Application of Toyota's Principles and Lean Processes to Reservoir Management: More Tools To Overload the Toolbox or a Step Change in Our Business?

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Summary

Aera Energy LLC was formed in 1997 to be a low-cost operator and producer in California. However, the low oil prices from 1998 to 1999 forced an examination of all operations in the office and in the field. Cutting costs, improving timekeeping, or reducing the scale of operations would not be sufficient without a step-change gain in efficiency. This step-change gain came from the use of principles and concepts developed in the automobile and construction industries. Toyota's twin pillars of just-in-time production and the ability of anyone to stop production rather than pass on defects, coupled with level-loading of work processes and reducing waste, were introduced. Toyota's principles were enhanced by the addition of "Last Planner" concepts developed for the construction industry. When both were implemented for reservoir-characterization and reservoir-development work, significant process improvements resulted. The resulting improvements are now being used throughout the company to improve quality by removing waste and reducing errors, to measure processes, and to improve cycle times.

The unconventional diatomite reservoirs and oil-sand reservoirs at the giant Belridge field produce 65,000 BOPD from 5,300 producing wells and 2,100 injection wells. The many drilling, completion, and workover rigs have a constant appetite for new wells. To maintain production and cost targets, everything in the office has to run reliably and efficiently at all times, as well as support field operations.

Different aspects of Toyota's principles and "Lean Manufacturing" are illustrated by use of project work for reservoir characterization, day-to-day reservoir surveillance, and the development work needed to plan and schedule new wells. The processes and projects typically have multiple customers and suppliers—internal and external. All involved, including knowledge workers (those who think for a living), need to work as a single system with a manufacturing mentality and to strive for continuous improvement. Customers of the knowledge work supplied by the geoscientists and reservoir engineers have benefited greatly from the introduction of the lean processes and the resulting smoother and more-effective workflows. In 2011, the Development Team's lean activities were recognized by the Association for Manufacturing Excellence, and the team received the Manufacturing Excellence Award that recognizes "continuous improvement, best practices, creativity, and innovation."

The oil industry has a reputation of being slow to adopt new technologies and techniques. However, a Lean Manufacturing mentality introduces new ideas and ways of performing knowledge work that may change this paradigm while contributing to the bottom line with reduced cycle time and improved quality. A significant additional benefit is that geoscience and engineering professionals can spend more time doing creative work and less time fixing problems or reacting to system upsets—as they simultaneously reduce waste. However, to realize all these benefits and the step changes they provide, a thorough understanding of Toyota's principles and a Lean Manufacturing mentality are essential.

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Introduction

Aera Energy LLC was formed by Shell and Mobil with a combination of their upstream onshore and offshore California assets. Aera began operating in June 1997 and is currently owned by affiliates of Shell and ExxonMobil. The purpose of founding the company was to generate economies of scale and efficiency so that the company would be the premier low-cost operator and producer in California (Allan et al. 2013). Aera's oil and gas production in June 1997 was 237,000 STB/D and 77 million scf/D, respectively, from 9,462 producing wells supported by 1,940 steam injectors and 680 water injectors in nine main oil fields **(Fig. 1).** At that time, this represented 25% of California's oil production. Aera's production from the Belridge field was 112,000 STB/D of oil and 48 million scf/D of gas from 4,000 producers—approximately half of the company's production. The posted price for 13°API heavy oil was USD 13.50/STB, the price for 26°API intermediate oil was USD 15.50/STB, and the index gas price was approximately USD 2/million Btu.

There was an emphasis on low cost and high efficiency, but there were certain inefficiencies and duplication of efforts because of the combining of the operating methods of the two companies. However, the newly formed company began with a blank slate for management strategies, and time was spent evaluating, testing, and implementing various techniques for creativity and different ways of thinking. Examples included

- Edward de Bono's *Six Thinking Hats* process for more-effective conversations and improved decision making by seeing an issue in different ways and focusing on essential wisdom (de Bono 1985).
- Min Basadur's *Simplex*® process, which applies creativity to problem solving and strategic thinking. It uses a cycle of work, discover, and validate (Basadur 1995).
- Genrich Altshuller's *TRIZ* theory of inventive problem solving for technical problems. It is a structured Russian way of creatively solving problems with one or more of 40 physical principles that was developed in 1946 (Altshuller 1994).
- Eliyahu Goldratt's *Theory of Constraints* to reduce constraints and increase throughput, in which constraints prevent achieving goals so buffer management (protection of the "drum") is essential until the constraints are identified and removed or managed (Goldratt 1999).

Relationships were also developed with organizations such as Pratt & Whitney's Rocketdyne Division, the National Aeronautics and Space Administration Jet Propulsion Laboratory, the California Institute of Technology, and others to learn how other industries and institutions applied systems thinking, and to develop leading-edge processes for developing innovative ideas. None of these took root or were transformative for the organization. However, valuable exposure to a variety of techniques for systems thinking, lean processes, and supplier collaboration had been gained.

Fig. 1—Aera's producing fields in December 1997.

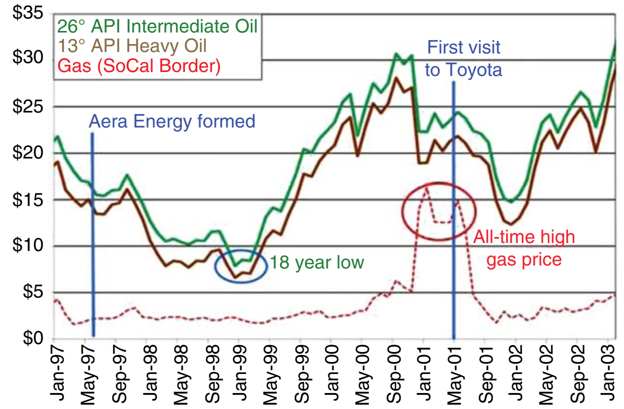

Fig. 2—Posted prices in California.

There was also the feeling among management and the technical staff that too much time was being spent in nonproductive meetings that added little real value. The solution was to track noncore staff time—defined as nonproductive time spent in meetings, training, and so forth. The goal was for everyone to spend more than 80% on core work. However, management expectation was interpreted as management decree, and soon the spreadsheet showed that everyone was working at near 100% on core work. Eventually, to popular acclaim, the spreadsheet faded away. However, the realization that greater efficiency was possible had been gained throughout the organization.

The posted price for 13°API oil averaged USD 14.96/STB for 1997 but began dropping at the end of the year **(Fig. 2).** By March 1998, it reached an 18-year low of USD 7.90/STB. Intermediate 26°API oil was USD 10.50/STB. The prices averaged USD 8.54/STB and USD 10.70, respectively, for 1998, and the ability of the company to generate cash after expenses was severely limited. Although the lighter oil was sold for slightly more per barrel, the margin between the cost of production and the sales price was small throughout the company. The reservoirs containing the heavy oil needed to be steamed, and the reservoirs with light oil (mainly the diatomite of the unconventional Monterey shale at Belridge) needed to be hydraulically fractured.

Although the company concentrated on core processes and producing oil, the significant duplication of software and paperwork (e.g., to recommend drilling and completing wells) in the office was slowing things down. Equally important was the variety of surface and downhole equipment used in the various fields along with large inventories of material kept at the fields. Senior management realized that the viability of the company required a dramatic change in operating mentality and methods. The solution came in April 2001, when two employees read *The Machine That Changed the World* by Womack, Jones, and Roos and then visited Toyota's Kentucky plant (Womack et al. 1990). The next 2 years were spent in a managed learning environment with pilot projects throughout the company, benchmarking visits, and research. Senior management approved of this and determined that the lean processes used by Toyota for manufacturing cars were very applicable for Aera. With the benefit of hindsight, the adoption of the lean process by Aera seemed obvious: The company's founding principles included statements such as "continuous improvement is a way of life" and "always learning from failures (plan, do, check, and act)." Although the adoption is still under way, the lean process is considered to be the silver-bullet strategy to take the company along the path to world-class performance.

The Toyota Production System (TPS), founded upon principles established by Toyota since the 1930s (developed from the 1930s to 1970s and codified in 1973 to 1977) and improved by learnings from W.E. Deming in the 1950s, was Aera's introduction to the lean process. The four rules of TPS are

1. All work must be precisely specified.
2. Customer/supplier connections must be direct.
3. The pathway for each product and service must be simple and direct.
4. Any improvement must be made by use of the scientific method at the lowest possible level in the company.

The four rules are achieved by smoothing workflows and eliminating all types of waste. Lean processes are then used to build upon the methods pioneered by Toyota. This was Aera's path to the manufacturing mentality that has resulted in processes with improved efficiency through continual waste reduction. With the need to get a statistical basis for increasing reliability and efficiency, Six Sigma methods were added in 2006. The thought processes and efficiencies from these Lean methods have been transformative to Aera and are now used throughout the company and by many of Aera's suppliers.

Background

TPS. In the aftermath of the Second World War, Japanese industries needed to rebuild. They were helped by financial aid from the US as well as by learning techniques for statistical process control and quality improvement principles from W.E. Deming (2012). One of the techniques was the Shewhart/Deming plan-do-check-act (PDCA) improvement cycle, developed in the late 1940s to 1950s. These techniques were implemented at Toyota, but it was not until a Toyota delegation was on a visit to several Ford automotive factories in Michigan in the mid-1950s that a breakthrough was made. The delegation was impressed by Henry Ford's moving assembly line and the flow of the cars through the plant—nearly single-piece flow with minimal inventory. They also took note of Ford's focus on standardized work, which was modeled after the Training Within Industry (TWI) programs developed during World War II (Huntzinger 2006). TWI programs had also been introduced to Japan after the war to help rebuild industries so the delegation was already familiar with its principles and products (Huntzinger 2002). The delegation also visited a Piggly Wiggly self-serve grocery store where they noted that customers served themselves, products were standardized, inventory was purposely kept low, and the inventory was only replenished when products were sold. This visit to one of the first modern supermarkets, coupled with Deming's principles; TWI; and Ford's moving assembly line, standardization, and efficiency provided the inspiration for what came to be called by the mid-1980s the Toyota Production System (TPS).

The TPS is built on two main pillars or principles: just-in-time production and *jikoda*, which is the ability of anyone to stop the production process if there are problems. Underlying both pillars is the philosophy "good thinking makes a good product." Equally important are level-loading, standardization of work, and waste elimination (Spear and Bowen 1999). The result is a "relentless pursuit of the elimination of waste" (Ohno 1988). The fundamentals,

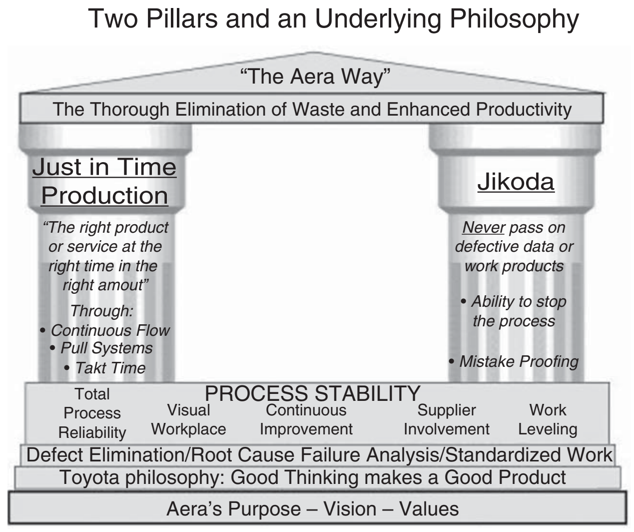

Fig. 3—The TPS at Aera: two pillars and an underlying philosophy.

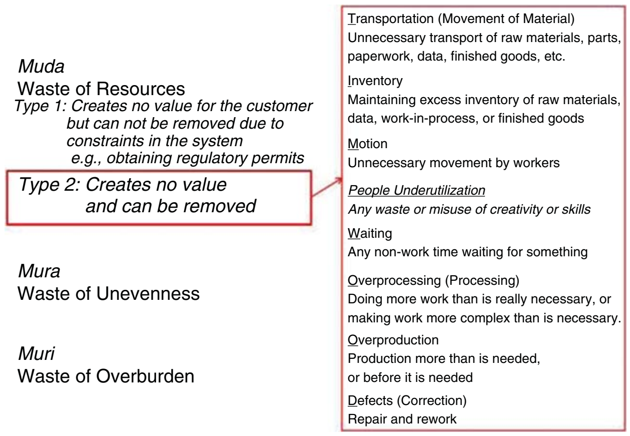

Fig. 4—Characterization of waste.

with Japanese terms in italics, are

- just-in-time production
- *jikoda*, or quality in station
- level-loading
- standardization of work
- waste elimination
- *kaizen*, or continuous improvement
- *gemba* visits to see "the real place" where work is performed

Fig. 3 illustrates Aera's depiction of the system.

Just-In-Time Production. Just-in-time production is producing what the customer needs when it is needed and in the amount needed—in other words, build-to-order rather than build-to-target, customer-driven "pull" rather than a target's "push." This is what underlies the reduction in inventory: whether casing on-hand, wells planned to be drilled, or cross sections from a geological model. It is derived from the following principles.

The Pull System. A customer "pulls" a product, and production of the replacement product is inspired by actual demand. An easily understood example of "pull" is that when a customer buys a loaf of bread in a supermarket, another loaf is then placed on the shelf. Instead of a sales forecast, a *kanban*, which is a signal or signboard system, can be used to match supply with demand by scheduling or beginning production.

Continuous-Flow Processing. This is the series of steps along a value stream that "flow" steadily and without interruption from the beginning of the process to the customer. Leveling of the processing steps makes problems more visible and also reduces the response time to any upsets. It is the opposite of traditional "batch-and-queue" processing in which large batches of products are produced and large inventories maintained—work-in-progress and finished goods.

