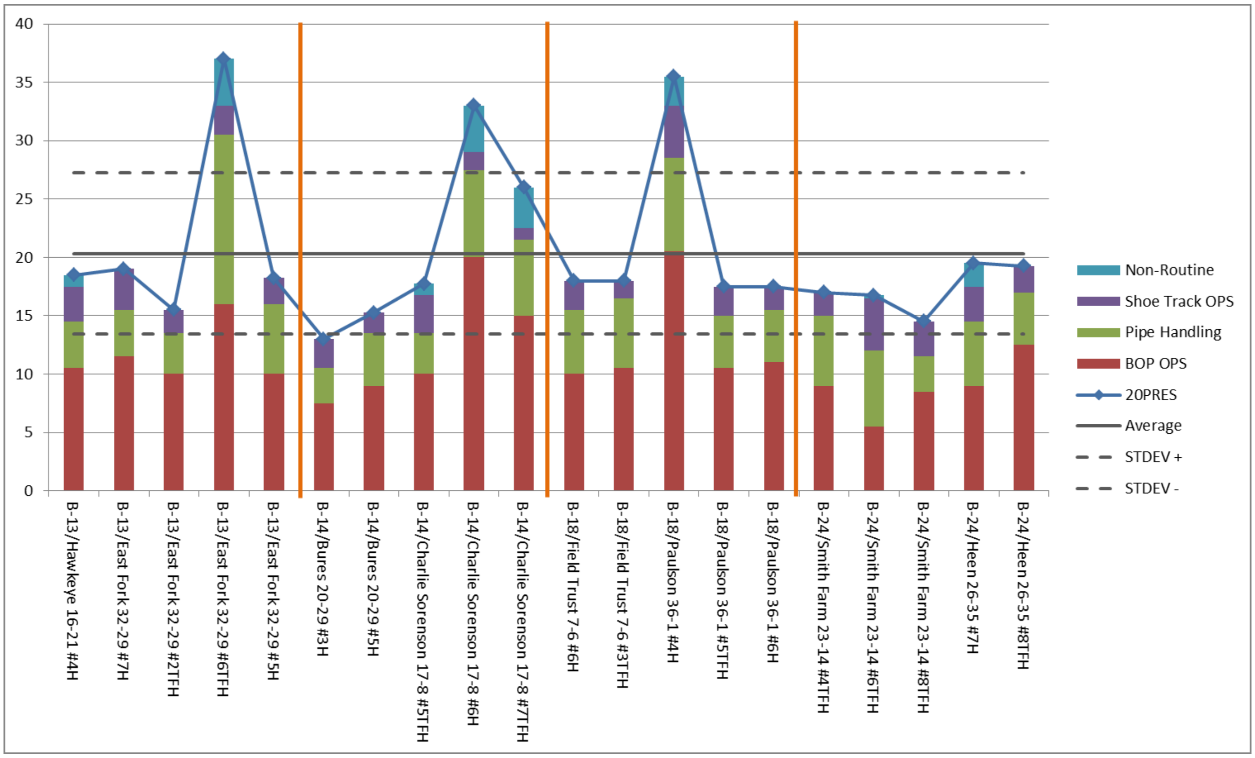


Fig. 14 - Pre-spud phase comparison

In the Toyota Production System if an error occurs to the product at a certain phase along the assembly line, the entire production line would be shut down to fix the problem instead of proceeding and fixing the problem afterwards. This places accountability on that station of the assembly line to maintain their equipment by applying a preventative maintenance program. This same philosophy should hold true for drilling since proceeding with the drilling process with an error usually results in excessive down time continually applying temporary fixes to failed components. In certain cases, proceeding with a problem can be life threatening such as in the case of an unsuccessful BOP test. This is an error that without exception must be fixed before continuing with the drilling process.

Rigs that are perpetual underperformers typically have either a weak crew or bad equipment to blame. In the situations where the equipment is underrated for the job, an upgrade is warranted. Bad crews on the other hand will typically blame the equipment but all too often the failing equipment is a result of a crew not following an adequate preventative maintenance program. One such example is the mud pumps and the selection and maintenance of liners. All too often a rig manager will save money by installing cheap steel liners that are less erosion resistant and will wash out rapidly if solids are high in a mud system instead of paying for more expensive ceramic liners. Pumps have many sealing parts and lack of a maintenance program often leads to leaks, loss of efficiency and eventually total washouts resulting in costly down time. Purchasing the right parts for the job and maintaining the equipment is essential to avoiding NPT and efficiency loss.

4.3.2.4. Elimination of Drilling Waste

Each sub-assembly of drilling process reviewed in the workshop was evaluated for the 7 types of waste. The 7 types of waste, are defects, waiting, inventory, transportation, excess motion, over-production and lastly over-processing which typically inundate most drilling operations to varying degrees. Some are easily recognized through data and simple observation while some are less apparent and might require recognition through a lean trained expert. The following are examples of the 7 types of that are common in drilling operations and possible solutions.

Fig. 15 - 7 types of waste (Leanguru.pro 2014).

Defects

Defects unfortunately are all too frequent in drilling operations but most are easily identified through equipment failures and can be fixed before continuing on with operations. Most defects result in NPT unless they can be fixed offline and range from the simple replacement of parts to excessive down time that can require multiple days to restore the problem. One of the most common defects are failed mud motors and MWD packages which in most cases require a trip out of the hole to replace the equipment.

Depending on hole depth and wellbore conditions, tripping operations can result in over a day of down time.

Some defects in contrast are not obvious during the drilling process and can cause well integrity issues for drilling's customers, the completions group and the production group. One of the most costly defects passed onto the customer are production strings with compromised pressure ratings that prevent the well from being stimulated. Work-overs to fix casing issues usually range from hundreds of thousands of dollars to total loss of the well and millions of dollars for plug and abandonment operations and redrilling of the well.

Solution

Developing a close relationship with suppliers is imperative to identifying defects, determining the root causes of the defects and performing corrective actions to ensure the problems do not reoccur. If the occurrence of a certain defect is low and the time associated with correcting the issue is also low, then pursuing a corrective measure may be of low priority. If the occurrence is high and time associated with correcting the defect is low or the occurrence is infrequent but the time associated with correcting the defect is extensive, then medium priority should be given to the problem. Defects that are frequent and with corrective actions that are lengthy in duration should be first priority.

A Pareto Diagram is a Lean tool that plots frequency and time associated with defects to visually display the significance of a problem. The chart is organized with the most severe problem closest to the Y-axis in descending order to the least significant problem. Priority should be given to the left most defect. As one problem is resolved, the next problem in sequence should become the primary focus.

Third party inspection services for critical equipment during or post manufacturing is a preventative measure that reduces the amount of defects that work their way into the well construction process. An example of inspection services widely used in the industry are in-mill inspections of casing strings. The benefits of inspection services and the corresponding costs far outweigh the costs associated with work-overs remediating the failed equipment after installation in the well.

Waiting

Most waste associated with waiting can be tied to poor and inadequate planning. Many service providers in drilling operations must travel to the rig site to perform their duties. Cementing is an example of a service that is often exposed to waiting. If the cementing company is not provided with a timely enough notice, the rig has to shut down and cannot continue with operations until the casing string is cemented in place. If the rig provides the cement company with too early of a notice, then the cement company charges the operator costly stand-by time.

Depending on the location of drilling operations in the US, the replacement of specialized equipment is often associated with multiple days lost to waiting as the parts are ordered and flown in or trucked from across the country. The company's operations that this thesis is based on are located in North Dakota where most service companies' warehouses and manufacturing facilities are located in the southern states. Extended periods of NPT waiting on parts has occurred on occasion.

Solution

Proper planning is as important in drilling operations as it is in any well run business. A look forward at upcoming operations and establishing standard milestones for calling out of services will minimize waste associated with waiting. Certain challenges exist for requesting services that are dependent on the completion of a prior process especially if the process is at the mercy of hole conditions. Cementing service providers often experience delays since they cannot start operations before the casing is on bottom. Multiple variables can contribute to casing running issues and excessive drag such as wellbore tortuosity, toe-up vs toe-down horizontals, high low-gravity solids in the mud and high plastic viscosities increasing wellbore friction, cuttings beds, etc. and can cause delays of several hours due to reduced casing running speeds. Each one of the variables mentioned represent issues that should be understood with the drilling process designed to minimize their effects.

