LIME KILN OPTIMIZATION THROUGH LEAN SIX SIGMA

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Abstract

A lime kiln is a stationary piece of machinery that converts calcium carbonate into calcium oxide by heat. It is usually operated in a continuous manner rather than a batch system. These systems are used across multiple industries, but are most common in cement production, fertilizer manufacturing, and in pulp and paper processing. In 2014, Sappi Cloquet LLC commissioned a Lean Six Sigma project around the lime kiln to increase throughput and uptime. This report contains a comprehensive report of the project, as well as the background for its justification. Over a one year period, the project saved Sappi an estimated $2MM.

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Introduction

Quicklime (also known as Calcium Oxide) has been used around the world for hundreds of years. The uses and production methods have changed over time, but it has proven to be one of the most versatile chemicals in modern history. Calcium Oxide is prepared by heating limestone (Calcium Carbonate), to extremely high temperatures. This heat liberates a carbon dioxide molecule, and quicklime results. Large-scale production of has been around for some time now, and is used in industries like cement production, fertilizers, and papermaking. In this paper the optimization of a modern rotary lime kiln will be examined. The kiln is located at Sappi LLC in Cloquet, Minnesota. The kiln at Sappi was underperforming in both throughput and uptime at the time of the project's commissioning. The project commenced as an official Lean Six Sigma black belt project under the direction of Brandon Hastings (Project Engineer, Pulp Technical Services) on October 31st, 2014, and ran for approximately one year until July timeframe of 2015.

History

Making lime is such a simple process, that there is no recorded "discovery" of its uses. Historical estimates put its first use at over 7000 years ago, in modern-day Turkey. (Keller) It is known that the initial application was in pseudo-cement production to hold rocks together. In the thirteenth century, lime became a viable way to adjust soil pH, in one of the first non-organic fertilizers. This was due to the discovery of coal as a fuel source, which made it inexpensive to produce lime in bulk. As demand increased, so did production methods. Kilns were dug into a half-egg shape and filled with alternating layers of coal and limestone. A small hole in the bottom of the kiln allowed a fire to be lit, thus lighting the coal and starting the firing. Once the firing was complete, the lime was extracted through the same hole at the bottom. These small, batch production kilns only fired once per week (as the firing process took 6 to 7 days), and produced around 25 tons per firing. (Keller) This is very small, especially when

compared to the 1,000 plus tons per day kilns of modern times. Some of these kilns still operate today, but solely for educational purposes. This type of open-pit firing was dirty, dangerous, and downright miserable. These types of kilns operated around the world from the 1800's to the beginning of the great depression. (Geocaching) Modern kilns are large steel tubes that rotate, and are set at a slight incline to move the calcium carbonate down the kiln, (see figure below).

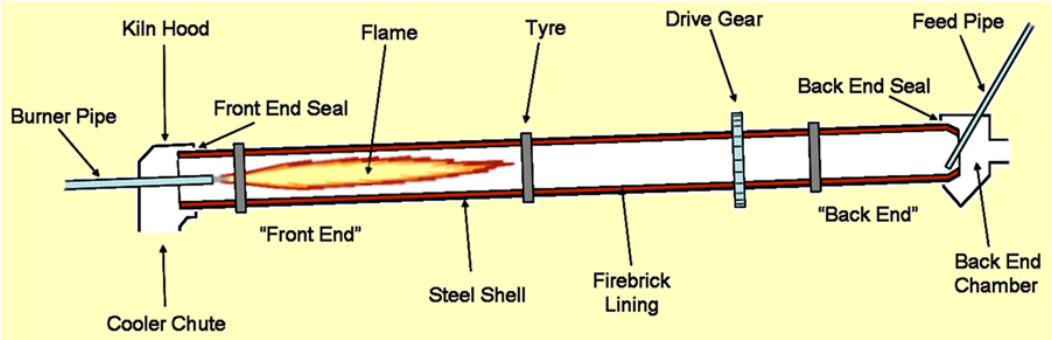


Figure 1: Modern kiln diagram, courtesy of cementkilns.co.uk

These kilns operate on a continuous basis rather than a batch system (like the open pit kilns did), meaning limestone is constantly coming in one end, and cooked lime is coming out the other. An open-pit kiln, as well as a modern one can be seen below.