Takt Time. From the German word *taktzeit*, meaning cycle time or period; this term was developed in the German aircraft industry in the 1930s. It is the pace of production required to meet customer demand. For example, if the drilling rigs (the customer) require 60 new well locations (the product) per 30-day month, the *takt* time for preparing each location is half a day.

Jikoda. *Jikoda* means "quality-in-station," where anyone can stop ongoing work if there are problems with quality. No known defects should be passed to the next step of a process. This helps prevent the accumulation of defects in the final product. An example would be to cease modeling porosity from log data when the log data are known to be wrong. A key tool for tracking the status and quality of a process is the *andon*, or signal, board. A typical example of an *andon* board at Aera displays the color-coded status of one or more processes, with green indicating OK, yellow indicating an early warning, and red indicating a breakdown or failure. This immediately shows where work is needed to fix a problem. *Poka-yoke*, or mistake-proofing, is also an integral part of the *jikoda* pillar.

Level Loading. Level loading, *heijunka*, is scheduling the amount and the mix of work needed for production to be smooth and consistent from day to day. There is no point in having one part of a process overproduce when the downstream part of the process cannot accept or cannot use the overproduction. Work needs to be smooth and balanced. This applies to all steps in the process and includes suppliers.

Standardization of Work. This means that work products should be uniformly produced and in the best way for the process. Standardization includes *takt* time, the sequence of work, and the available inventory needed for the work at hand. Standards represent the best known way to perform a defined task and to have uniformity among data families. Standards and the best practices required to attain them need to be documented so that they can be used as the starting points for improvements.

Waste Elimination. This applies to all areas of the business—from management to knowledge workers to field hands, and from the geosciences to engineering to business support functions. It is the key to the success of TPS and Lean. Waste falls into one of three categories or domains: *muda, mura*, and *muri*. Type 2 *muda* is further divided by Toyota into seven forms that can be remembered by the mnemonic "Tim Wood." For knowledge workers, an eighth form—people underutilization—is added and the mnemonic becomes "Tim P. Wood." The inclusion of this waste is fundamental because it is easy to overlook creative and innovative skills, and also to use knowledge workers for tasks that should be performed by others with a less expensive set of skills. The various forms of waste are shown in **Fig. 4.**

Kaizen. *Kaizen*, meaning improvement, is an essential and prominent element of any lean culture. The word is applied to the process of continual improvement and the activities where improvements are sought. Continuous improvement is typically accomplished through small incremental steps implemented by an individual rather than large breakthrough changes. Although *kaizens* can be any size and realized in a variety of ways, at Aera they are generally thought of as focused efforts—called *kaizen* events or blitzes—by small cross-functional teams to address a narrowly scoped or well-defined problem in a value stream. Common elements in these *kaizen*s are the use of the scientific method within Deming's PDCA cycle and "asking why five times" to get to the root of a problem. However, the majority of *kaizen*s are much smaller efforts by individuals observing their own processes with the aim of improving them. The small efforts are often the result of reflecting on mistakes, *hansei* in Japanese, and taking personal responsibility to learn from them.

One essential element of the success of the *kaizen* process and a person's willingness to participate in a *kaizen* is that the improvements should not cause any increase in workload. Also, like other

Fig. 5—Cue cards explaining Toyota's principles.

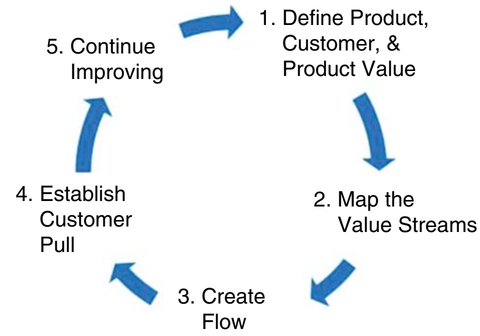

Fig. 6—Five-step strategy to implement lean.

aspects of Lean, *kaizen*s should be used for process improvement, not purely for cost reduction. At Aera, one focus question asked at each *kaizen* is whether the improved process is safer than the previous process—incorporating the safety aspect is absolutely essential.

Gemba. *Gemba*, or "the real place," is a word generally used to mean the place where value is created and where problems can be seen firsthand. A "*gemba* walk" is when management and technical staff visit the field or wherever the work is being performed to review processes and seek to understand the current state of processes that could be improved (Womack 2013).

Discussion

Lean Implementation and a Lean Manufacturing Mentality. The term "lean" was coined in 1988 by John Krafcik, an ex-Toyota engineer and colleague of Womack and Jones, to describe the Toyota way of eliminating any waste to create enhanced value for the customer (Krafcik 1988). "Value" for the final customer is what the customer is prepared to pay for. It is not to be confused with adding value to a product that is beyond what the customer needs. "Value" for customers within a process can be thought of as being what they need to receive to do their work. As waste is reduced and workflows are smoothed out, there is a reduction in work required, costs, and processing time. When an organization makes the decision to go lean, there must be sincere commitment from the top of the organization and a vision of the future state of the company that can be communicated to all levels. It can also be very helpful to give employees the opportunity to visit successful lean companies to gain a better understanding of what a successful lean company looks like and how their culture feels. Aera accomplished this through many visits to the New United Motor Manufacturing Incorporated (NUMMI) factory in Fremont, California; several aerospace companies; mining companies; and others. In particular, NUMMI (a joint venture between Toyota and General Motors that used TPS principles) was visited by many people in the Development Team. Aera also leveraged connections made through the Association of Manufacturing Excellence (AME) to build an extensive network of lean companies and lean thinkers.

The spread of understanding of Toyota's principles and Lean thinking was also helped by the distribution in 2006 of a set of cue cards explaining the principles **(Fig. 5).** The ripple effect of implementing Lean was large because it was a major change in the operating philosophy of the company.

At its simplest, implementing Lean at Aera required a five-step strategy **(Fig. 6).**

1. Define the product and the customer, and identify the product's values from the customer's perspective. The product, which can vary in scale from a well's target location to the oil put into a pipeline, varies with the process being improved. It needs to be defined in terms of the customer's needs while considering the cost of supplying the needs and the time at which the needs must be met. Although the customer is traditionally defined by most companies as the final end user of the product, it is equally important to consider the intermediate customers in the value stream as well. The usefulness of each step of the process as a product is being made needs to be from the perspectives and needs of the customers along the value stream.

2. Map the value streams. A value stream is the succession of activities through which a product is made or a service is performed (Rother and Shook 1998). Once the end product is identified, the current state of the value stream (e.g., its steps and the *takt* time for each step, material products, and information flows) can be mapped. This map is then used to identify and categorize waste (e.g., steps that do not add value, unnecessary interim products) so that the future state and true worth of the tightened value stream can be realized. Without a full understanding of the value stream, *kaizen*s to eliminate waste and to smooth the flow may be suboptimized and have poor results.

3. Create flow by changing from traditional "batch and queue." Once waste is eliminated, the remaining steps in the value stream—all value-added steps—need to flow smoothly from origin to the final customer. Level-loading throughout the value stream and the removal of functional barriers are essential. Quality can be kept high by mistake-proofing techniques and *andon* boards to warn of problems.

4. Establish customer pull. This step begins with the initial suppliers and finishes with delivery of the end product to the final customer. Involvement of external suppliers (e.g., drilling companies, cementing services, software companies) is essential, and the external suppliers need to be linked in to the flow. The customer at each step should be able to pull products as needed, get value from them, and complete the steps needed to pass the product to the next customer at the pace needed by the next customer.

5. Continue improving by looping back to Step 1. With true continuous improvement, there is no end to the process of reducing effort, time, space, cost, and mistakes. It is important to realize that although perfection in providing exactly what the customer wants may never be truly reached, it must always be the goal.

Aera started with a strong culture of continuous improvement, but TPS and lean brought new tools and a new way of thinking. At the same time, a manufacturing mentality spread across different parts of the company, and this allowed a more thorough implementation of lean. Through the new mindset, the company moved from what has been described in other industries as "craft production with a mass production mentality" to a lean manufacturing mentality. Key examples of the techniques used and the results of the new mentality are highlighted later in this paper.

Six Sigma and Lean Six Sigma. In the 1970s and 1980s, Motorola USA discovered that increasing the quality of their manufacturing processes would decrease overall costs. This might seem counterintuitive, but the cost reduction comes from the reduction in repair cost and rework coupled with an increase in reliability seen by the customer. In 1986, Motorola gave the name "Six Sigma" to their strategy of improving manufacturing quality by ruthless pursuit of reduction in variation of manufactured products and their associated processes (Harry 1986). The term came from the sigma rating of manufacturing processes—the percentage of products that lack defects. A product with a Six Sigma rating would only have 3.4 defects/million, and a process with a Six Sigma rating would operate with downtime of only approximately 1.5 min/yr **(Fig. 7).** However, the value of the term is that it uses statistical and fact-based approaches to focus on deviation from an acceptable variation about a mean.

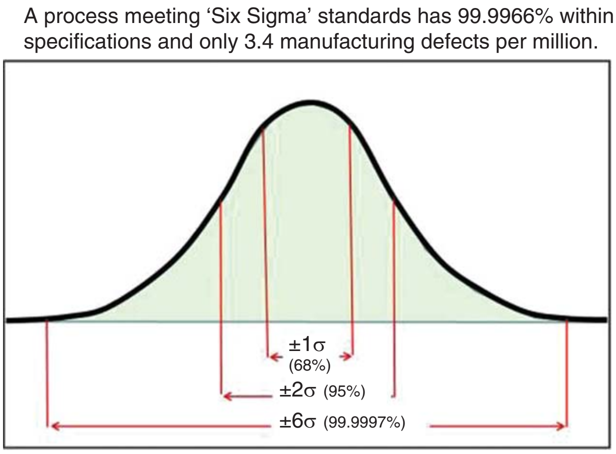

Fig. 7—Statistical basis for Six Sigma.

Key aspects for applying the Six Sigma strategy to existing processes are

- The belief that all manufacturing processes can be measured and improved.
- Implementing define, measure, analyze, improve, and control (DMAIC) methodology, the roots of which are in the Shewhart/Deming PDCA cycle for existing processes.
- Having champions within an organization who lead and facilitate Six Sigma projects. The champions and those carrying out Six Sigma projects are ranked by a series of belt colors similar to the different levels of karate. Currently, Aera has 10 Black Belts and 90 Green Belts. Approximately half the Green Belts are engineers.

Within the DMAIC process **(Fig. 8)**, various tools can be used to reduce variation in process output. They include Pareto analysis, which combines a bar chart and a line graph to capture the main elements by use of the 80/20 rule (e.g., 20% of the causes result in 80% of the problems); fishbone or Ishikawa diagrams to identify factors causing an effect; Toyota's "Five Whys" questions; and control charts and run charts.

According to sources and reasons easily found by means of the Internet, companies that get the most benefit from Six Sigma have many processes and tend to have more than 500 employees. This is because of the specialized staff needed to train other employees and sponsor Six Sigma processes. Aera, with many thousands of processes being measured and more than 1,300 employees, fits into this category.

Care must be taken to ensure that Six Sigma studies are statistically correct (e.g., use enough samples, can be controlled) to make validated improvements and variability reductions of a process. Otherwise, it is very easy to view them as plain cost-reduction techniques.

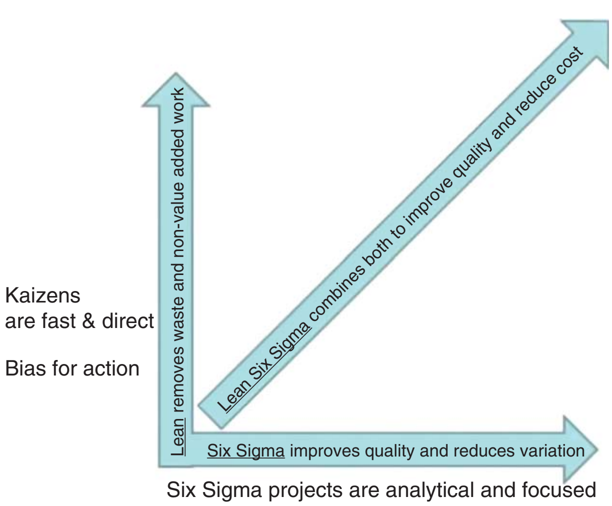

Fig. 9—Lean and Six Sigma combine to form lean Six Sigma.

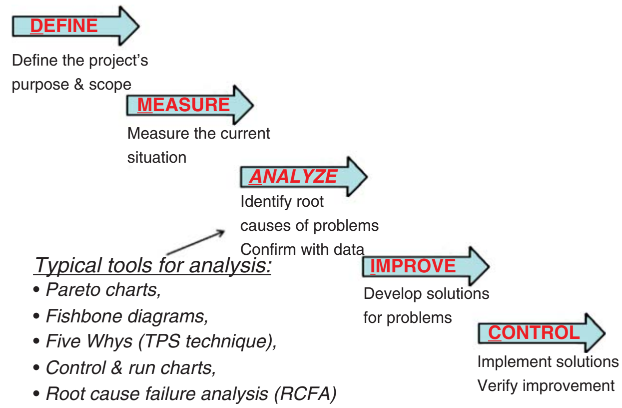

Fig. 8—DMAIC methodology, the heart of Six Sigma.

"Lean Six Sigma" combines lean thinking with Six Sigma and brings the benefits of both techniques **(Fig. 9).** By itself, Lean removes waste and work that does not add value, but does not usually include statistics. It begins with improvement at the lowest possible level, and performing a *gemba* visit to where the work is performed is very important. Six Sigma uses statistics to improve quality and reduce variation. However, there is significant overlap between them, and in reality, they are complementary. Combining the two improves quality and reduces costs, and it simplifies the processes at the same time.