The service providers should have an intimate understanding of their equipment and should maintain spare parts as necessary to prevent costly delays associated with ordering and shipping. They should know the frequency of failures of their equipment, which components are most prone to failure and maintain inventory volumes of replacement parts within a storage facility nearby the drilling operations. Just as operators should establish good relationships with their service companies, service companies themselves are customers relying on quality raw materials or products from suppliers and should also maintain good working relationships and open communication.

Inventory

Though excessive inventories do not cause the same problems as the buildup of buffer stocks and finished products in warehouses, inventory waste in drilling causes problems in other ways that are less apparent but not to be overlooked. If an excessive inventory of equipment and parts is kept with the rig, valuable time is lost during the mobilization phase since trucking space is consumed and additional loads are required. A build-up of equipment that is never used is also quite common on rigs over time and usually ends up stashed in the corners of the pad taking up valuable space leading to tight locations, decreased mobility and increased HSE risk.

Solution

The rig crews and drill site supervisors should perform regular walk around assessments of the rig site to determine what is required and regularly used for operations and what is not. It is easy to overlook equipment that has taken up permanent residency with the rig. All of the excess equipment should be removed. Equipment that is used but only on occasion should be removed from the rig site if it can be provided through a call out on an as needed basis. Applying Lean's principle of 5S can assist in the process of sorting through wasteful inventories. 5S will be discussed in depth later on in this write-up.

Transportation

Transportation waste is found in most drilling operations and is mostly associated with the layout of rig-site equipment and the storage of tools. Optimization of the layout of equipment is often disregarded with parts and tools located in inconvenient locations that require trips up or down the steps to the rig floor or across the rig site. Time wasted to transportation at the rig may not be as obvious as time lost to a defect but builds up quickly and can mean the difference of hours in the total drilling process.

Solution

Optimizing the layout of rig site equipment should be just as important as moving the rig in a timely matter. Often this part of a move is neglected and equipment is left where it is dropped off causing undue time for the retrieval of tools, part and equipment. Understanding where the equipment will be used the most and placing it within close vicinity of that location is key. Further optimization of equipment layout may also warrant the addition of smaller toolboxes that can be placed a few feet from where the tools are used. One example is adding a toolbox with tools for nippling up BOPs in the subs below the rig floor. The philosophy of 5S also applies for the layout of equipment.

Motion

Different from Transportation, excessive Motion is time wasted due to unnecessary movements or poor placement of tools within a station. An example of waste associated with motion is found during connections and the rig crews' preparedness and placement of the tools required for the job such as slips, the pipe dope bucket and brush, and the floor hands stabbing the pipe in the connection. Other wasted motion on the connection can be caused by the driller and where he sets the drill pipe in the slips in reference to the tool joints position above the rig floor. If the pipe is set too high or low, then make up / break out of the connection with the iron roughneck is not possible and the pipe has to be lifted out of the slips and repositioned.

Solution

Observe the positioning of the floor hands, their equipment and their efficiency of movement. If permissible by the drilling contractor, record a video of the connection to review with the rig crew and ask them what they can do better. Supply connection performance data from other rigs to establish benchmarks while stressing not to hurry at the risk of exposing the rig personnel to increased safety risks. As the military adage goes “Slow is smooth, smooth is fast”.

Over-processing

Over-processing is doing more than is required for the job at hand. A perfect example in drilling is reaming after the drilling of each stand. On occasions reaming may be warranted as a result of deteriorating hole conditions or insufficient cuttings lift but usually it is not as the properties of the mud, flow rate available during drilling, regular sweeps and rotation of the pipe provide all of the required hole cleaning mechanisms to prevent a stuck pipe situation.

Solution

Monitor the conditions of the hole using the rig's Electronic Drilling Recorder to limit reaming on an as needed basis. Early signs of hole cleaning issues or wellbore instability will become recognizable through increases in the circulating pressure, pick-up and slack of weights trending higher or lower than expected respectively, sudden spikes in bit weight and increasing torque values and will provide the driller the necessary information to limit reaming operations to only on an as needed basis.

Over-production

Over-production is the waste of creating more of a product than is necessary. An example of over-production in drilling is the volume maintenance of mud inventories, particularly oil-based which cannot be disposed of in a reserve pit. The build-up of low gravity solids will cause increased friction factors resulting in hole drag and poor weight transfer while drilling in horizontal wells. To maintain low gravity solids percentages at acceptable levels, base oil is added to dilute the system or the system is processed through solids removal equipment. If dilution is the primary method for solids control and outpaces the typical losses to cuttings, volumes will increase and can become a problem if pit capacity is limited resulting in costly handling and storage logistics.

Solution

A steady state balance needs to be struck between the usage of solids removal equipment and dilution rates to maintain properties at acceptable levels instead of solely depending on dilution. The mud company and the solids control company need to establish a close relationship where there is open communication regarding proper controlling of solids.

4.3.2.5. Non-Productive Time and Root Cause Analysis

During the WTCRW it was determined that a further analysis of NPT was warranted. The most common Non-Productive time results from equipment failures whether on the surface or downhole, rig equipment or 3rd party. Inherently, failures that occur downhole have a larger impact on rig efficiency due to the fact that most will require a replacement trip that can take from only a few hours to more than a day depending on the hole depth and conditions of the well. Therefore it is critical that any component of the drill string passes a strenuous inspection process for quality and either has limited prior run hours or has been refurbished to a near new state. Should any of these steps be neglected, an operator is at increased risk of costly NPT. It is much cheaper to prevent a problem proactively than to fix a problem after it has occurred with all inclusive rig spread rates ranging from $2,500 to $3,750 per hour in a typical drilling scenario.

To determine the frequency and severity of equipment failures, lean makes use of Pareto Diagrams. Pareto Diagrams are bar graphs with the bars representing either a summation of cost, either time or money, or a count of events arranged in descending order. The first bar represents the most prevalent equipment failure and should be prioritized as the first item to address. Once the issue has been resolved, the subsequent bar becomes the next priority for corrective actions.

One method for assisting in the determination the root cause of a failure is a Fishbone Diagram, or Ishikawa diagram as it is referred to in Lean. The diagram breaks the possible causes in into categories, e.g. Man, Machine, Method and Material, which all lead to an effect. Other cause categories can be added to the diagram as necessary to perform a proper analysis. **Fig. 16** is an Ishikawa Diagram that was created to analyze what the potential causes were of slow Rate Of Penetration (ROP) on a well. Once the analysis was fully conducted, it was determined that the elastomer was not rated to the temperature of the well and was therefore weakened and eventually led to a motor failure.

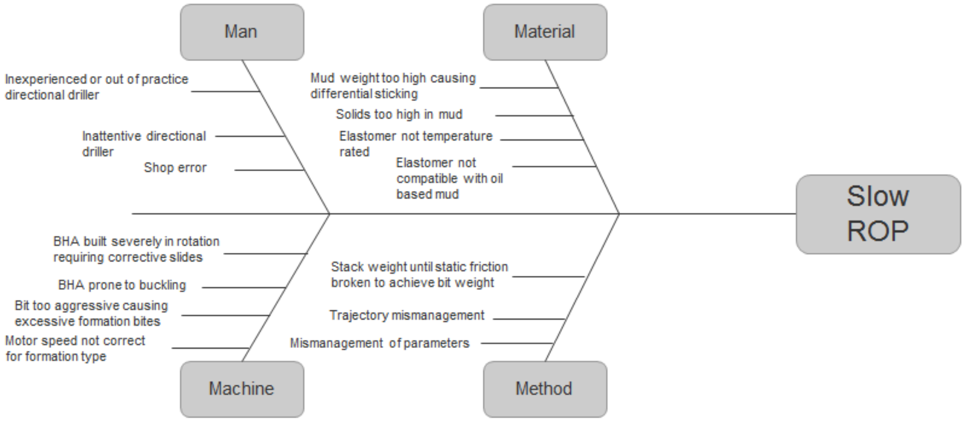


Fig. 16 - Ishikawa diagram for slow ROP

In an analysis of the operator's NPT for the second half of the year of 2015, the main offenders of downtime were easy to distinguish. **Fig. 17** is the Pareto Diagram of the analysis.