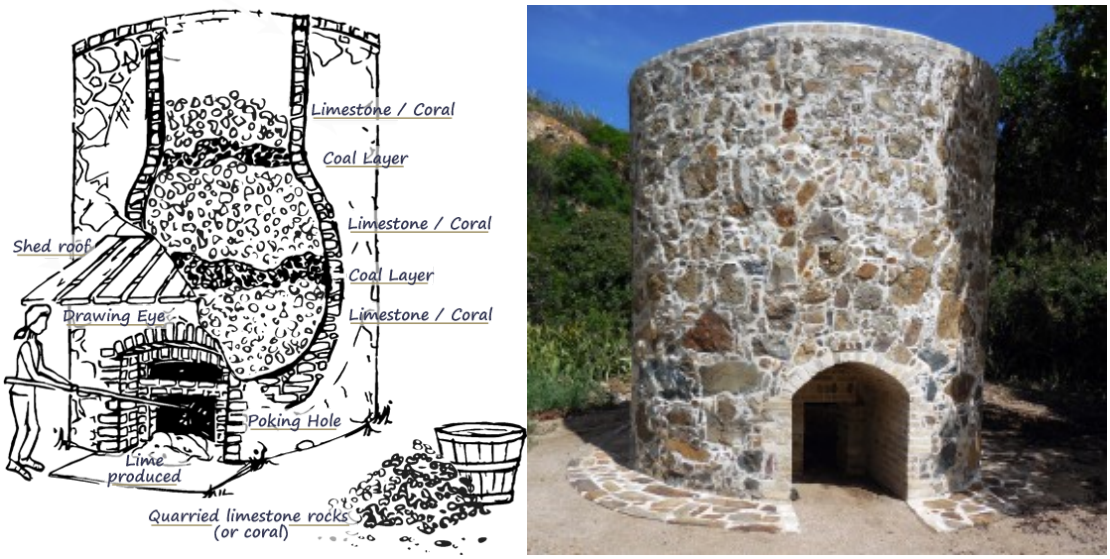


Figure 2: Open pit kiln, courtesy of Hassellsland.com

Figure 3: Modern-day lime kiln outside Stockholm, Sweden, courtesy of Steuler-KCH

Today's modern kilns pump out hundreds of tons of cooked lime per day, and can run 24/7/365. As seen in Figure 1, the kiln has a slight incline with the heating source (usually a natural gas burner) on the downhill end. The kiln gradually rotates (one to two revolutions per minute), and heats the lime until it reaches the 2,000 degrees Fahrenheit necessary for the reaction to occur. A burner resides on the downhill or "hot end" of the kiln and the flame is directed parallel to the kiln's rotational axis. On the "cool end" or uphill portion of the kiln, a vacuum fan pulls air through the kiln to maximize the amount of heat transferred to the lime.

Chemistry

Calcium carbonate ($CaCO_3$) is a very common mineral found throughout the Midwestern United states, and other areas around the globe. Before the reaction occurs, it is commonly referred to as

"lime mud", as there is frequently water mixed with the calcium carbonate. This gives the lime mud a consistency similar to damp sand. The reaction to make quicklime from limestone is called calcination, and can be seen below. (Terry Adams)

$$CaCO_3(s) + Heat \rightarrow CaO(s) + CO_2(g)$$

Equation 1: Calcining Reaction

This process only occurs at extremely high temperatures, and although not necessarily endothermic (consumes heat), and requires an immense amount of energy to proceed. The industry standard is around 8.4 million British thermal units per ton of lime produced. (Terry Adams) This is the equivalent of keeping a 40 Watt fluorescent bulb on for over seven years. Multiply this by a 400 ton per day kiln, and one can start to see the amount of energy being discussed. Once the reaction has occurred, the powder-like substance begins to coalesce into golf ball sized spheres. At this point, the lime falls out of the kiln for cooling. In some kiln systems, the heat in the cooked lime is somewhat recovered by passing the combustion air over the lime (prior to the air entering the kiln) to cool it. At this point, the process is complete, and the lime is ready for further processing or use.

Lean Six Sigma (LSS)

Lean and Six Sigma are two different problem solving systems that are combined to obtain a fast and perfect solution to obstacles, large and small, in business and everyday life. Lean is the process of eliminating unnecessary waste in a process. The terms "value added" and "non-value added" are used to describe activities in every process. For example, to make coffee in the morning, one might get out of bed and walk downstairs to the kitchen (non-value added). Next, they grab a coffee filter, the coffee, and put both into the coffee maker (value added). Then, they fill the coffee maker with water and push the button to initiate brewing (value added). Next, they must wait until the coffee is brewed (non-value added). Lean focuses on eliminating these non-value added steps. For the coffee example, someone

thought this walking downstairs and waiting was unnecessary, so they invented the delayed timer coffee maker. In this machine, the person prepares the coffee maker the night before, and sets a timer for the coffee maker, so it will start brewing on its own. This effectively eliminates the need to walk downstairs to initiate the coffee brewing process, as well as the waiting time for the coffee to brew.