Lean Concepts Applied to the Reservoir and Development Processes. There are several spreadsheet and database tools used to support the lean processes. From the engineering and geology perspectives, the goal is for all processes to be transparent, for information to be readily accessible, and for defects not to be passed on.

CER Database. The first step in the process is to populate the cost estimate request (CER) database **(Fig. 10).** Spreadsheets were previously used for this, but they could not be easily queried, which reduced their transparency. The purpose of the database is to store the following well data needed to permit and secure funding through an Authority for Expenditure (AFE) form:

- Well design (e.g., total depth, completion stages, casing design) used to generate cost estimates for AFEs
- Production performance for economic input used to generate AFEs
- Drill-program data (e.g., surface and target coordinates, well type, openhole logs to run)
- Regulatory permitting data (e.g., name of lease, target formation, expected pressures)

There are standard forms/interfaces for the major well types and well functions: diatomite producers or injectors; heavy-oil producers or steam injectors or observation wells; and deep wells. These standard interfaces encourage consistent practices by the many engineers and geologists who use the single CER database.

Another lean concept is *poka-yoke*, or mistake-proofing. Many of the data fields are drop-downs with the choices the teams have agreed to (e.g., standardized logging suites). Other fields are automatically filled in. For example, when the Cost Center is chosen, the lease name, working interest, and net royalty interest are automatically completed as well. Currently there are more than 14,000 wells in the CER database, so all this helps to reduce mistakes, increase standardization, and improve transparency.

Kanban is the lean concept of a scheduling system so that the parts needed for the different stages in a process will be available in just the right amount when needed. This was implemented in the project design area. With the specific data that are needed identified in the CER, the sources for the data were also identified. In addition, many data sources were loaded into the ArcGIS platform so that the information was one mouse-click away. This included the well-naming scheme, the ground level, the production performance, and

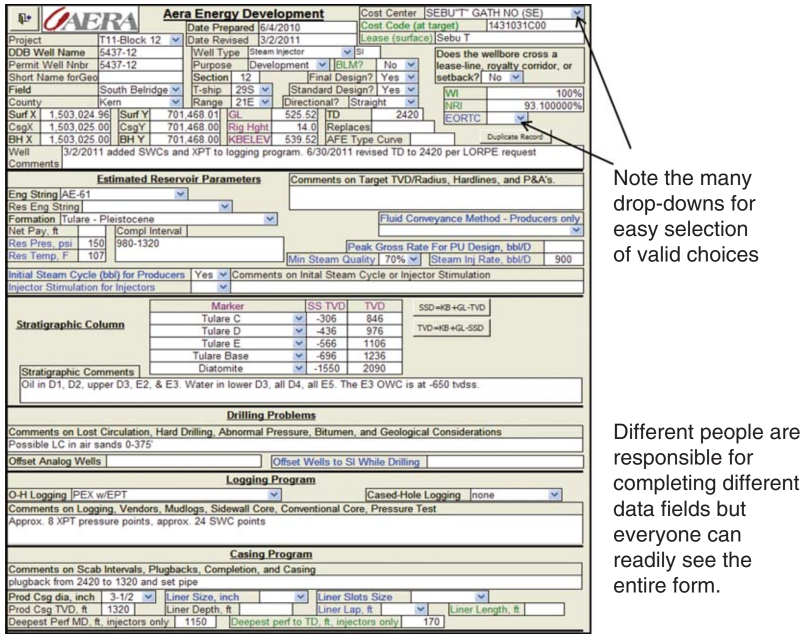

Fig. 10—Screenshot from the CER database.

so forth. Every Thursday, the engineer, geologist, and technician in the Development Design subteam work cell would use ArcGIS and the 3D property model to obtain the necessary information for that week's wells and enter it into the CER. An example of the ArcGIS layer for well planning is shown in **Fig. 11.**

When the project information in the CER is filled in and quality checked, the project is released for the well walk. After the well walk and any necessary adjustment of the surface location, the surface *xyz* coordinates are loaded into the CER data table. The project is then deemed "frozen," and released to the implementers. At that point the wells are permitted by the California State Division of Oil, Gas and Geothermal Resources (DOGGR), the state regulatory agency; the AFE is approved; facilities design begins; and the drill programs are prepared.

Product Family Spreadsheet. This spreadsheet is a classic example of a tool used in the lean concept of *heijunka*, or production smoothing: a *heijunka* box. It has product families on horizontal rows and time intervals on the vertical columns. There are two kinds of people in the world, complicators and simplifiers, and because Lean directs one to the simple and elegant solution, this spreadsheet belongs to the simplifiers. The spreadsheet, shown in **Fig. 12,** keeps track of the weekly projects for the producers and injectors. The numbers below the generic project names are the numbers of wells in each project with an attempt to have the same number of wells in each weekly project. Because the steam injectors require a longer lead time because of the facilities' design, they are packaged earlier and in packages that cover more than a 1-week time interval.

Last Planner®. The Last Planner tool is a concept and methodology developed by Glenn Ballard in 1992 for the construction industry (Ballard 1994). Last Planners are widely used throughout Aera and are often linked to scheduling software. They have a

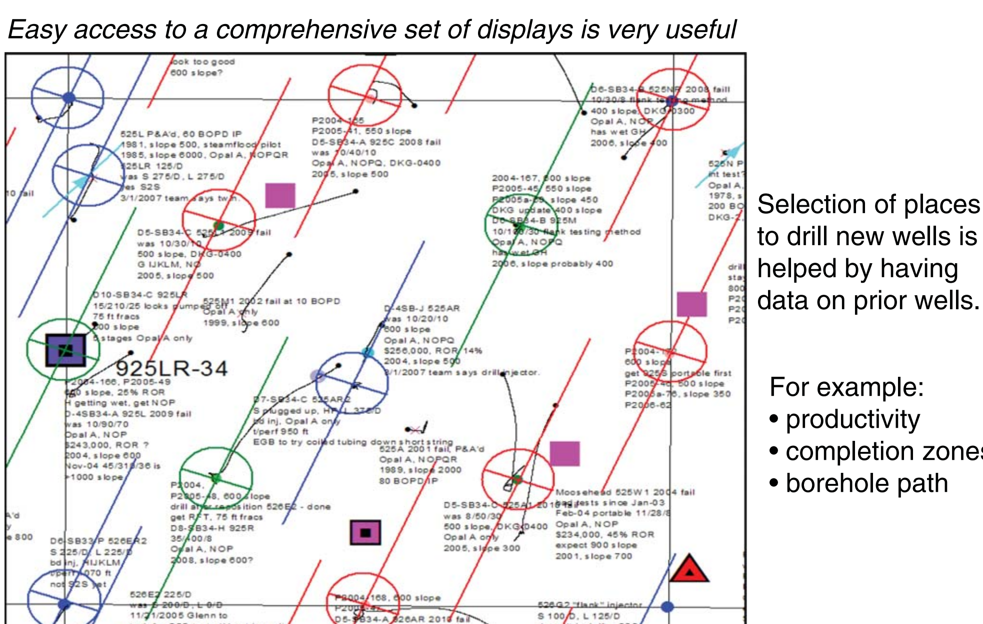

Fig. 11—Screenshot of well-planning layer in ESRI's ArcGIS.

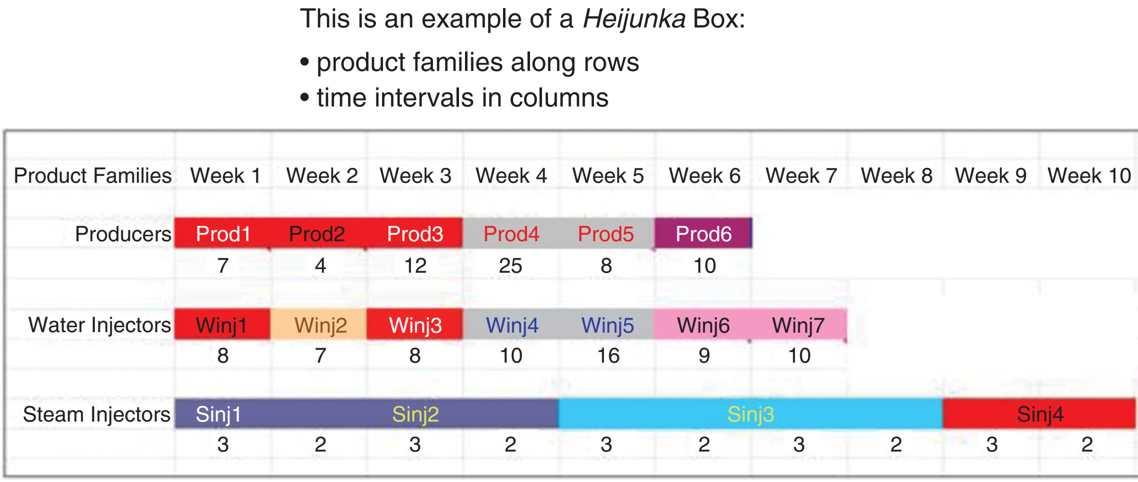

Fig. 12—Screenshot from Development Team's product-family spreadsheet.

broad scope (**Fig. 13**) and typically contain weekly or biweekly lists of tasks to be completed, the name of the task leader, and the start date and due date of the tasks. Key milestones that are important to customers or stakeholders should be readily apparent. When a task is completed on time, it is checked off. However, when a task is not completed on time, the reason for the variance, delay, or inability to perform the task is recorded into one of several categories (e.g., lack of prerequisite prior work, lack of time, vacation, lack of skill set, weather). Management and staff can then review the reasons for the incomplete tasks—typically on a Pareto tornado chart—to identify what different actions should take place or potential process-improvement opportunities.

Within the Light Oil Team, simplified versions of Last Planner spreadsheets are used to keep track of the activities needed for completion of each major project and for any minor project that is falling behind schedule. They contain the next major steps in the project and their deliverables. The team reviews the spreadsheets either weekly or biweekly to make sure the processes and each project are moving forward and questions those items that may be falling behind. The steps for one week in the spreadsheet for a geologic-modeling project are shown in **Fig. 14.**

Before Last Planners were used at Aera, the team tended to have a "look-and-see" process for planning and scheduling the work in the Light Oil Team and used complex project-planning software that determined time relationships between each task. Any changes caused ripple effects throughout the schedule. With the introduction of the Last Planner tool, the planning and scheduling process has become much more efficient, and product handoffs along the way have become more defined.

WellPlanner and FracScheduler. Two databases are used to schedule the drilling and hydraulic fracturing of new wells. They both pull data from the CER and send data to the production control application. In both cases, the schedules for the six to eight drilling and completion rigs and the hydraulic-fracturing teams were previously kept in spreadsheets. The disadvantages of the spreadsheets were that they could not readily be queried and were not connected with each other. The result was an opaque process. Before the current databases and before Lean, the team used a "look-and-see" process for planning and scheduling the work. For example, because the value stream manager was not absolutely sure which wells were ready for a completion rig, the value stream manager would drive around to "look-and-see" which wells were ready for rig work. With these new tools, the planning and scheduling process has become much more efficient.

Production Control. The third important tool that converted the Development Team from look-and-see scheduling to actually

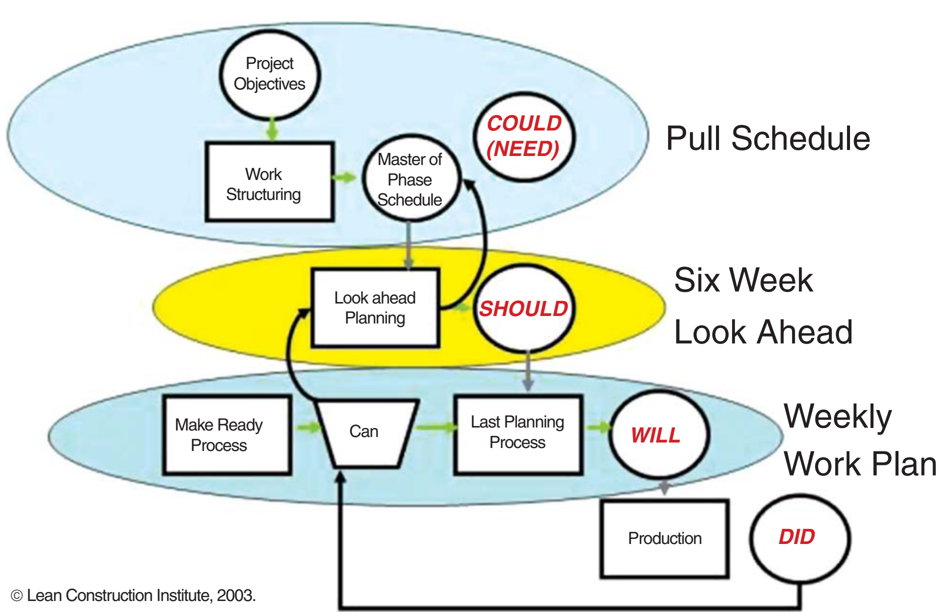

Fig. 13—Overall scope of generic Last Planner.