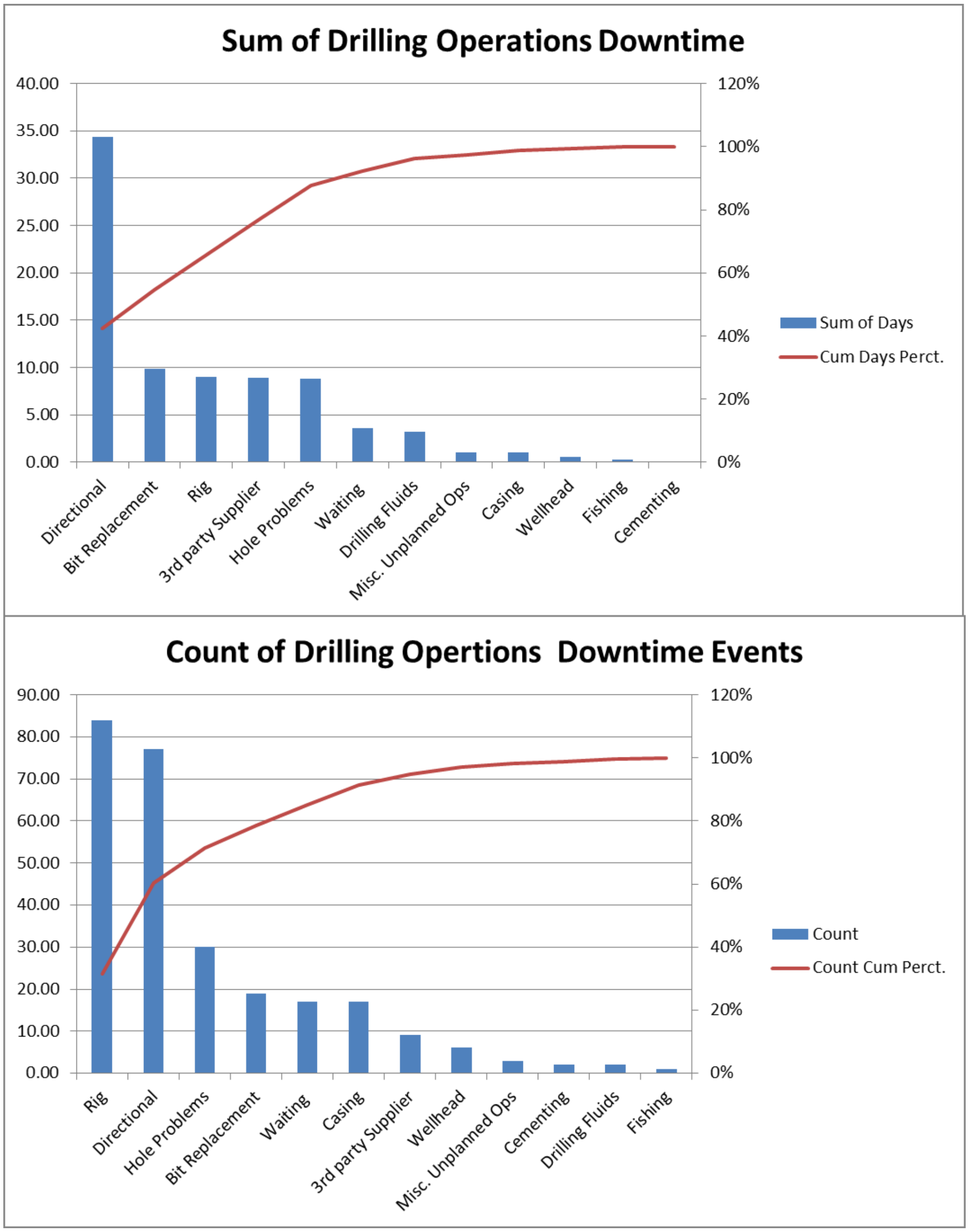


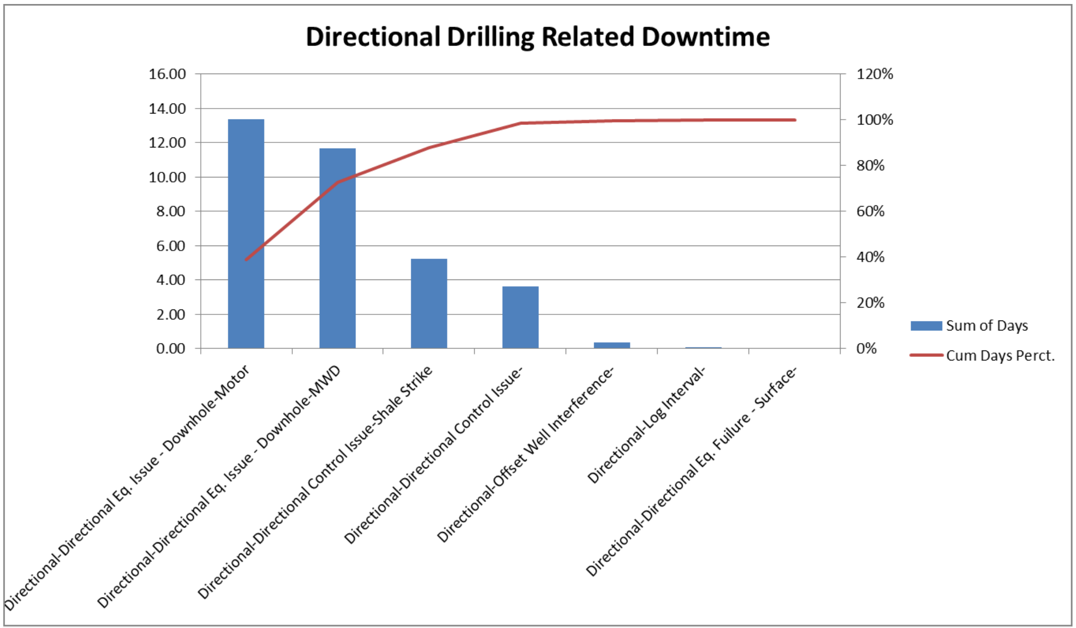
Fig. 17 - Sum of downtime, top; count of downtime events, bottom

In **Fig. 17**, the graph on the on top is the sum of days associated with NPT whereas the graph on the bottom is the count of downtime events distributed by category. Based on the Pareto Diagram on the top, the majority of NPT is a result of issues associated with directional drilling equipment failures. The impact is very significant for a four rig drilling fleet. Just under 35 days of downtime were associated with directional drilling issues. With the average drilling days (spud to release) down to 15.7 days in 2015, a complete elimination of this downtime would result in two additional wells for the second half of the year.

When comparing the two graphs, the sum of days vs the frequency of the events, it can be observed that the time associated with non-productive issues does not correlate with the number of occurrences. What this implies is that though an event may happen less frequently, the time loss may be of much greater impact. In the graph at the bottom of **Fig. 17**, the rig downtime events led the group in count. Time lost associated with the rig is much less however and places the associated rig related issues in 3rd for time lost. The primary reason that directional drilling NPT dominates the group is that with the majority of failures, a trip is required if surface trouble shooting efforts are unsuccessful. This category is also further populated by time lost to sidetracking in the event that build-rates are inadequate to land the well within the target zone or if one of the troublesome shales is penetrated should geo-steering interpretations be off or a loss of directional control occur. Bit issues also require replacement trips which is why it comes in second in the NPT category.

Based on the information in the graphs, the leading issues can be targeted and broken down on a finer scale to hone in on category specific problems. **Fig. 18** are the graphs of the directional drilling problems and **Fig. 20** are rig related issues. The majority of NPT related to bit replacements are a result of premature dulling of the cutters which, based on the extensive development and design iterations of the bits made specifically for the Bakken, are usually caused by mismanagement of drilling parameters. For this reason, the bit replacement category has been excluded from breaking down to a finer level for this paper. A close collaborative relationship with bit vendors and extensive dull analyses can accelerate the design curve in new areas. Developing a method for monitoring and reviewing drilling parameters will also help reduce downtime associated with bit dulling issues.