DelSur Geologic Modeling - Weekly Work Plan

CATEGORIES OF VARIANCE			
1	Lack of Decision	6	Non-Project Demands
2	Lack of Prerequisites	7	Priority Change
3	Lack of Staffing	8	Underestimated Effort
4	Staff missing skill set	9	Poor Data Quality
5	Scope Change	10	Act of God

TOTAL ACTIVITIES	10
ACTIVITIES COMPLETED	7
PERCENT PLANNED COMPLETE	**70%**

STARTING ON 03-Apr-06 — PPC ANALYSIS

	ASSIGNMENT DESCRIPTION **Criteria for release of assignments** Defined - Sound - Proper Sequence - Right Size - Able to Learn	RESPONSIBLE PARTY	COMMENTS or Conditions of Satisfaction (COS)	Mon 3-Apr	Tues 4-Apr	Wed 5-Apr	Thurs 6-Apr	Fri 7-Apr		DONE? YES	DONE? NO	REASONS FOR VARIANCE and / or COMMENT	Cate-gory
1	Evaluation/recommendation of planned wells for logging services (ongoing, weekly)	**MEA**	Weekly e-mail sent to Dev. Team by Wed., 1:00 pm			X				**YES**			
2	Correlation of newly logged wells (ongoing, weekly)	**MEA**	Within 3 days of receipt of digital logs or end of week				X			**YES**			
3	Finish Porosity (Phi) modeling in EarthVision for all intervals	**MEA**	Generation of 3D grids for each interval (DIAT to ANTELOPE_R) and fault block for property				X			**YES**			
4	Finish Oil Saturation (So) modeling in EarthVision for all intervals	**MEA**	Generation of 3D grids for each interval (DIAT to ANTELOPE_R) and fault block for property				X			**YES**		Should make fine-grid model next time.	
5	Finish HPV (SoPhi) modeling in EarthVision for all intervals	**MEA**	Generation of 3D grids for each interval (DIAT to ANTELOPE_R) and fault				X				**NO**	Need to make fine-grid model.	9
6	Finish faces files for Oil Sat and HPV (SoPhi) models in EarthVision	**MEA**	Generation of sliced and unsliced faces files for properties								**NO**	Grids are too large for faces files to be made	8
7	Finish indicator faces files for Porosity, Oil Sat, & HPV (SoPhi) models in EarthVision	**MEA**	Generation of indicator grid files for properties				X				**NO**	Need to make fine-grid indicator grid	2
8	Document cutoffs to be used for project	**MEA / MR**	Send e-mail				X			**YES**			
9	Develop scripts in EarthVision for grid-grid calculations	**MEA**	Scripts ready for use				X			**YES**			
10	Activities associated with String-to String wells, bundled duals, SFT interpretation, etc.	**MEA**	Attend meetings, send e-mails, etc.				X			**YES**		Ongoing for next month or so. . .	
11	OTHER ACTIVITIES:	**MEA**	Complete activities	- -	- -	- -	- -	- -		- -	- -		

Fig. 14—Screenshot from Light Oil Team's Last Planner spreadsheet.

planning the work for the week is production control. Each step in the process is assigned to a process bucket. The well is not released from that bucket until all the steps are complete, with the expectation of zero defects, and ready to be passed along to the next step. **Fig. 15** shows the task sequence needed to put a diatomite producer on line and the teams responsible. If there is a defect or the work was not performed on the scheduled day for that week, an exception comment is captured for later review. **Fig. 16** shows the different buckets in production control in the left column. The columns show the number of wells scheduled for the week, the numbers on schedule and off schedule, and the weekly release rate for each bucket.

A key measure in the Last Planner system is to track the "percent plan complete" or "percent of promises complete" (PPC), which is a measure of the reliability of planning. For example, if the work scheduled from Monday through Friday was completed on the assigned day, then the PPC is 100%. **Fig. 17** shows a graph of the weekly PPC. The typical PPC target is $\geq$80% of what was scheduled for that day completed on that day. **Fig. 18** shows the reasons that the work for the final completion process was not performed on the scheduled day. Other charts show cycle times, work in progress, and wells on line.

Andon and Kanban Boards. These boards are key tools for clearly showing the state of a process and giving an early warning of problems. One of Aera's showcase examples of a combination *andon* and *kanban* board is the exception-based surveillance software tool **(Fig. 19).** It was developed in-house after comments made by experts from the Toyota Supplier Support Center while on a visit to the Belridge field. They were impressed by the thousands of wells but said that a way was needed "to let the wells talk to you." They also believed that we were too tied to technology and needed to simplify. The solution was the exception-based surveillance software tool (Yero et al. 2010). This software tool combines key aspects of *andon*s and *kanban*s because it processes massive amounts of data from the oil fields and only displays data that are actionable based upon sets of defined rules. The *andon* board aspect of the software gives a visual representation or signal of the wells or other items that need some action. This helps to level-load the resources and makes the flow smoother because it shows the progress in addressing the signals. The *kanban* aspect of the board provides "pull" into the well and reservoir-surveillance processes. The bottom line is that the staff does not have to drill down through large amounts of data to find the wells that are not performing properly. These wells are signaled to them and are then reviewed by use of well-defined and well-written standard operating procedures. The standard operating procedures guide the decision process, and the actions recommended generally do not vary much from engineer to engineer. A future upgrade of the tool may incorporate data mining and automated analytical software that will recommend standards-based solutions derived from the success rate of past solutions used for similar problems.

Kaizens. As discussed previously, *kaizen*s are ongoing efforts to improve by eliminating waste and reducing variation. They can be small efforts by individuals trying to improve their work processes or focused efforts by a team—ad hoc or already established—to understand waste within a process. Either way, a process is observed with the aim to eliminate waste and make improvements. The small efforts are generally the result of people doing their regular work but with an eye focused on looking for places to improve. The focused efforts, which Aera calls *kaizen* events, generally last from 1 to 5 days. They begin with a stated scope and some prework by the team, then the event is held, and they finish with the postwork and documentation. These events need to include those whose work is being analyzed so that there is buy-in to the resulting changes. Since Aera's Lean Manufacturing journey began in 2002, there have been many thousands of improvements, both large and small **(Fig. 20).** It is important to document the major *kaizen*s so that the improvements can be incorporated in the new standards for that process. Apart from the *kaizen* events, all employees should be involved in improving their own processes by individual *kaizen* efforts, although this initially may need to be driven by management. These small, so-called "open-eye" *kaizen*s depend on employees thinking for themselves and observing their own processes with the aim of simplifying and improving them. In addition, the suppliers for Aera are also involved in *kaizen*s.

One thing to guard against during any *kaizen* is the natural human tendency to stop drilling-down during the problem-finding phase of a *kaizen* once the first or second potential solution or countermeasure to a problem is found. Per Toyota, there is a need to ask "why" five or more times to uncover the true root or roots of a problem. A second thing to guard against is looking only for high-visibility aspects of a process that might be thought most amenable for waste reduction and problem removal. Often the accumulation of small changes implemented

Task #	Task Ord.	Task Description	Estimated Date	Actual Date	Task Group
10	1	Engineering Inventory	6/8/2011	6/8/2011	0_Initiate
80	2	Added from CER	6/8/2011	6/8/2011	1_Eng
120	3	Permit	6/14/2011	6/14/2011	2_Predrill
191	4	Flowline Reroute	6/15/2011	6/15/2011	2_Predrill
192	5	Electrical Reroute	6/15/2011	6/15/2011	2_Predrill
193	6	Flowline Offset	6/15/2011	6/15/2011	2_Predrill
194	7	Electrical Offset	6/15/2011	6/15/2011	2_Predrill
195	8	Injector Offset	6/15/2011	6/15/2011	2_Predrill
196	9	Pumping Unit Offset	6/15/2011	6/15/2011	2_Predrill
145	10	Set Conductor	6/16/2011	6/16/2011	2_Predrill
197	11	Sump Search	6/20/2011	6/20/2011	2_Predrill
198	12	Complete Sump	6/20/2011	6/20/2011	2_Predrill
220	13	Drill Spud	6/21/2011	6/21/2011	3_Drilling
230	14	Rig Release			3_Drilling
250	15	Cement Deemed OK			3_Drilling
270	16	Back Fill Sump	6/29/2011		3_Drilling
280	17	Housekeeping	6/30/2011		3_Drilling
290	18	Well Head Test	6/30/2011		3_Drilling
70231	19	Release Location	6/30/2011		3_Drilling
477	20	Resets Pumping Unit	6/30/2011		5_Surf_const
478	21	Injector Reset	7/5/2011		5_Surf_const
479	22	Flowline Reset	7/5/2011		5_Surf_const
480	23	Electrical Reset	7/6/2011		5_Surf_const
485	24	Injector Skid PLC Check After Reset	7/6/2011		5_Surf_const
310	25	Frac Program Complete			4_Frac
340	26	Frac Well	7/19/2011		4_Frac
510	27	COROP MIRU			6_COROP
560	28	COROP RDMO			6_COROP
410	29	Complete Pumping Unit Setup			5F_Final_const
441	30	Flowline Hookup			5F_Final_const
430	31	Electrical Install			5F_Final_const
600	32	Install Chemical Pump			5F_Final_const
30998	33	Well Ready For Service (PSSR)			5F_Final_const
640	34	First Test			7_Prod_Cust_tran
660	35	Custody Transfer			7_Prod_Cust_tran
9999	36	End			End

Fig. 15—Task sequence for a producer well, diatomite reservoir.

Group	Scheduled	On Schedule	Off Schedule	5 Day Release Rate Total	5 Day Release Rate Actual	PPC Last Week
Pre-Drill	21	15	6	21	4.20	71
Drilling	22	17	5	22	4.40	77
Construction	20	17	2	19	3.80	85
Completions	23	23	0	24	4.80	100
COROP	18	17	0	17	3.40	94
COROP Misc	4	4	0	4	0.80	100
Final Construction	16	16	0	16	3.20	100
Custody Transfer - Producers	8	8	0	8	1.60	100
Custody Transfer - Injectors	22	22	0	22	4.40	100

Refesh

Fig. 16—Screenshot 1 from Development Team's production control database.

Fig. 17—Screenshot 2 from Development Team's production control database.

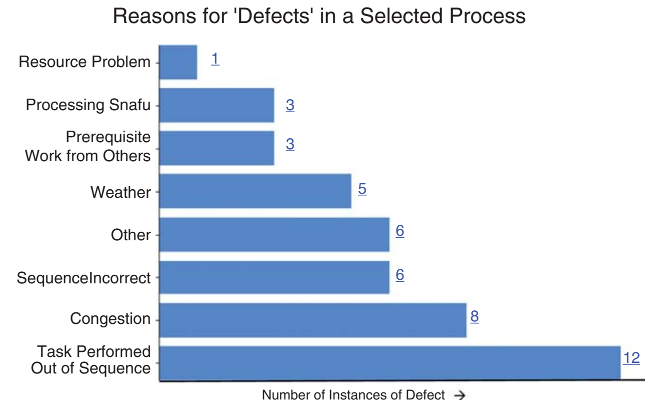

Fig. 18—Screenshot 3 from Development Team's production control database.

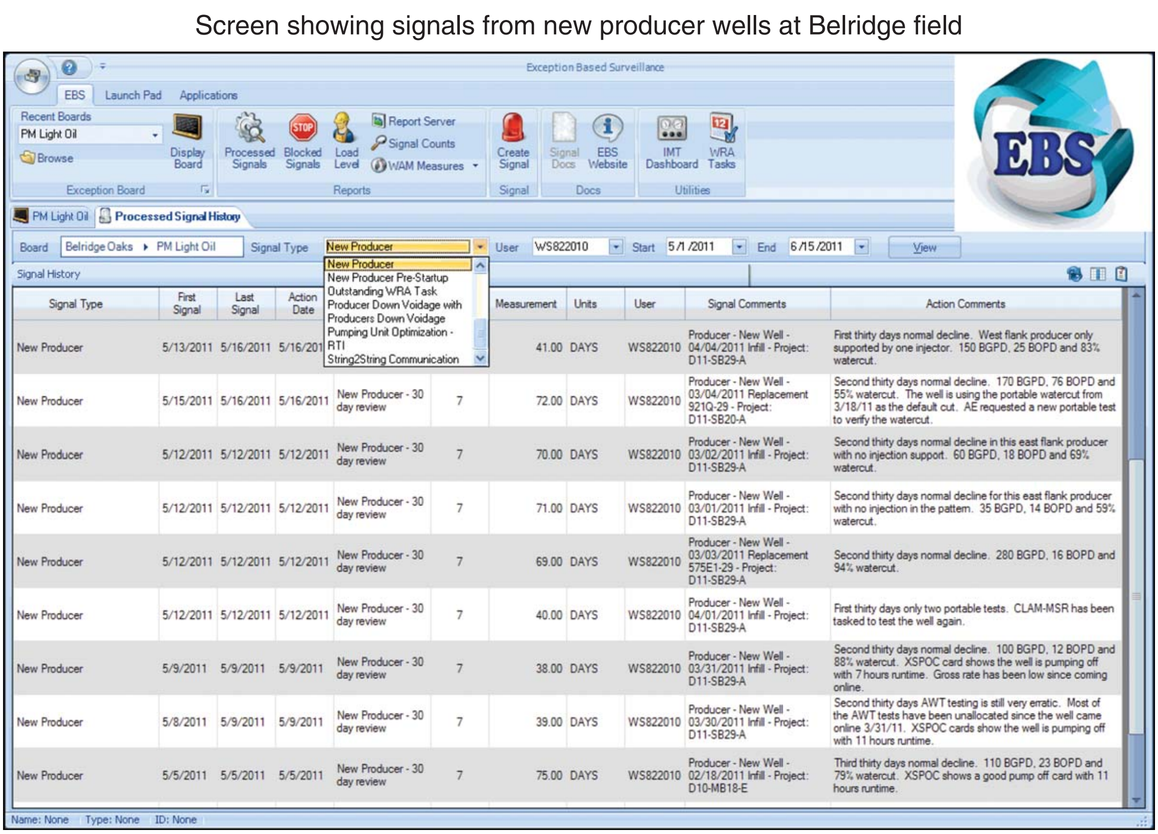

Fig. 19—Screenshot 3 from the exception-based surveillance program.

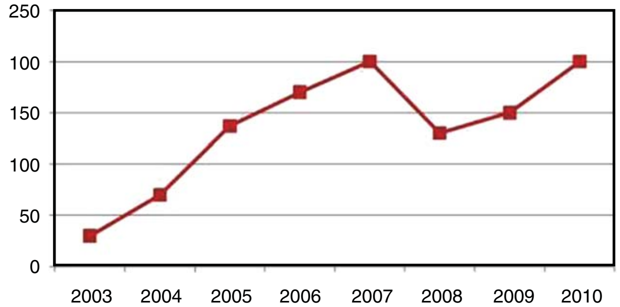

Fig. 20—Graph showing number of *kaizen* events by Development Team.

from open-eye *kaizen*s results in the biggest and most-lasting improvements.

Product Families and Mapping the Value Streams. The traditional definition of a value stream is the steps to provide a product or service. Value streams at Aera are typically considered as the tasks and products made by a single team led by a manager, although there may be considerable input from other teams. Value-stream mapping is a lean technique used to show the steps needed for products and information to go from supplier to consumer. This can be performed at any scale—from a person's daily work to the complete sequence from proposing a well location to putting the well on production. It is an excellent start for any program of *muda* waste reduction.

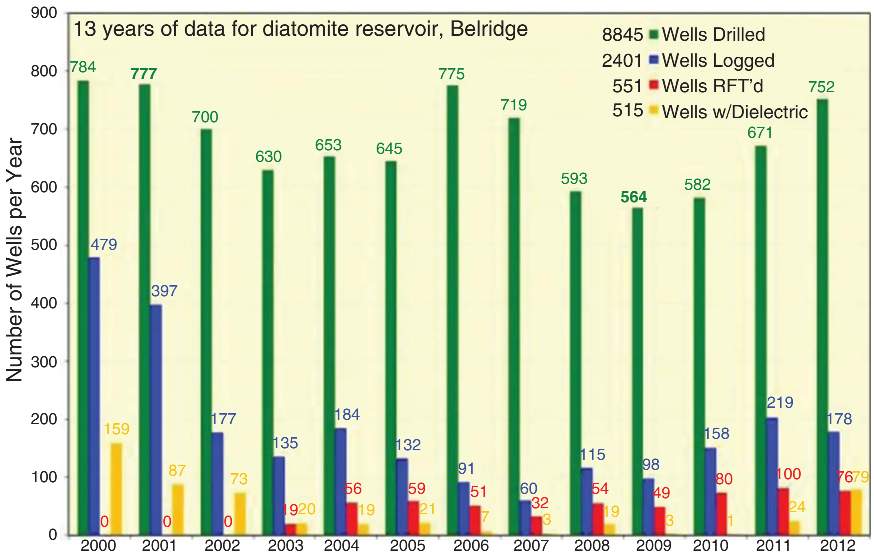

Fig. 21—Number of diatomite wells drilled each year.

One example of the value of input from one value stream to the next is the input from the geological characterization of the diatomite reservoirs by the Light Oil Team provided to the Development Team's initial processes needed to bring a well from the proposal stage to being on line. In 2002, the decision was made to drill enough infill wells to halve the well spacing. This decrease in well spacing was needed because of the ultralow permeability and ultrahigh porosity of this unconventional reservoir. The decision has resulted in 560 to 775 new diatomite wells (producers and injectors) each year ever since **(Fig. 21).** Although the average well depth is a relatively shallow 2,200 ft, every new well is preplanned with a surface location, wellbore trajectory, and depths of key geological markers. Every new well also has synthetic log curves back-interpolated from a 3D geological model several months before spudding. The synthetic log curves are used to plan the hydraulic-fracture intervals in the producers and the perforated completions in the water or steam injectors. This step is generally completed approximately 4 to 6 weeks before spud. The wells are chosen on the basis of geological input, an assessment from openhole formation pressures, liquid-voidage calculations, and productivity in nearby wells.

Lean Implemented In Reservoir Characterization and Development. The next three parts of this paper discuss Lean thinking and the implementation of Lean Manufacturing at Aera within the reservoir-characterization to well-completion workspace. These examples show how waste reduction and Lean combine to make the workflows smoother, more predictable, and transparent. There can be much of what Toyota terms "waste" in the reservoir-characterization and -development workspace—much of it difficult to see—that needs to be removed to obtain lean processes. The waste can be broadly defined as unnecessary work that the customer does not need or want.

With knowledge workers, waste is generally not as obvious and visible because it is in a traditional manufacturing facility, so it can be conceptually difficult to find and then root out. [The term "knowledge workers" is used for those whose work depends on information and its interpretation—those who think for a living (Drucker 2006)]. Knowledge work has changed significantly since the introduction of TPS and Last Planner concepts. The visible results are shorter lead times, outcomes focused to the needs, and more efficient use of technical resources. All three domains of waste identified by TPS apply to knowledge work as surely as they apply to the manufacturing processes downstream. These wastes, if not identified and eliminated, result in poor management of intellectual capital.

The first part of the next subsection focuses on several Lean and waste-reduction techniques and illustrates their application in reservoir-characterization work. The second part focuses on the steps taken since 2002 for the large infill-drilling programs to change from delivering large batches of wells to the drilling and completion teams to a lean and level-loaded program with delivery of weekly groups of wells. The third part discusses a program to drill tightly spaced horizontal wells by use of a well-factory approach.

Waste Reduction and Lean Techniques Applied to Reservoir Characterization. The following four examples illustrate the application of lean techniques for waste reduction in reservoir characterization.

Standardization and Standards for Work Products and Information. Standardization and written standards for work products are essential elements of the TPS. Within the area of knowledge management, there should be easy and ready access to the standards so that silos of knowledge are less likely to develop. The amount of data obtained each day and stored at Aera is immense, and all of it needs to be accessible instantly by means of a variety of computer operating systems (e.g., Linux, Windows) and specialized programs. Standardization of data and interpretation tools across the company has made it much easier to find valuable nuggets of information without getting bogged down in a morass of data fields. Written standards for key reports and documentation are also very important (Bowen and Purrington 2006).

An example of knowledge standardization at Aera is the use of templates for documenting geological field studies. Each section and subsection has a list of topics that need to be addressed in the section or subsection **(Fig. 22).** The result is more-complete documentation and a standard look and feel for the field studies. It is also a significant help with knowledge preservation, especially if the documentation is kept updated or evergreened.

An example of data standardization is the simple consistency in the naming convention for wireline-log curves used by the geologists working on the diatomite reservoirs at Belridge (Allan et al. 2012). No matter what year the raw log curve (e.g., gamma ray, bulk density, deep resistivity) was recorded by a service company, it will have the same simple name (e.g., GR, RHOB, DRES). The raw log curves are then rescaled to a standard depth increment of one data point for each half-foot of depth starting at the surface, and edited by nulling out their tails (below the first valid reading) and any anomalous responses such as the resistivity inside casing. The edited curves are then ready to be used for calculation of porosity and saturations. Any geologic program can "see" all the edited curves, and all the geologists in the team use the same single set of log curves.

Inefficient Movement of Data and Information. One aspect of *muda* (waste of resources) for knowledge workers that can be

'Hints' for Documentation needed for Reservoir Characterization Reports

Summary of Current Geologic Models

[Describe the state of the most current geologic model(s) in use for the reservoir of interest. This includes file names, storage locations, author, date created or modified, software used (including version), etc. In some cases, the most current model in use may actually be a model created many years ago, or one that came from external sources. Also describe any suggestions for improving future models or modeling efforts, such as Business Process Improvement (BPI), Lean Concepts, Enterprise Architecture Implementation (EAI), or other relevant continuous improvement initiatives.]

The diatomite reservoirs of the North Grande and King-Ellis areas. . . . .

Structure

[Describe the predominant structure(s), trapping mechnisms, strike and dip characteristics, and how these relate to the regional strctural trends. Include maps and structural cross sections of horizon tops, subcrops, and fluid contact markers. If faulting is present, include a discussion on fault geometry and sealing characteristics.]

The Belridge anticline is an elongate, doubly plunging anticline. . . . .

Fig. 22—Example of knowledge standardization.

significantly reduced by standardization is the inefficient or unnecessary movement of data and information. At its simplest, this may be duplication of information at different locations throughout the company instead of a single location that can have the information evergreened and easily found by all. This type of waste may also be caused by having to reformat data to each worker's personal preference or possessing multiple sets of software that have the same function. For example, possessing several types of geomodeling software, with each having a steep learning curve and slightly different capabilities, puts a strain on the geoscientists as well as on the support systems.

At about the same time that the oil price dropped and TPS started to enter Aera, the company moved from a building with individual offices to a building with cubicles arranged in pods, with several pods of four cubicles for each team. Although the move to cubicles was not popular, it created an environment of closer work collaboration and much easier access to coworkers. Information became less siloed and more accessible, and the knowledge workers began to work increasingly in teams. The move to a cubicle/team environment resulted in the multifunction teams developing better enterprise-wide perspectives and common objectives, while doing away with silos arranged by function or technical discipline. In TPS terminology, the teams became work cells, with each cell responsible for part of a value stream. Once in a team environment, data generation and interpretation became a team effort with much less redundancy of work and movement of data.

Overproduction of Knowledge Work and Pull of Information. Another of the seven types of *muda* (waste of resources) is overproduction, which is a natural tendency when performing reservoir-characterization studies. It is easy to overdesign the project by adding detail that does not add value. For example, the huge amount of petrophysical data allows the construction of very detailed geological models. The current models for the diatomite reservoirs at Belridge each have approximately 700 million cells. These models test the limits of the modeling software and computer hardware. It is therefore essential to construct the models so that the granularity is matched to the purpose of the models: A model used for generating synthetic logs for proposed wells needs more vertical resolution than one used only for oil-

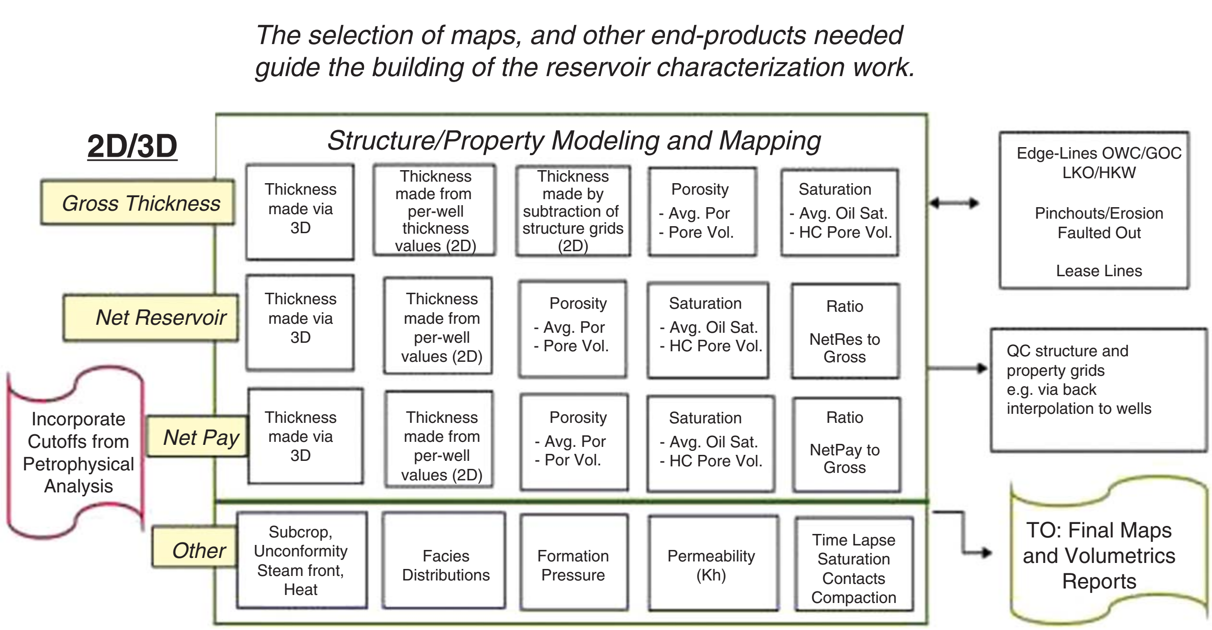

Fig. 23—Standardized end products from reservoir-characterization projects.

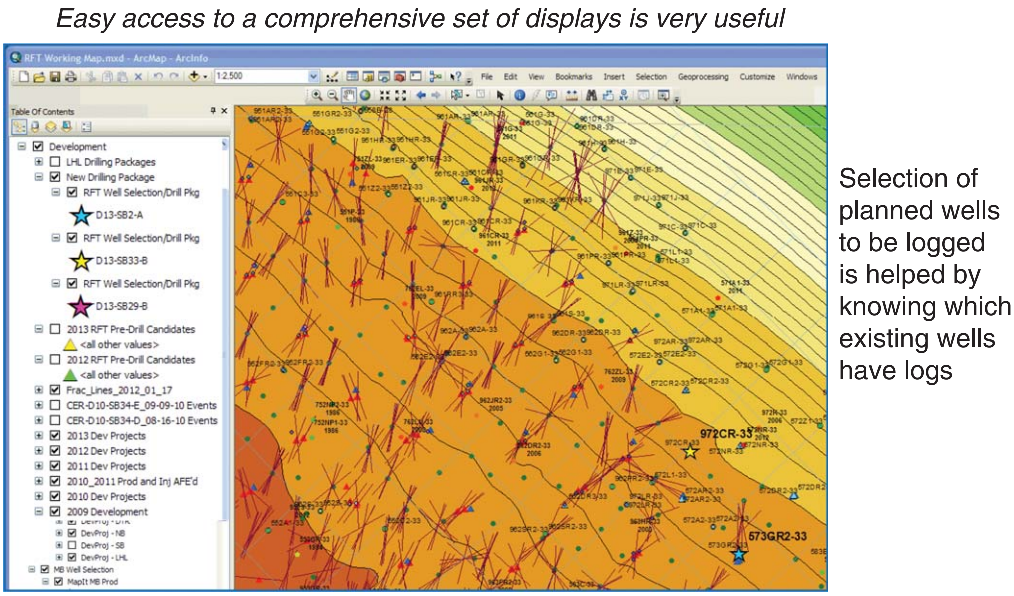

Fig. 24—Screenshot of log-coverage layer in ESRI's ArcGIS.

originally-in-place studies, whereas a model used to study faulting does not need to contain a full set of petrophysical data.