Directional Drilling Related NPT



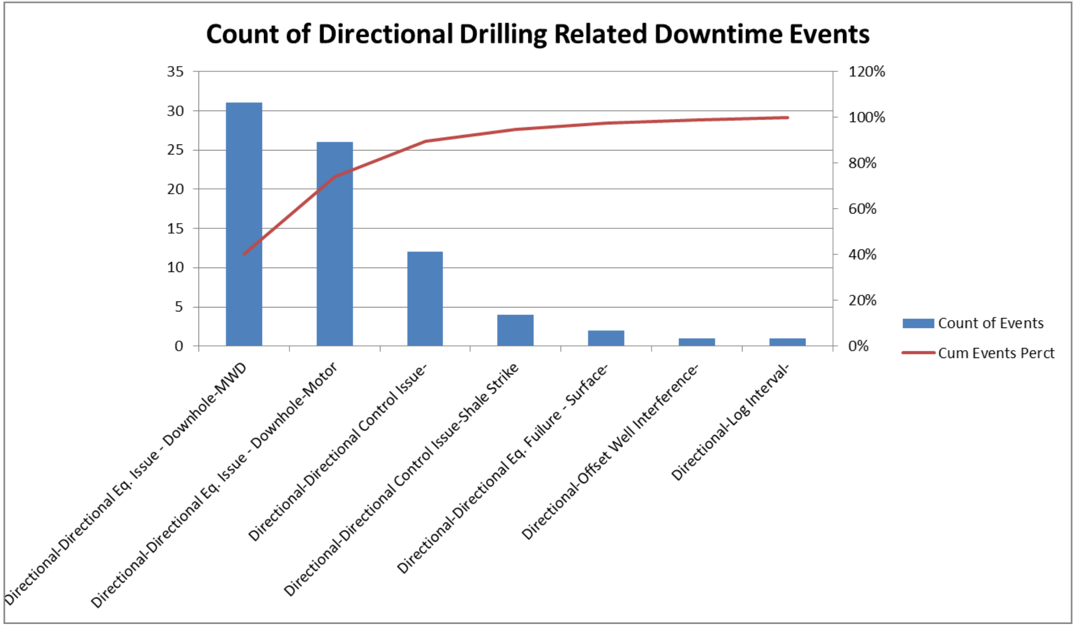


Fig. 18 - Sum of directional drilling downtime, top; count of directional drilling downtime events, bottom

When broken down into sub-categories, the directional drilling related issues are still dominated by problems that require a trip out of the hole. This highlights the criticality of having the highest quality downhole directional drilling equipment. The motor and MWD equipment are exposed to an environment with high torques, high axial loads, high differential pressures, high intensity vibrations, high temperatures and abrasive solids moving at high velocities. Given that the directional BHA components have to perform under such extreme conditions, it is not surprising that this is most reoccurring culprit of downtime. Dependence on the service provider to use parts that have enhanced engineering designs, normally associated with higher costs, will improve reliability and mean time between failures. Even with the high failure rate, the directional drilling contractor used by the operator leads the industry in Mean Time Between Failures (MTBF), a KPI used to determine the frequency of failures. Anytime a problem does occur, the directional drilling company provides the operator with an in-depth tear down report. The tear down is a post failure inspection to determine the root cause. What is promising is that the majority of the failures can usually be traced back to a controllable root cause allowing for corrective measures to be incorporated in the design and assembly process thus permitting continuous improvements to the MTBF metric. Commonly when the directional motor fails, the reason is due to the motor being run out of spec through a mismanagement of parameters. It is important to success that the rig crews understand the importance of balancing penetration rates with maintaining down hole equipment within their limits. It is still all too common that a rig will aim for running the most extreme parameters to maximize ROP with the anticipation that something will eventually fail but they can quickly trip for a replacement. Not only does this expose the crews to increased safety risks associated with the additional handling of the drill string and BHA, rarely does this method outperform steady on bottom drilling to the section TD.

In **Fig. 18** MWD issues lead the count in failures but not time. The reason for this is that MWD problems can sometimes be resolved from surface through troubleshooting methods. The MWD subcategory also includes anytime associated with re-logging of an interval if gamma readings were poor over a depth interval. The majority of MWD failures are caused by high vibrations, e.g. stick-slip, whirl, lateral and axial vibrations. High vibrations can be a result of poor BHA design, parameters mismanagement, formation or inadequate hole cleaning. Noisy bits that are too aggressive for the formation are one of the leading reasons for high vibrations resulting in a failed MWD. Multiple iterations of bit designs have improved the vibrational noise level while maintaining high penetration rates and reliable durability.

Categorizing the failures by hole section, **Fig. 19**, shows that the majority of Mud Motor and MWD problems occur in the production hole. This can be attributed to the high differential loads that are used for drilling in the lateral with the slim hole tools being less resilient than the larger tool sizes. The failure count for the intermediate and the production hole are similar but the length of time required to trip out of the lateral is what causes the prolonging of time.

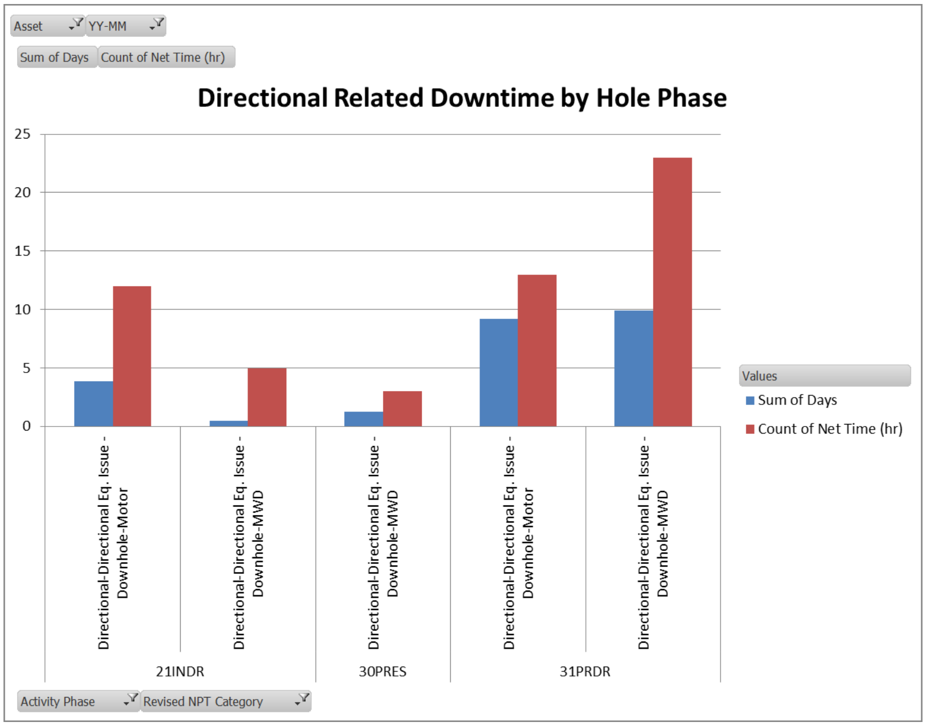


Fig. 19 - Motor and MWD failures by hole section.

When a failure report is generated, it is important that the drilling engineer takes the time to understand what the cause of the failure is and holds the directional company accountable for taking the necessary corrective measures should the failure be related to their equipment. The operator should also be embracive to feedback if the cause of the failure was mismanagement of parameters at which time he should inform the drill site supervisor.

In the beginning of the operator's drilling in the Williston Basin, the downtime associated with directional control issues and shale strike issues were much more frequent and costly. The control issues primarily were localized to the curve where build rates would be inadequate to land within the geology determined target zone. After multiple design iterations of the BHA, it was determined that the motors provided by the directional drilling contractor were the reason for the build rate issues. The solution was to source the curve motors from a 3rd party which reduced the frequency of trips for more aggressive build assemblies.

Shale strikes reduced in frequency with time as the geo-steering team became more familiar with the gamma markers and as more wells were drilled providing enhanced control when drilling development offsets. Clear communication between the drilling group and the geo-steering group also improved the frequency of shale strikes. The geo-steerers were unaware that drilling in one part of the target zone would subject the BHA to hard chert stringers that would cause uncontrollable deflections upwards into the shale resulting in the need for a sidetrack. Once the geology group was made aware that drilling within what was thought to be the "sweet spot" was causing the high frequency of shale strikes, they agreed to lower their targets thus reducing shale strikes dramatically.