A key concept in Lean is that data and information should be pulled, not pushed. For knowledge work, this means that every study must have a defined customer with defined needs. No study should be performed without a customer or a need. Ideally, the end products of the study should be defined before starting **(Fig. 23).** This eliminates misunderstanding and reduces overproduction. Again, standardization of end products, with the same "look and feel" (e.g., title blocks in same position, same scales and colors), makes things simpler and easier. Easy and wide access to a comprehensive set of displays is very important because this lets staff see what they need and everyone is able to instantly access identical material **(Fig. 24).**

Another aspect of overproduction is distributing information too widely. An example of this is emailing multiple people requesting a decision when only one person is empowered to make the decision. This is often because of a lack of understanding and distinction between those who need the data for their work downstream and those who like to be kept updated. Making a swim lane diagram will clarify supplier/customer relationships and also show where bottlenecks of lost time or data are occurring **(Fig. 25).** Preparing a RACI chart (developed from goal-directed project management work in the 1970s and published in 1984) with its assignment of "responsible," "accountable," "consult," and "inform" for use with the swim-lane diagram will also make transfers and duties clearer, and show ownership at each stage. As well as reducing possible duplication of effort, RACI charts also provide a clear mechanism to settle debates and differences of opinion between people or teams on the best way forward: "accountable" decides on the basis of input from "responsible," who will be doing the work and the "consulted" subject-matter experts.

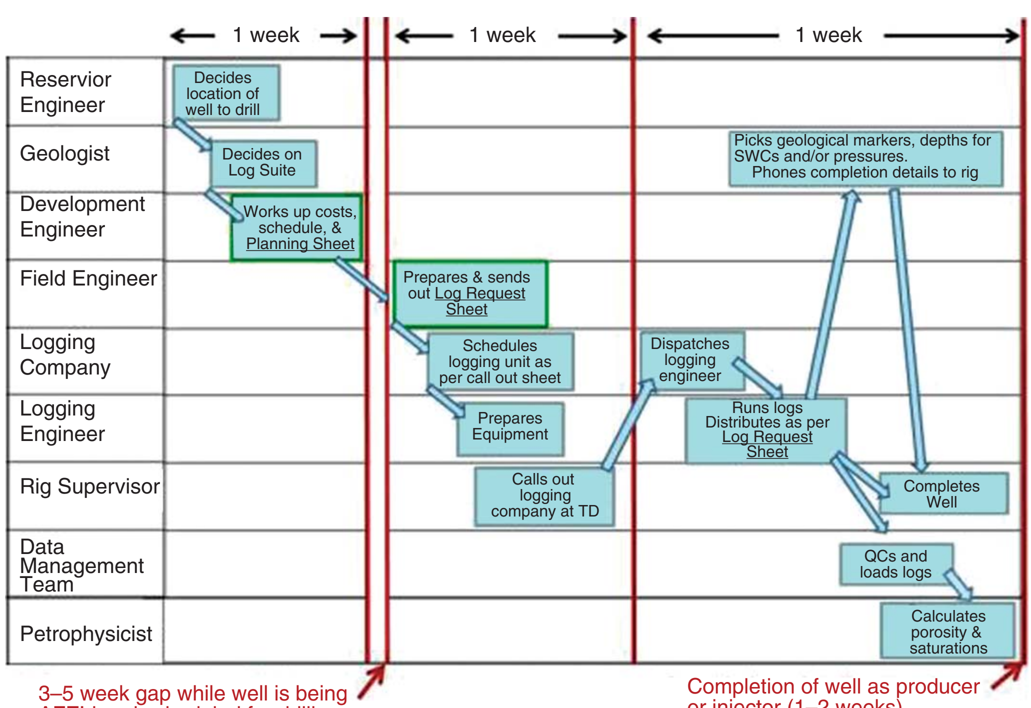

Fig. 25—Swim-lane diagram for openhole logging.

Fig. 26—Value stream for the development process.

Poka-Yoke or Mistake-Proofing. With increasing volumes of information, mistakes are easily introduced and interpretations can be derived from incorrect facts. However, possessing a series of automated data-quality rules for the various data families is an easy way to catch many of the mistakes.

Within the reservoir description and geology, it has been relatively easy to develop a series of rules that check the data stored in the corporate information factory. Most of the rules are fairly obvious: The depth of a geological marker pick in a well must be less than the well's total depth (TD); marker picks need to be in the depth order specified by the defined geological column; the true vertical depth at TD must be equal to or less than the measured depth at TD. With up to 800 new wells being added to the geological databases for the Belridge field each year, all quality control automation is greatly appreciated.

Another aspect of mistake-proofing is the removal of conflicting interpretations of data so that a user "sees" a single interpretation. This can be somewhat controversial because an interpretation by a knowledge worker (e.g., a geologist or reservoir engineer) is typically an individual effort and personal pride is often involved. However, possessing a single interpretation can often be a great starting point for more-detailed work, and it generally means that interpretations are more easily standardized, more robust, and more repeatable. An example that has saved countless months of time by geologists and geologic technicians is the single interpreter identification of "GEO," used when picking all the 40 to 50 markers that define the geological intervals of the diatomite reservoirs at the Belridge field. Every geologist uses the same GEO identification when making picks in new logged wells, and each is free to improve the picks in existing logged wells. The single set of picks, coupled with one official stratigraphic column and a single set of log curves, results in much less duplication of noncreative, noninnovative work. The geologists can spend more time doing complex 3D modeling work without worrying about the quality of the data being used.

Program for Infill Producers. In 2002, Aera began ramping up an infill program for the diatomite reservoirs in the Belridge field. Because of the ultralow permeability and ultrahigh porosity of this unconventional reservoir, the well spacing needed to be decreased in the better areas from $1^1/_4$ acre/well to $^5/_{16}$ acre/well (0.50 to 0.125 hectare/well). Although the average well depth was a relatively shallow 2,200 ft (670 m), every new producer needed to have multiple hydraulic fractures. The program resulted in between 560 and 775 new wells (including producers and injectors) each year for the past 10 years (Fig. 21). This presented many challenges in the areas of well selection, well design, government permitting, programs, AFEs, facilities, drilling, hydraulic fracturing, running the tubing/rods/pump, and getting each well on line in a timely manner. These challenges were met and overcome by applying lean thinking and manufacturing principles to the upstream portion of the development program—well selection to well spud. The big difference between "normal" Lean Manufacturing and Aera's Lean Manufacturing is that in a normal Lean Manufacturing facility the product moves and the workers are stationary, whereas Aera's "factory floor" is 20 miles (32 km) long and the product is stationary, whereas the processes shown in **Fig. 26** move across the field.

As illustrated by Fig. 26, the Development Team has two subteams: Design and Implementation. The Design subteam is responsible for engineering (reservoir, production, and facilities), reservoir description, and capital management. The Implementation subteam is responsible for drilling support, hydraulic fracturing, constructing surface facilities, installing the pumping unit/injection equipment, and custody transfer (Charles et al. 2012).

Phase 1—Long Cycle Times and Large Projects. The first challenge for the infill development program was how to change from various sizes of packages of wells passing sporadically through the system to a level-loaded flow of similar-sized packages. At the start, each package contained a project containing from 30 to 150 wells that needed to go from planning to drill, complete, and on line. The packages were generated at a pace that depended upon the urgency and number of wells planned for a project. The projects were sent out intermittently and at irregular intervals as a batch-and-queue process. Of course, large packages and projects were assumed to be the most efficient because that seemed to be common sense. However, as Toyota's Taiichi Ohno says, "Common sense is always wrong." Once the packages were released from Engineering, the wells were well walked to stake the surface locations, the facilities were designed, and the AFE was prepared, budgeted, and approved. Only then could the downstream activities of ordering equipment, constructing facilities, and drilling the wells begin. The result of these large projects was that the work-in-process was many hundreds of wells, and the

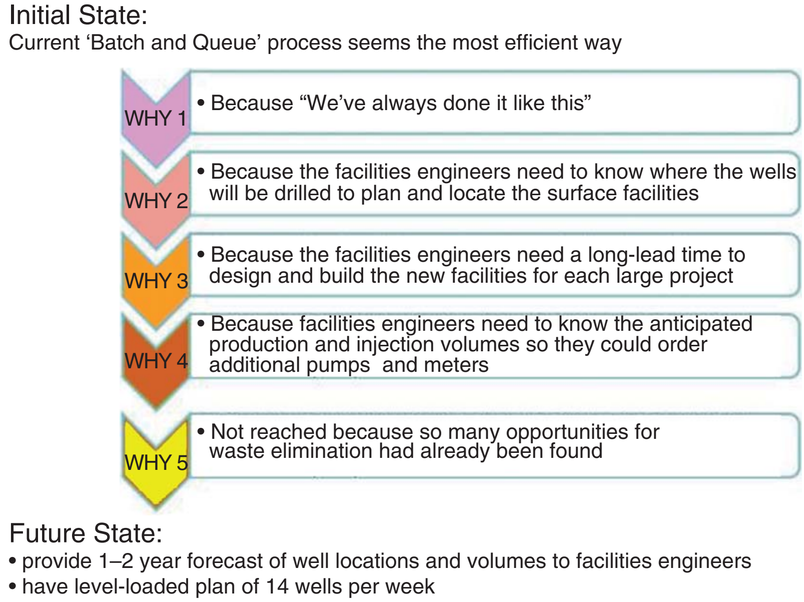

Fig. 27—Five "why" questions for traditional process.

time from picking well locations to drilling wells to oil flowing into the pipelines was almost a year. If there was an engineering design change during that time (e.g., a new fracture completion design, casing design, wellhead design), there were hundreds of wells that had to be moved through the process before the new design could be implemented.

When the lean journey began, the team first questioned these large projects and asked "why" five times about the current state **(Fig. 27).** Of course, the first "why" was that it had always been done that way and it seemed to be the most efficient way to package the projects; the second "why" was that the facilities engineers needed to know the production from the wells and where the wells will be drilled to plan and locate the surface facilities; the third "why" was that the facilities engineers needed a long lead time to design and build the new facilities; the fourth "why" for existing facilities was that the facilities engineers needed to know the production so they could order additional pumps for the testing stations; and the fifth "why" was not needed because the answers to the first four "whys" provided many opportunities for waste elimination.

Throughout this process, the team realized that the facilities engineers should just go ahead and order the pumps because, in any event, they will be used. The team also realized that it was not necessary to go through the entire process of putting the large >100-well packages together, do the well walk, and get the AFE approved just to design the facilities. The solution was to provide the facilities engineers a 12- to 24-month look-ahead of the near-precise locations where the wells would be drilled and their approximate production rates. With this information they could plan new facilities and identify where existing facilities needed to be upgraded.

Two other concepts of Lean were also applied at this time. The first was product families/value streams. The two product families were identified: oil producers and water injectors. Each well type required a different process after drilling: Producers needed to be hydraulically fractured, have tubing/rods/pump installed, and be connected to test stations, whereas injectors needed perforating and hooking up to water-injection lines. All teams involved would be led by a value stream manager. The second concept was *takt* time (pace of product delivery in response to customer demand). Aera's annual operating plan for 2002 called for 730 new producers. This was equivalent to a level-loaded 14 wells per week—the project design cadence.

Phase 2—Weekly Projects Over a 4-Week Cycle Time. On one auspicious day in March 2002, the team decided to stop doing the large projects and start packaging each AFE project with 14 producers. There would need to be one new project of 14 wells working its way through the system each week to meet the annual plan requirements. The wells in each project needed to have their surface locations reviewed for suitability with respect to road access, nearby pipelines, access to power, and so forth, so a weekly well walk was scheduled for every Tuesday morning. Because the surveyors needed time to stake the locations before the well walk, the engineering portion consisting of well names and subsurface target *xyz* coordinates needed to be completed by the Thursday before the Tuesday well walk. Each week, when the engineering portion was complete, an email was sent to the well walk team to notify them that the project was "released"—finalized and ready for the customers in the well walk team. Since that time in 2002, a well walk has been held on every Tuesday morning (except for holidays and rain).

Each project of 14 wells was completed over a 4-week period. The well names and target coordinates needed for the well walk were entered in the first week. The project was well walked the second week. During the third week, the final surface coordinates were obtained and the remaining well information, such as completion intervals and TDs, were entered into the database. The project was then assigned an AFE and approved during the fourth week.

One "complaint" voiced about Lean Manufacturing was, "It is just as easy to do [any task] on 100 wells as it is to do it on 14 wells." This was almost always because of the lengthy setup time, and was certainly true for some parts of the process. The solution was to find a way to make it more efficient to do a task for 14 wells as for 100 wells by reducing the setup time. One specific example is the way the formation tops that are needed for planning completion intervals were obtained, and locating surface locations in a densely spaced field. With the large megawell projects, the formation tops were obtained by putting the target *xy*-coordinates (wells were generally vertical through the pay zones) into the 3D structure models and back-interpolating the depths of the key geological markers. Given the setup time, it was just as easy to do this for 14 wells as it was for 100 or 1,000 wells. However, the output still needed to be quality checked. Also, if the surface above the pay zone was congested, the well might need to be directionally drilled and/or the surface location changed almost on the fly. The solution was to generate a data grid of the surfaces for the key formation tops in ESRI's ArcGIS program by use of data from the 3D geological model, and obtain the formation tops for each well from that grid. This was a simple and easy solution that required no setup time and the tops were quality checked as they were entered into the data table containing the well data.

Phase 3—Weekly Projects Over a 1-Week Cycle Time. The key to the TPS is waste reduction, and one of the seven forms of *muda* is waiting. The waiting was easy to identify when the process

In order to release a project at the last responsible moment:

- what do I need to do this week?
- what do I need to do next week?

Project Name	Person Responsible	Task	Time Group	Task Date	Task Compl Date
D12-Project-A	Nathan	Infrastructure Requirements (Long Lead)	90-120 Day	6/14/2012	6/14/2012
D12-Project-A	Jim	Well Walk	60-90 Day	6/14/2012	6/14/2011
D12-Project-A	Donna	Frozen CER	60-90 Day	6/15/2012	6/16/2012
D12-Project-A	Jeff	Management of Change Approval	60-90 Day	6/16/2012	6/16/2012
D12-Project-A	Jim	Order Project Specialty Materials	60-90 Day	6/16/2012	6/18/2012
D12-Project-A	Steve	Project AFE Approval	60-90 Day	6/16/2012	
D12-Project-A	Anthony	Drill Permits Submitted	60-90 Day	6/20/2012	
D12-Project-A	Travis	Abandonments Initiated	60-90 Day	6/20/2012	
D12-Project-A	Donnie	Pumping Unit Design	60-90 Day	6/21/2012	
D12-Project-A	Yvonne	PM Orders Released (Fac-Drill-Compl-Corop)	60-90 Day	7/4/2012	
D12-Project-A	Layne	Load Project in Production Control	60-90 Day	7/4/2012	
D12-Project-A	Jim	**Pad Walk**	60-90 Day	7/6/2012	
D12-Project-A	Layne	Well Signs Ordered	60-90 Day	7/21/2012	
D12-Project-A	David	**Sand Forecast**	7-30 Day	8/1/2012	
D12-Project-A	Travis	Abandonments Complete	7-30 Day	8/1/2012	
D12-Project-A	Anthony	Identify Injectors to Shut-In While Drilling	7-30 Day	8/1/2012	
D12-Project-A	Anthony	Drill Order	7-30 Day	8/1/2012	

Fig. 28—Screenshot from Development Team's Last Planner spreadsheet.

was mapped: The engineering and geology project design was at the time worked in three stages over a 3-week period for those 14 producers "pulled" each week, with a fourth week to put the AFE together. That meant for any given week there would be 56 producers in engineering and geology working their way through the process. In March 2003, after mapping the current process, the team found that it actually took 15 work hours (approximately two work days) to put a 14-producer package together (excluding the AFE time) if there was no waiting—defined as the continuous flow time, compared with the 3-week process with hours and days of waiting between steps. So in August 2003, the process was transitioned from the 4-week process from well design to approved AFE, to a 1-week process where the project was released on Thursday, it was well walked on Tuesday, surface coordinates were received on Wednesday, and the project AFE signed on Thursday. Then, the weekly process would begin again with a new project released on Thursday.

Many improvements were made in this upfront design process. And where previously it took months, then several weeks, then 1 week to populate the data needed for the AFE and for permitting, the team was able to reduce the design time for each well—for target coordinates, TD, estimated completion intervals, GEO picks, and so forth—to a fast 8 minutes/well. So a 14-well project could then be assembled in less than 2 hours.

At the same time that the project process was being reduced from 4 weeks to 1 week, the time from well walk to spudding the wells was reduced from approximately 6 months to one month by means of a similar process of mapping of the value stream and *kaizens* focused to remove waste. However, the external customers expressed concern that lead time with this process should include the time it takes to get the permits to drill the well from the regulatory agency and then complete the necessary flowline reroutes, complete the necessary well abandonments, and so forth. Also, what happens to the process time if permits are delayed or not given (this would be an example of Type 1 *muda* that cannot be removed)? This balance between the advantages of minimizing work in process and the other activities that must be completed before the well was drilled needed to be continuously discussed and adjusted as the conditions changed. The current time between the well walk and well spud is now approximately 8 weeks to allow more time to complete the required plug-and-abandon process and facilities design before the new wells are drilled.

Another lean concept is "pull" from the customer rather than "push" from the supplier. Although some inventory is needed for smooth flow as a buffer, production needs to be driven by the needs of the customer. To accomplish this, Engineering meets weekly with Drilling to see how the drilling rigs are progressing for the different well types (currently producers, water injectors, and steam injectors). At the meeting, Drilling discusses which well types and number of wells they would like to pull from Engineering for the next week's well walk. As a result of reducing the cycle time for project design from months to 3 weeks to 1 week, and by reducing the well walk to well spud time from months to weeks, there are many fewer project revisions and scope changes with the new lean process than with the previous process, which had large projects and long lead times. An added benefit is that the data are current and not stale. All this leads to better project planning, more time spent on value-added activities instead of rework, and more confidence in the development process. Lean literature (Womack et al. 1990) also discusses cases where the dramatic reduction in cycle time greatly reduces defects—and the team observed that same result.

A key component to the successful reduction in cycle time and the level-loading is the use of Last Planner methodology with tasks and responsibilities broken down into weekly projects **(Fig. 28).** One of the key concepts of Last Planner is to release the project at the last "responsible" moment—emphasis on responsible. For each of the three product families (producers, water injectors, and steam injectors), there is a different project-release lead time that reflects the differing needs of each product family.

Well Factory Approach for Program To Drill Tightly Spaced Horizontal Wells. The southwest flank of the Belridge field has a vertical thickness of net pay that was not enough to justify vertical wells that needed two or more hydraulic-fracture stages to be economic. However, the flank was wide enough to develop the area with horizontal wells drilled as close as $37^1/_2$ ft (11.4 m) apart and completed with two to three longitudinal hydraulic fractures, each varying from 200 to 500 ft (60 to 150 m) in length. The project started in late 2001 and finished in early 2008. During that $6^1/_2$-year period, 188 horizontal wells were drilled and most of the area was developed with a 3:1 producer/water-injector ratio. All this took place as normal vertical drilling continued throughout the rest of the field. Paper SPE 133511 has the full details (Allan et al. 2010).

The project began with a pilot program of four horizontal wells draining the same small area: Two wells were aligned roughly east/west and completed with transverse hydraulic fractures, and two wells aligned roughly north/south and completed

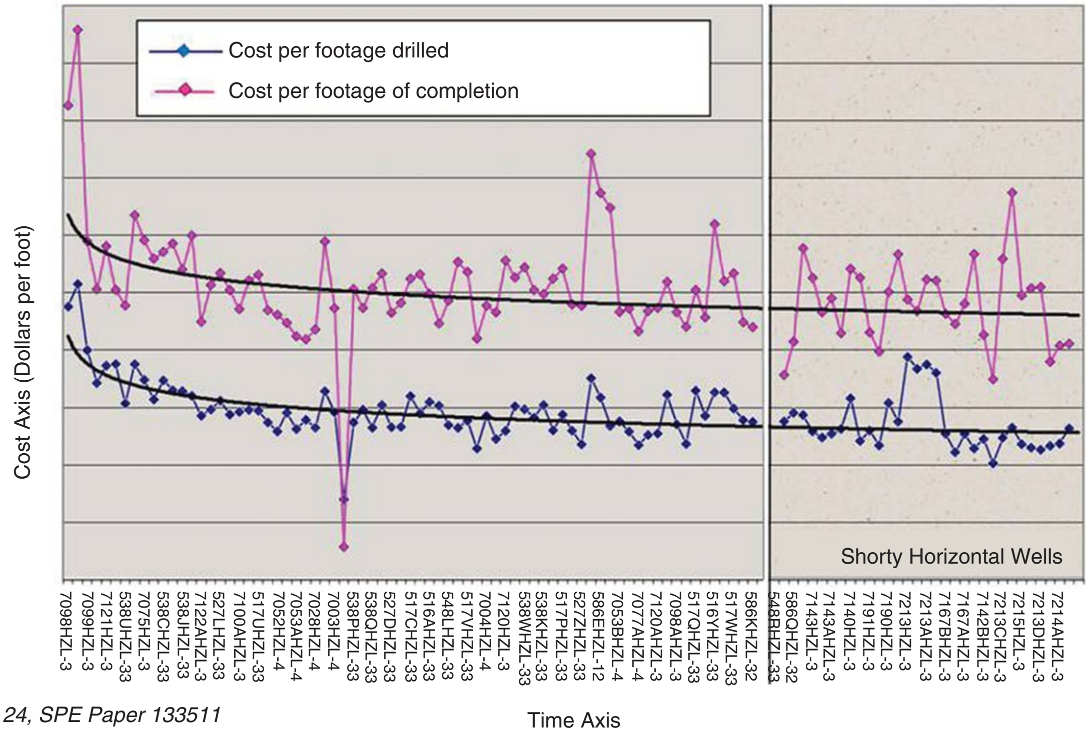

Fig. 24, SPE Paper 133511

Fig. 29—Cost reduction for drilling and completion, longitudinal horizontal wells.

with longitudinal hydraulic fractures. The completion and production from each pair of wells were closely monitored and measured. The north/south wells performed better and were easier to plan and complete. The decision was then made to move forward with similar north/south wells on the basis of hard evidence rather than simulation or gut feeling.

The development of the southwest flank by horizontal wells was ideally suited for the Lean Manufacturing assembly-line approach. The reservoir parameters of net-pay thickness, structural and stratigraphic dip, and width of the target were very similar from the northwest to the southeast of the flank, which simplified the geological input values to the process. However, planning the trajectory of the intervals to be completed in each well required significant iterative work between the geologist in the Development Team and the company (supplier) doing the directional planning. Each week a package of wells was released by the Development Team, the wells were walked in the field and then assigned an AFE in the office. Every few days a new well would be spudded, and then several wells would be grouped together for completion on the same fracturing pad.

Many process improvements were made during the period, and costs for drilling and completion were continually driven down. Also, the time taken between spud date and initial production date was steadily reduced. The "well factory" approach to the project was possible because the wells were very similar and the geology was roughly the same throughout. The same drilling rig and rig crew drilled all the wells so they were able to steadily climb the learning curve. Although the wells were planned individually and then processed in weekly batches, each could be drilled and completed in similar ways once the learning curve from the first few wells was climbed. **Fig. 29** shows the steady cost reduction during the project. It is also worth noting that it is important to normalize the data on a cost-per-foot basis to be able to get an "apples-to-apples" comparison between wells.

External Suppliers. Two other key elements in the adoption of TPS at Aera were closer relationships with key suppliers (contractors) and the reduction in the number of suppliers. Different companies supplying identical items can cause variations in material quality. Reducing the number of suppliers, building long-term business relationships with them, and involving them in TPS have resulted in significant supply-chain improvements. When Aera Energy was formed in June 1997, there were more than 2,500 unique suppliers, whereas today fewer than 30% of those suppliers remain. Along with the reduction in unique suppliers, there has also been a significant decrease in the number of major suppliers doing the bulk of the work. Today, key suppliers maintain staff at the office facility and also at the field locations. Supplier staff members work seamlessly alongside Aera staff with increased levels of involvement, responsibility, and engagement for the long term. Such relationships result in what TPS and Lean call a "virtual company" or "extended lean enterprise."

The Development Team has approximately 50 employees and 800 supplier personnel through 20 companies. It has been critical to include these suppliers on the Lean journey, and most of the 20 suppliers have been with Aera since the inception of the journey. In the initial years, the key suppliers were paid on a gain-sharing basis with risk and reward components. Today, many of the repetitive and standardized activities (e.g., cleaning a production meter or laying a concrete well pad) have more-structured costs that allow us to forecast accurately while providing suppliers an incentive to improve their processes.

Many of the *kaizen*s are started by the suppliers because they have found the *kaizen* process to be a very helpful way to reduce their costs. The Development Team has an annual contest called "Top Dog" that often recognizes suppliers on the basis of the involvement and dedication of the suppliers to process improvements and work excellence.

Continued profitability over the past 10 years would not have been possible in an inflationary environment without Aera's sustained emphasis on cost containment. Cost reductions because of greater operating efficiency (as shown in Fig. 29) go only a certain distance, but working closely with suppliers and sharing information so they can plan for the long term can help mitigate the effects of inflation and pressure to transfer equipment and personnel to other locations. As illustrated by **Fig. 30,** our drilling and completion costs have held flat in nominal terms between 1997 and 2011, whereas industry costs more than doubled (Charles et al. 2012).

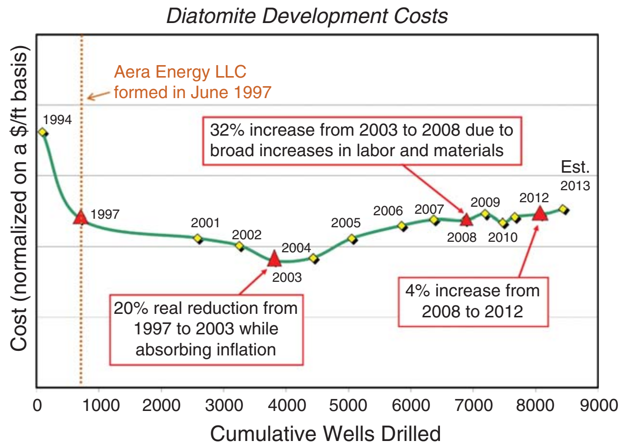

Fig. 30—Containment of drilling and completion costs, diatomite development costs.