Rig Related NPT

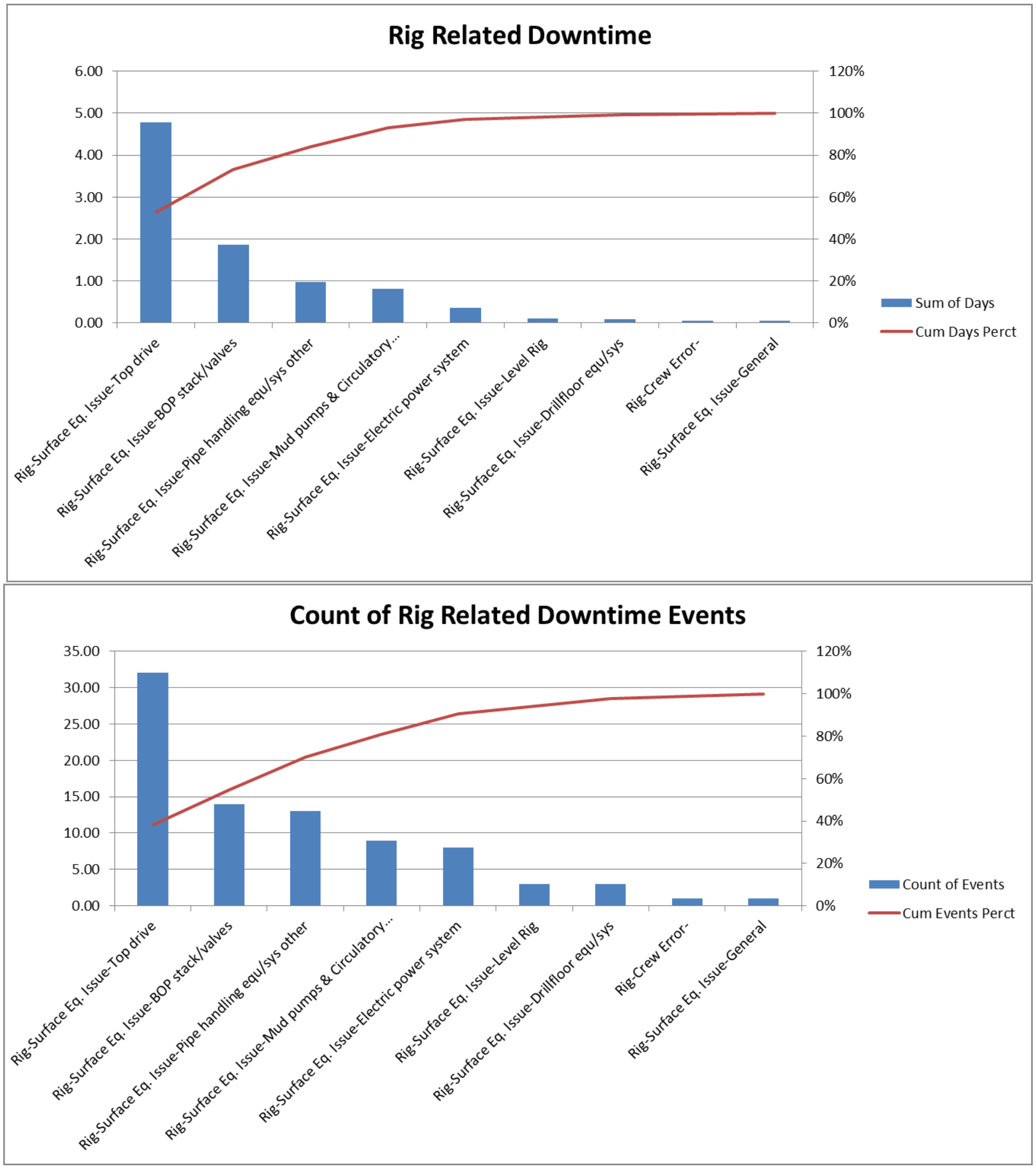


Fig. 20 - Sum of rig related downtime, top; count of rig related downtime events, bottom.

The rig related downtime category is any time lost due to equipment failures or rig crew errors. Fortunately for the rigs that were analyzed, rig crew errors are seldom and usually not very severe. This usually is not the case when a rig crew is inexperienced or has not been working together for an extended period of time. The group is dominated by a wide margin by Top Drive issues which puts it at the top of the list for problems to resolve. Since the Top Drive is a complex machine with several working mechanisms that serve specific purposes e.g. the gear box and drilling motor which transmits rotary motion and torque to the drill pipe, and the swivel, a bearing assembly which allows for the transfer of rotating loads to the lifting components, etc. , it needs to be further broken down to determine which components are failing.

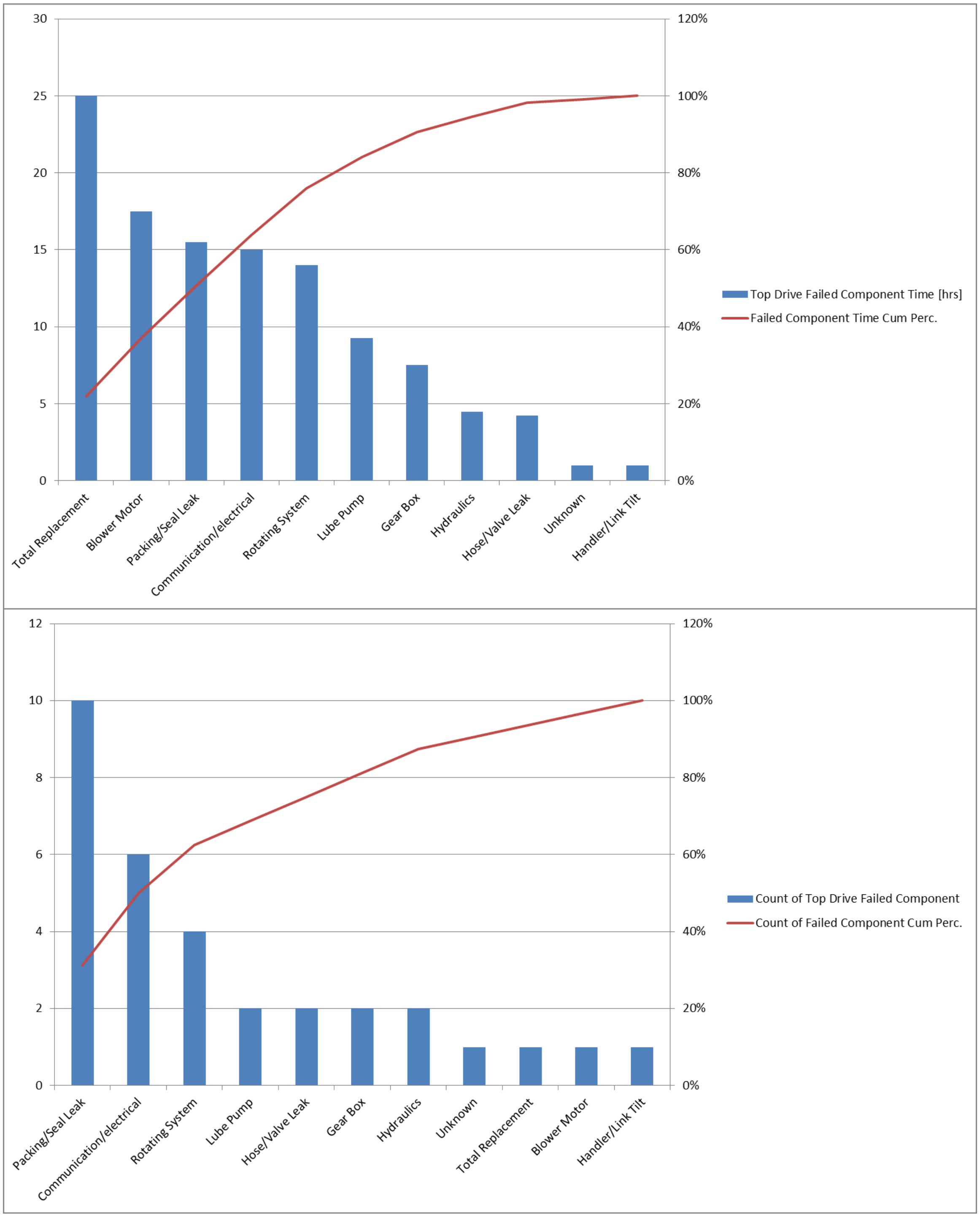
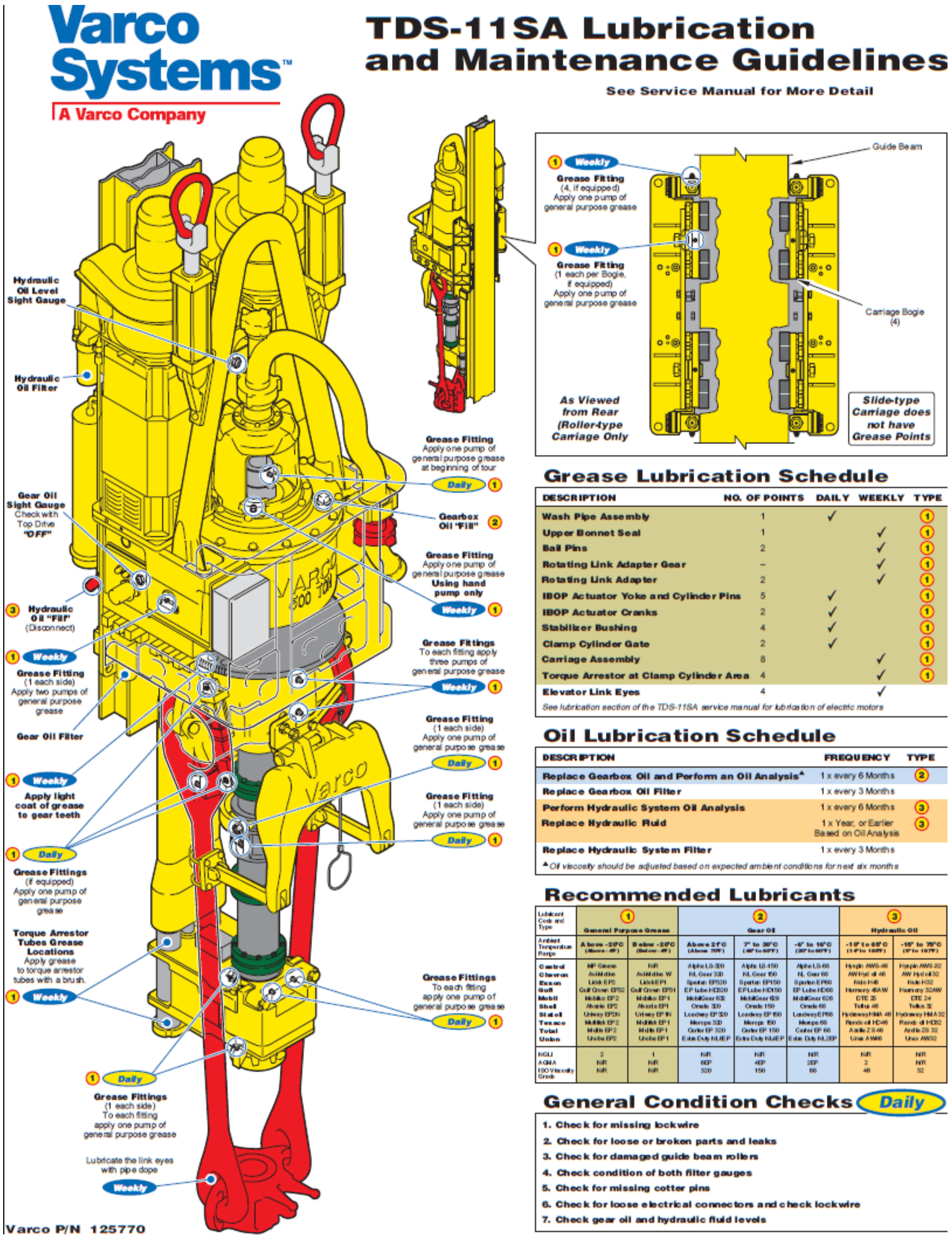


Fig. 21 - Top drive specific NPT time, top; top drive specific NPT events count, bottom.

Based on the Pareto Diagram, a total replacement of the Top Drive is very costly resulting in over a day of NPT but rarely occurs. Proper maintenance of the Top Drive and frequent inspections will dramatically reduce the probability of a catastrophic failure requiring a full replacement. Failure of the blower motor will also result in a significant amount of time lost but is also infrequent. The two leading causes of NPT are washpipe packing leaks and losses of communication or electrical issues. The main factors that affect washpipe packing life are standpipe pressure, top drive revolutions per minute, the washpipe diameter and mud temperature (Varco Systems 2004). Varco recommends grease injections at a minimum on a daily basis as preventative maintenance. Failure to follow recommended lubrication schedules will accelerate the wear of Top Drive components. **Fig. 22** is a Lubrication and Maintenance guide for a TDS-11SA showing all points of injection for the grease as well as the frequency of injections.



TDS-11SA Lubrication and Maintenance Guidelines

See Service Manual for More Detail

Grease Lubrication Schedule

DESCRIPTION	NO. OF POINTS	DAILY	WEEKLY	TYPE
Wash Pipe Assembly	1	✓		①
Upper Bonnet Seal	1		✓	①
Ball Pins	2		✓	①
Rotating Link Adapter Gear	–		✓	①
Rotating Link Adapter	2		✓	①
IBOP Actuator Yoke and Cylinder Pins	5	✓		①
IBOP Actuator Cranks	2	✓		①
Stabilizer Bushing	4	✓		①
Clamp Cylinder Gate	2	✓		①
Carriage Assembly	8		✓	①
Torque Arrestor at Clamp Cylinder Area	4		✓	①
Elevator Link Eyes	4		✓	

See lubrication section of the TDS-11SA service manual for lubrication of electric motors

Oil Lubrication Schedule

DESCRIPTION	FREQUENCY	TYPE
Replace Gearbox Oil and Perform an Oil Analysis▲	1 x every 6 Months	②
Replace Gearbox Oil Filter	1 x every 3 Months	
Perform Hydraulic System Oil Analysis	1 x every 6 Months	③
Replace Hydraulic Fluid	1 x Year, or Earlier Based on Oil Analysis	③
Replace Hydraulic System Filter	1 x every 3 Months	

▲Oil viscosity should be adjusted based on expected ambient conditions for next six months

Recommended Lubricants

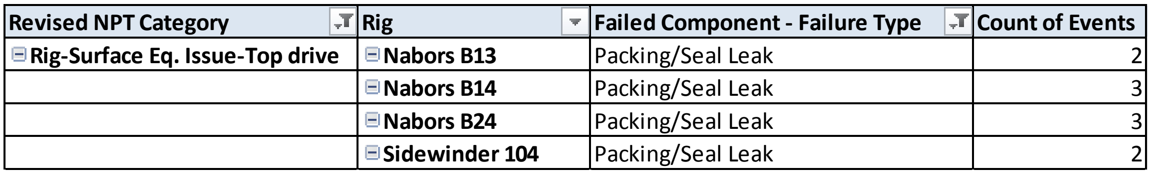
Lubricant Code and Type	① General Purpose Grease		② Gear Oil			③ Hydraulic Oil	
Ambient Temperature Range	Above -20°C (Above -4°F)	Below -20°C (Below -4°F)	Above 21°C (Above 70°F)	7° to 30°C (45° to 85°F)	-6° to 16°C (20° to 60°F)	-10° to 85°C (14° to 185°F)	-15° to 75°C (5° to 167°F)
Castrol	MP Grease	N/R	Alpha LS-320	Alpha LS-150	Alpha LS-68	Hyspin AWS-46	Hyspin AWS-32
Chevron	Avi-Motive	Avi-Motive W	NL Gear 320	NL Gear 150	NL Gear 68	AW Hyd oil 46	AW Hyd oil 32
Exxon	Lidok EP2	Lidok EP1	Spartan EP320	Spartan EP150	Spartan EP68	Nuto H46	Nuto H32
Gulf	Gulf Crown EP#2	Gulf Crown EP#1	EP Lube HD320	EP Lube HD150	EP Lube HD68	Harmony 46AW	Harmony 32AW
Mobil	Mobilux EP2	Mobilux EP1	MobilGear 632	MobilGear 629	MobilGear 626	DTE 25	DTE 24
Shell	Alvania EP2	Alvania EP1	Omala 320	Omala 150	Omala 68	Tellus 46	Tellus 32
Statoil	Uniway EP2N	Uniway EP1N	Loadway EP320	Loadway EP150	Loadway EP68	Hydraway HMA 46	Hydraway HMA 32
Texaco	Multifak EP2	Multifak EP1	Meropa 320	Meropa 150	Meropa 68	Rando oil HD46	Rando oil HD32
Total	Multis EP2	Multis EP1	Carter EP 320	Carter EP 150	Carter EP 68	Azolla ZS 46	Azolla ZS 32
Union	Unoba EP2	Unoba EP1	Extra Duty NL6EP	Extra Duty NL4EP	Extra Duty NL2EP	Unax AW46	Unax AW32
NGLI AGMA ISO Viscosity Grade	2 N/R N/R	1 N/R N/R	N/R 6EP 320	N/R 4EP 150	N/R 2EP 68	N/R 2 46	N/R N/R 32

General Condition Checks Daily

1. Check for missing lockwire
2. Check for loose or broken parts and leaks
3. Check for damaged guide beam rollers
4. Check condition of both filter gauges
5. Check for missing cotter pins
6. Check for loose electrical connectors and check lockwire
7. Check gear oil and hydraulic fluid levels

Fig. 22 - TDS -11SA Lubrication and Maintenance Guide (Varco Systems 2016).