Critical Factors for Successful Deployment of TPS and Lean Principles. The following are seven of the main factors for Aera's successful deployment of TPS and lean principles:

- Commitment from all levels of management that this would be a long-term strategy, not the latest "flavor of the month" and soon to be replaced by something else.
- Buy-in from employees that they will benefit from TPS and Lean as much as the company. When TPS and what later became called the "Toyota Way" were introduced in 2001, everyone realized that Aera could not be a successful oil company in times of low oil prices without a shift in behavior and that Toyota principles could provide that shift. Employees were eager to adopt the techniques and could readily see improvements in their work.
- Trust and respect at all levels—between employees and with suppliers—is a core value of the Toyota Way (Liker 2004). Without this, individual, team, and company performance will be compromised. Willingness to stop work—"pull the *andon* cord"—rather than pass a defect to the downstream customer needs to be encouraged.
- Develop a culture of evidence-based management and decision making. Deming's PDCA cycle and Six Sigma's DMAIC steps cannot work without evidence and measurement of processes. Decisions should not be made without hard data that are readily available and visible at all levels.
- Support from other departments. The Information-Technology Department understood the core processes that needed to be error-proofed and provided the technical support for design of the databases needed, plus upgraded several applications for corporate-wide use. This facilitated the move to Lean by those involved in reservoir management.
- Understanding that TPS and Lean are not tactics to apply for cost-reduction goals. The main impacts in the upstream oil business are increased productivity and timely delivery of everything in the value streams, from the initial knowledge work through to the final oil for sale. Cost reduction and containment will occur because of the increased efficiencies of the processes.
- Recognition that TPS and Lean can be applied as successfully in knowledge value streams as in traditional manufacturing value streams. Handling information, high variability, and creativity is not an easy fix because their waste is often difficult to define. However, the reward is well worth the challenge.

The role of managers also needs to evolve as TPS and lean principles are deployed. Changing from a traditional management-by-objectives way of working requires a change in mindset. Managers must change from being problem solvers to leaders who build the capacity of their teams to solve problems themselves. Coaching and mentoring of team members must become an important part of daily routines. Regular *gemba* walks used for inquiry about a process should also be seen as an opportunity to interface with the people doing the actual work.

The results have been very profitable for the company and have allowed the knowledge workers to spend more time doing creative work and less time chasing information errors or reacting to problems. Application of TPS and Lean principles is not complex, but it certainly requires a cultural adjustment for any company wanting to change and for its employees, who must also be willing to change.

Benchmarking against external companies or by consultants is a valuable way to confirm that the transition to Lean is added value for the company. However, the authors would like to caution the reader that lean thinking is not inherently intuitive because it is different from the way that one would normally think about doing one's work. But once exposed to lean-thinking principles, most people will certainly have an "aha!" moment (first developed in 1939) and realize that they could immediately apply lean techniques to their work.

Academic studies by the Massachusetts Institute of Technology, Harvard Business School, and the University of Michigan have also shown that moving from traditional mass production in the automobile and aerospace industries to Lean Manufacturing will produce lead-time reductions of up to 50% across multiple value streams, 20 to 40% fewer defects, and increased flexibility (Bowen and Purrington 2006). Aera has seen similar improvements.

Employee Buy-In. Toyota estimates that approximately 5% of employees in a typical company are willing to push for change, approximately 5% are so-called "anchor draggers" who will resist change, and the other 90% are fence sitters waiting on the margins. Management needs to support those who are willing to change but must take care not to focus on changing the behavior of the anchor draggers. As the lean transformation occurs, anchor draggers tend to move away or get with the program. Today, when someone is called out as an anchor dragger, they seem to get the message.

A key tenet to getting and retaining employee buy-in is to emphasize redeployment of personnel when efficiencies caused by waste reduction and improved processes result in excess staffing. The redeployment has allowed Aera to build capacity for other development opportunities and process improvements.

At Aera, the improved quality of data has resulted in increased productivity of the knowledge workers performing their normal work because they do much less rework and more value-added work. They are also now able to spend time on innovative work—creative work performed for a purpose—which has resulted in more job satisfaction. In addition, the increased stability of processes has meant that much less time is spent being reactive instead of proactive. An added bonus is that TPS and Lean have strengthened Aera's ability to train new personnel. Sustaining and improving processes by use of TPS and Lean are essential competitive advantages.

Although Aera began with its TPS and lean journey in 2001, it took a few years before it was fully implemented for the office and field operations associated with the Belridge field. Today, *kaizen* events and *gemba* walks are run by the teams with little to no involvement of the few specialists from other parts of the company or noncompany advisors. Within the Development Team, each employee is expected to participate in several *kaizen* events each year.

The cost to move to Lean Manufacturing is very small for the gains obtained. When quantifiable, most of the cost reduction comes from waste reduction. Examples include reducing inventories at warehouses in the field, which is easily quantified and in the tens-of-millions-of-dollars range, and moving from batch-and-queue processing of planned wells to weekly processing, which is difficult to quantify but is a definite addition to profitability.

There has been a similar reduction in the number of software programs available to the knowledge workers. At first glance this may seem like a step backward, but the results have been very positive because the reduction has allowed program updates to be installed faster, and has also made sharing of data and software skills much easier.

Application of Well Factory Approach to Unconventional Plays. Aera has applied the well-factory approach to all aspects at the giant Belridge field, which covers approximately 50 sq miles (130 km^2). In April 2013, Aera's daily production from the

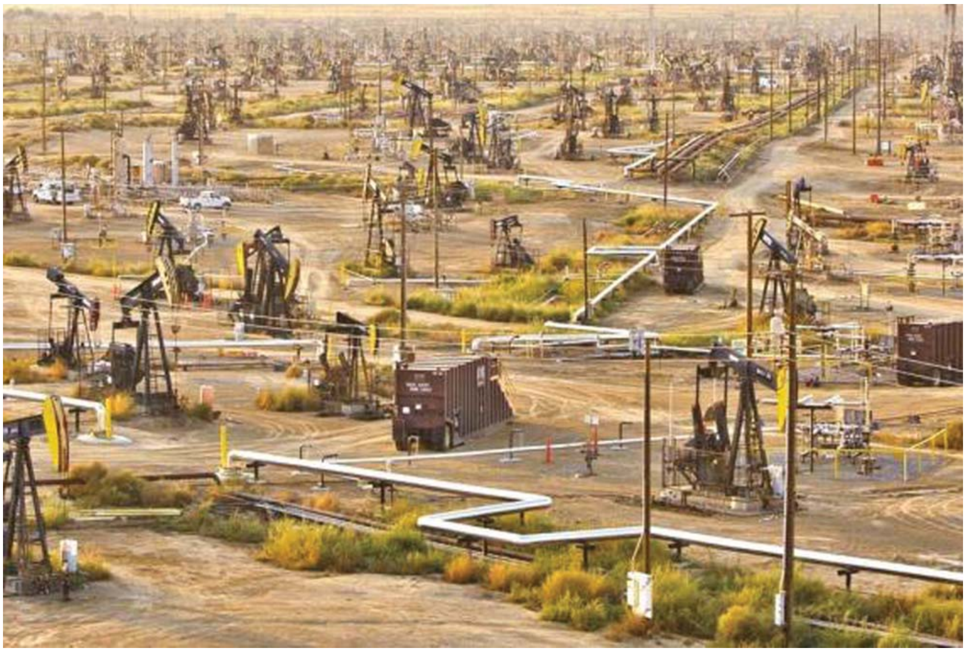

Fig. 31—Surface crowding at Belridge field.

field was 65,000 STBO and 28 million SCFG from 5,300 producers that were supported by 925 steam injectors and 1,150 water injectors. (The average well produces 12 STBO/D, with a water cut of 92%.) Compared with the historical low prices shown on Fig. 2, the oil price is now more than USD 100/bbl, and the increased profitability because of the increased spread between production cost and selling price means that the cost advantages as a result of TPS and Lean are less important than in the low oil price times. The current high oil sales price also means that management focus has moved from using TPS and Lean to reduce costs by driving out waste to using TPS and Lean to increase production.

Because of the stacked nature of the reservoirs and the lack of synergy between their exploitation techniques, the surface infrastructure at the Belridge field is very crowded **(Fig. 31).** This is quite different from the large distances between wells of the other unconventional reservoirs that are tapping thin, ultratight reservoirs. However, Aera's well factory approach to the drilling of new wells, as well as the maintenance of thousands of existing wells, could be directly applicable to the unconventional plays in North America and elsewhere. There are many similarities and learnings from the repetitive operations at Belridge that can certainly be applied elsewhere to gain efficiency:

- Multiple wells drilled from one central pad
- Standard design of facilities
- Standard design and drilling of wells
- Standard design of completions, but with the ability to modify them on the fly
- Unified data flows across the company that are readily available and are used by everyone

Costs are relatively high in the large water- and steamfloods of the Monterey diatomite reservoirs and the mature steamfloods in the overlying Tulare sand reservoirs, so efficiencies of scale are essential. Also, when margins are small and production declines are rapid, any efficiency that can lower costs is important (Rahman et al. 2013). Lean process can certainly be implemented by standardizing processes, reducing work in process, and eliminating defects. Development of computer systems and customized databases to plan large numbers of wells by use of multiple rigs needs to go hand-in-hand with Toyota's principles for elimination of waste, level-loading of work, and Deming's PDCA cycle. It is also essential to work closely with key suppliers, share goals with them, and move to efficiencies that benefit all parties.

Conclusions

Aera's business in the upstream oil and gas world matches well with traditional manufacturing processes. The work is repetitive and scalable but very amenable to standardization, and capital costs are high. When Aera adopted the Toyota Production System (TPS) and understood the value that waste reduction and Lean Manufacturing could bring, it was realized that a paradigm shift could be made in the way the company operates. The paradigm shift that has occurred was caused by following a set of Lean Manufacturing and Last Planner principles that are currently used throughout the company. Toyota's principles and lean concepts have given Aera the tools to define waste and the processes to deliver value that could then be optimized, and additionally to operate more safely. It has also been crucial for Aera to bring the supplier companies along the lean journey because they are a large and essential part of the business.

For lean transformations to take place, it is necessary to start with both large and small lean improvements. And when lean improvements are made, it is important to broadcast those gains to other parts of the company that may not be implementing lean as energetically. Company leadership must be engaged throughout the lean journey through persistence, listening, respect, and recognition (Gold 2012).

The customers of the knowledge work supplied by the geoscientists and reservoir engineers have benefited greatly from the introduction of the lean processes and the resulting smoother and more-effective workflows. However, over the next few years, Aera will need to focus on sustaining the lean culture and mindset as the "big crew change" occurs. Codifying best practices by standardization of work processes and documentation has been an essential part of Aera's knowledge management and will help pass tacit knowledge from more-experienced workers to new employees.

Although TPS and Lean Manufacturing, with their emphasis on waste and leveling of flow, might seem to be yet more additions to an already heavy workload, they should be viewed as essential tools and skills for our industry's technical professionals. The use of them will allow a step change in efficiency throughout the value chain, coupled with a shorter "time to market" between planning the wells to be drilled and producing the hydrocarbons.

In conclusion, the Toyota principles and Lean thinking adopted by Aera are broadly applicable to other upstream oil and gas companies that need or want to move to the next level of efficiency. The oil industry has a reputation of being slow to adopt new technologies and techniques, but a Lean Manufacturing mentality introduces new ideas and ways of doing knowledge work that can change this paradigm while contributing to the bottom line with reduced cycle times and improved quality. A significant additional benefit is that geoscience and engineering professionals can spend more time doing creative work and less time fixing problems or reacting to system upsets—all while reducing waste. However, in order for it to cause a step change in efficiency for our upstream industry, a thorough understanding of Toyota's principles and a Lean Manufacturing mindset need to be key additions to everyone's personal toolbox.

Acknowledgments

This paper is a compilation and condensation of a huge body of work based on Aera's journey into the TPS/Lean Manufacturing/ Last Planner system and Six Sigma over the past 10 years. The main idea generators at Aera who introduced and applied these concepts were Dave McKay, Mike Furman, Greg Williams, Bob Palermo, Stan Badger, and Chris Hooper. The authors thank Greg Williams for reviewing and greatly improving the paper.

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This paper uses a variety of terms, acronyms, and service marks that were developed by their respective originators. In rough chronological order these include:

- *Takt* time by German aircraft industry in 1930s
- "Aha!" moment (moment of sudden insight or discovery) in 1939
- TRIZ by Genrich Altshuller in 1946

- Toyota Production Systems by Toyota (developed from 1930s to 1970s and codified in 1973 to 1977)
- Plan-Do-Check/Study-Act cycle by Shewhart and Deming in late-1940s to 1950s
- RACI charts developed from Goal Directed Project Management work in 1970s, published in 1984
- Six Sigma by Motorola in 1986
- Lean Production by John Krafcik in 1988
- Six Thinking Hats by Edward de Bono in 1985
- Last Planner by Glenn Ballard in 1992

SI Metric Conversion Factors

acre	× 4.046 856	E−01 = ha
°API	141.5/(131.5+ °API)	= g/cm^2
bbl	× 1.589 873	E−01 = m^3
ft	× 3.048	E−01 = m

*Conversion factor is exact.

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