To further determine what may be the reason for the NPT associated with the washpipe packing, the maintenance records should be checked to ensure that proper grease injection schedules are being followed. It may be possible to swap the sealing elements to a higher grade material should failures remain a problem even with proper preventative maintenance. When the problems are broken out by rig (Table 5), it can be seen that all experienced downtime associated with washpipe packing leaks.



Revised NPT Category	Rig	Failed Component - Failure Type	Count of Events
Rig-Surface Eq. Issue-Top drive	**Nabors B13**	Packing/Seal Leak	2
	Nabors B14	Packing/Seal Leak	3
	Nabors B24	Packing/Seal Leak	3
	Sidewinder 104	Packing/Seal Leak	2

Table 5 - Count of NPT events associated washpipe packing leaks.

One approach to mitigating the downtime associated with washpipe packing failures can be to take a proactive maintenance approach and replace the washpipe packing offline while the while the rig is moving from one well to the next.

4.3.2.6. Total Productive Maintenance

The frequency of equipment failures resulting in NPT can be improved by establishing a Total Productive Maintenance (TPM) program. TPM improves the maintenance practices for equipment and infrastructure, and enables the prediction and/or prevention of anticipated failure. TPM aims to remove deficiencies from machines to minimize or eliminate defects and downtime. According to the publication by Munro et al. (2015) TPM addresses inefficiencies in the following manner.

- Avoiding reduced, idled, or stopped performance due to equipment breakdown.
- Reducing and minimizing the time spent on setup and changeover of equipment, which can otherwise idle machine operations and create bottlenecks.
- Avoiding stoppages arising from the processing or discovery of unacceptable products or services.
- Ensuring that processes and equipment are operating at the speed and pace for which they were designed. If the pace is slower or delayed, work to address and rectify the source of the delays.
- Increase the yield of acceptable material to reduce material waste, scrap, rework, and the need for material reviews.

As in the case with the issues with the washpipe packing discussed above, any time there is a leak, operations have to be stopped and the component replaced. Though this can be taken care of in less than 30 minutes, the issue is so frequent that it builds to become a much greater problem but is often overlooked as a source of downtime. Following a TPM for the top drive and its components is essential to limiting the downtime which would otherwise be much more prevalent.

A drilling rig is subjected to extreme operating conditions and without a proper maintenance program will experience frequent NPT that can be costly to both the contractor and the operator. Since the drilling contractor is responsible for maintaining the rig equipment, drilling contracts allow for shutting down of operations for half an hour to a full hour per day for servicing the equipment without penalization. This is an example of TPM for the rig which includes the maintenance of the top drive. If an equipment failure leads to downtime in excess of a contracted amount, the operator is no longer liable for payment of the rig rate until the equipment has been repaired and normal operations can resume. Therefore it is in both parties best interest to strictly adhere to the TPM established for maintaining the rig.

Since the rig is the primary and most costly tool used for the drilling process, the alliance with the drilling contractor is extremely important to ensure that quality of the equipment is maintained and that they are invested in the quest for perfection. Regular service quality meetings should be held with the drilling contractor to discuss successes as well as performance and equipment gaps that were experienced over the prior period. Corrective actions should then be established to address the issues in an effort to eliminate them from future occurrences striving for continuous improvement.

4.3.2.7. 5S

5S is a Lean organization concept that makes use of 5 steps to achieve order at the work place. The 5 steps are the following.

- Sort – Sort out the necessary items required for a work station and remove those that are not needed.
- Straighten – Organize the work station in logical arrangements so that they are easily and readily used.
- Shine – Keep the work station clean. A tidy work station makes identification of defects easier.
- Standardize – Use the first three steps regularly to maintain the condition of the work station.
- Sustain – Rely on the steps to sustain the organization of the workshop.

Maintaining a regimental 5S discipline will significantly improve working conditions at the rig both from an equipment perspective but also an HSE perspective. The rig can be a very chaotic and dirty workplace given normal operating conditions. Oil based muds and grease that are a normal part of operations will adhere to rig equipment and personnel which can potentially lead to dangerous working conditions but also to the concealment of impending defects. Sorting and straightening of rig equipment and cleaning on a regular basis should be part of the normal daily work flow on the rig.

During a visit to the rigs, a 5S analysis was performed by the operator to improve organization. The following observations were made.

- Unorganized tool storage containers **(Fig. 23)**. Time was often wasted trying to find an item in the container. Excessive tools and replacement parts not required for the job could be found in the container.

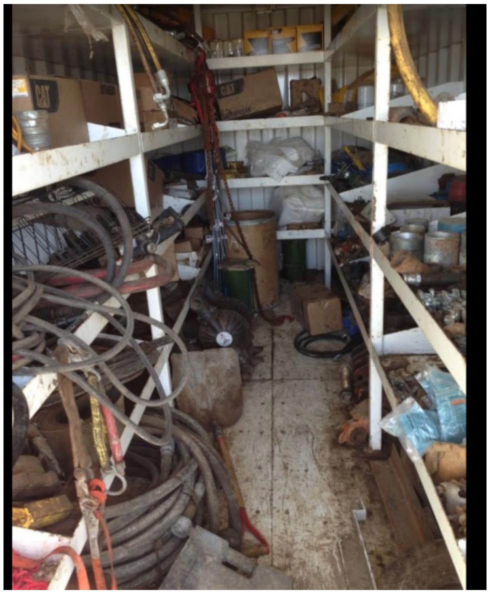


Fig. 23 - Unorganized tool storage container

- Tool stations were not straightened in any logical order **(Fig. 24)**. Finding the right sized tool often meant pulling several tools off the rack and sorting through them.

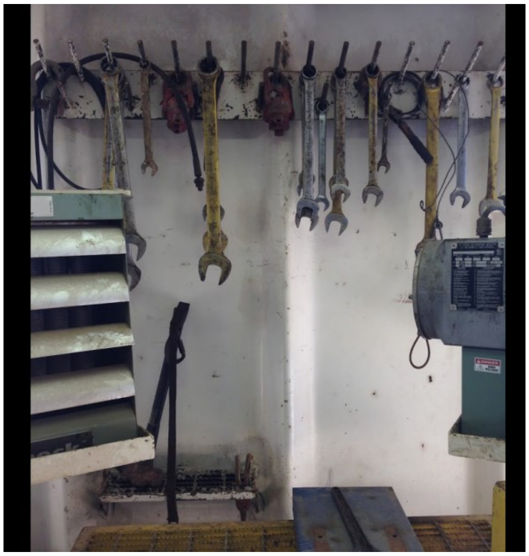


Fig. 24 - Unorganized wrench tool station.

- Excess drill collars that had not been used in years located on the pipe storage racks
- Varying numbers of fluids storage tanks across rig fleet
- Damaged hoses needing to be disposed of stashed in open top containers

These items were addressed with the drilling contractor to initiate 5S organization at the rig. Once implemented, job times decreased because of the elimination of searching for tools and parts, rig move times decreased because of the elimination of unnecessary trucking loads, and rental costs decreased by releasing excessive equipment that was being charged to the operator. The crews also started maintaining their rigs in cleaner condition as time was freed up not having to search for items.

4.3.2.8. Mistake Proofing (Poka Yoke)

Mistake proofing, or Poka Yoke as it is referred to in Lean, is the concept of assisting an operator in avoiding mistakes. Many drilling rigs incorporate mistake proofing to varying degrees, in particular modern day computerized AC (Alternating Current) rigs. Critical rig functions that are controlled on the driller's dashboard often require an override before being able to engage/dis-engage associated equipment. **Fig. 25** is an example of a Poka Yoke check that would prevent the driller from releasing a string of casing unless absolutely certain this was the course of action he wanted to take.

CAUTION

You are attempting to:
RELEASE THE CASING
Do you want to proceed?

Fig. 25 – Driller's control dashboard displaying casing release override.

Further opportunity for mistake proofing exists beyond just the computerized controls of the rig. Color coding or labeling the BOP hydraulic lines in **Fig. 26** is an opportunity for mistake proofing and would assist in properly connecting the hoses to the correct BOP components.

Fig. 26 – Accumulator hydraulic hoses.

Incorporating Poka Yoke at the rig and into the drilling process as much as possible, where applicable, will improve efficiency through the elimination of downtime associated with corrective measures for frequently made mistakes.

4.3.2.9. Results from WTCRW II

Going into the second workshop, a certain level of skepticism hung in the air over what could really be achieved since the operator felt that most of the low hanging fruit had been picked. During the workshop, it quickly became apparent that there was a substantial amount of room for improvement through further incorporation of lean concepts. A few of the attendees of the workshop from other functional groups were trained in lean and helped drive the direction of which concepts to use in certain situations. After the workshop, the lean initiatives were handed over to the drilling group which had a mixed background of exposure to Lean but no one with any formal training. Some of the concepts would have to be learned through self-education.

Similar to the first workshop, the leading indicator of success would be reflected in the drilling days. One difference in this case was that the operator used total days on location instead of Spud-to-Release days to encompass rig move efficiency. **Fig. 27** is a graph of days on location from 2014 up through March 2016.

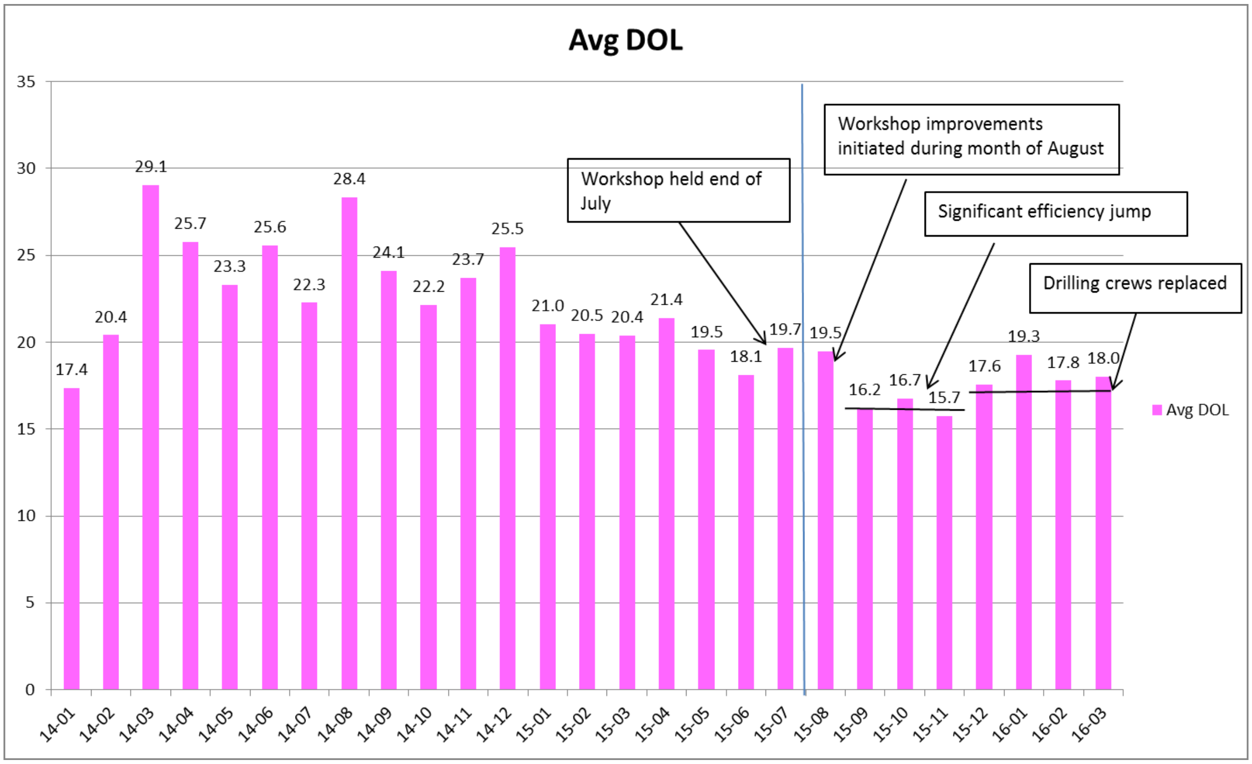


Fig. 27 - Drilling days on location.

In the graph above, it can be observed that in the subsequent months after the workshop, the operator had its best months of drilling performance delivery it had yet achieved. At the same time that drilling efficiency was improving, oil price remained at a near historical low which forced the operator to cut back its operations down to one rig. The story was the same for all operators in the Williston Basin which in turn forced the drilling contractor to reduce personnel as a widespread stacking of rig took place. In doing so, many of the seasoned rig personnel that had risen through the ranks were demoted in effort to keep the most qualified employed. Several of the tool pushers that were demoted to drillers had never operated a modern day AC rigs and were only familiar with drilling with DC (Direct Current) rigs with break handles. Though the concepts were the same, the modern technology made operating the rig drastically different from what they were familiar with. The increase in days shown in **Fig. 27** for December 2015 is a direct reflection of the impact the changeover of personnel had on rig efficiency.

4.3.2.10. Lessons Learned from Workshop II

Some of the lessons that were learned from the first workshop paved the way for a much easier second workshop and corresponding incorporation of changes. Some of the new lessons that were learned were the following:

- Searching for waste later in the field development cycle requires increased effort to identify opportunity
- Though it requires more work, ample opportunity exists even within a mature drilling program
- Personnel turnover has a significant impact on performance

- Even with a daily quality checking regiment by the engineers, drilling reports are still prone to mistakes associated with human error

5. Conclusion

As is the case with most industries, lean has its place in oil and gas and can be used to successfully improve efficiency and reduce costs. A hand-full of oil and gas companies, both operators and service/equipment providers alike, have successfully used lean to improve their operations. Operators have used lean to reduce the time and costs for the well construction process while service providers have used lean to improve the manufacturing process of equipment and tools. Equipment providers' operations are more in line with the conventional model of factory manufacturing that lean was founded on compared to the well construction process since production usually occurs along an assembly line.

Since 2013 the operator discussed in this paper has relentlessly pursued efficiency improvements in effort to deliver quality wells on-schedule at reduced costs. This has primarily been out of necessity to improve well economics, especially in the time of depressed oil prices, but also as a result of the desire to be a best-in-class company. Some of the improvements realized resulted from progressing through a typical learning curve associated with any field and refining the standard operating process while others have been accomplished through the application of improvement initiatives, in particular through the use of lean and the elimination of waste.

The operator's journey with lean has been in progress for nearly three years and has experienced several challenges along the way. The operator has managed to overcome acceptance barriers that were initially in place and, as the drilling team, both in the office and in the field, have grown comfortable with change, the pursuit of perfection has become easier.

The drilling process of a well requires an alteration to the conventional manufacturing model of a product being passed along from station to station in an assembly line, to account for a stationary product with the work assemblies as the moving component. Counter to the lean concept of continuous flow, batch-and-queue has its advantages on a multi-well pad drilling scenario such as the operator's in the Williston Basin.

Data integrity is crucial to being able to conduct a proper analysis of drilling performance and should be a part of any improvement initiative where quality may be lacking. The daily drilling report data can be used on a large scale to identify areas for improvement but shouldn't be used to perform too granular of a performance analysis. Grouping sub-assemblies into logical cells with common goals allows for easier management of activities on a more meaningful scale when using the daily drilling report data. The use of a drilling state detection service that is fed off of sensor data is the most reliable source of drilling performance data and can be used for a to-the-second level of analysis.

For the drilling process, this paper explored the following Lean tools which have been used by the operator to improve well delivery.

- SMED
- 5S
- TPM
- Continuous Improvement
- Pareto Diagrams
- Root Cause Analysis (Ishikawa Diagrams)
- 7 Types of Waste
- KPIs
- Mistake Proofing (Poka Yoke)

Only the surface has been scratched in what is achievable through the implementation of Lean. A deeper reach into the Lean tool box will aid in the continued effort to further eliminate waste and pursue drilling process perfection.

6. Bibliography

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List of Acronyms

NPT – Non-productive Time

ISO - International Standardization Organization

TPS - Toyota Production System

JIT – Just In Time

SMED - Single-Minute Exchange of Dies

TVD - True Vertical Depth

MD – Measured Depth

KOP – Kick Off Point

TD – Target Depth

BHA – Bottom Hole Assembly

WTCRW – Well Time and Cost Reduction Workshop

BDP – Best Demonstrated Performance

BOP – Blow Out Preventers

MWD – Measurement While Drilling

KPI – Key Performance Indicator

ROP – Rate of Penetration

MTBF – Mean Time Between Failures

AC – Alternating Current

DC – Direct Current