Six Sigma is the process of achieving quality perfection through statistical analysis. Sigma stands for the standard deviation of a normal data set. In a normal curve three standard deviations or "sigmas" in either direction includes 99% of the data points. We know that any points outside of these six sigmas constitute an unusual disturbance or special cause. This idea can be expanded to many aspects of processes including statistical significance and confidence intervals of means, but this paper would be much too long if each of these topics were investigated to their entirety.

The history of Lean Six Sigma has two independent development paths, and were not married until recently. Lean was established (as we know it today) by Henry Ford with the invention of the assembly line. (Lean Enterprise Institute) In the 1930's Toyota took hold of Ford's idea and ran with it. They realized consumers wanted variety as well as quality and a low price (Ford only offered the latter two). They developed the concept of lean into what we know today, and are a continued leader in the concept. Six sigma arguably was born with the invention of the normal curve by Carl Friedrich Gauss in the early 1800's. (iSixSigma) However, the phrase was officially coined by a Motorola engineer named Bill Smith of Motorola. (iSixSigma)

Today, forms of Lean Six Sigma are used around the world by thousands of companies and organizations. Some companies include: Rolls Royce, Toyota, Caterpillar, GE, Cliffs, Anheiser Busch, and of course, Sappi. (Benda) Another concept is that of belts, like the martial arts. Within Sappi, there are green belts, black belts, and master black belts. The belt levels correlate to the amount of training one has received, and proven skill with real-world projects. The Kiln project at Sappi was commissioned as a

black belt level project, as the potential savings reached into the millions of dollars. The project was assigned to Brandon Hastings, a project engineer within the pulp technical services department.

Project Background

Sappi is a South African based pulp and paper making company (the name was an acronym for South African Pulp and Paper Industries, however it is now trademarked as just Sappi). They also make dissolving pulp (high purity cellulose) for use in other applications such as animal food filler and rayon production. Pulp is produced by cooking wood chips at elevated temperatures in vessels called digesters. A chemical mixture called white liquor, containing sodium hydroxide (NaOH) and sodium sulfide (Na_2S) is also added to aid in hemicellulose and lignin removal. Lime provides the sodium hydroxide (through some side reactions) in white liquor, with the lime kiln essentially acting as a chemical recovery and regeneration system. The lime kiln at Sappi Cloquet was built in 1998 and again in 2016, but the project was done in 2014, so this report will not discuss the recent upgrade. It was originally designed to produce around 250 tons per day (TPD). As the output of the pulp mill increased, (and switched to dissolving pulp in 2013), the demand on the lime kiln continuously increased. The pulp mill at present needs around 460 TPD of cooked lime to keep up with chemical demand. At the time of the project's inception, kiln production was roughly 375 to 400 TPD, with many interruptions that caused unnecessary downtime. The financial implications of this downtime (along with the cost to purchase makeup lime) reached into the millions of dollars.

Sappi as a corporation is heavily invested in the problem solving, and optimization technique known as Lean Six Sigma, or LSS. Once the financial implications of the kiln's shortcomings were realized, a LSS black belt project was commissioned to increase uptime and production. The project began in late October of 2014, and lasted well into the following summer. Although some specifics of

the project are unavailable for confidentiality reasons, the methods, hiccups and successes are not, and are discussed in the following sections.

The Project

Pre-Define/Define

The project began on Halloween day, 2014. During this time, the main topics of concern were: team selection, investigation, communication, and knowledge sharing. The team consisted of approximately twenty members. This is much larger than a typical Lean Six Sigma project, although it was more of a two-tiered system. The inner circle of the project (the main stakeholders) only numbered five. A weekly meeting was scheduled, so that the team could catch up and communicate progress. In the first weeks, the problem of the lime kiln was explored, and all team members expressed their concerns. The operators were consulted, and experts were contacted (including the original designer of the kiln). A brilliant strategy of LSS that was implemented was the sticky note. In this exercise (that takes place during a full-team meeting), each person is given a stack of sticky notes. They write what they know about the problem/equipment, what they don't know about the problem, and questions that they have. The reason for this is to seal up gaps in what one person might know secondhand, and someone who might be asking that exact question. This allows the team to get on the same page. After these first few meetings, the team was excited and motivated to move into the next phase of the project.

Another extremely important technique that was employed by the team was the technique "Genchi Genbutsu", which translates to "Go and See". Doing this forces the team to get up and out of their desks, and physically look at the equipment. All too often, process engineers and associated team members can get too comfortable sitting behind a computer screen and looking at Pi (Pi is a process monitoring software that allows anyone on the mill's servers to access every temperature, pressure,

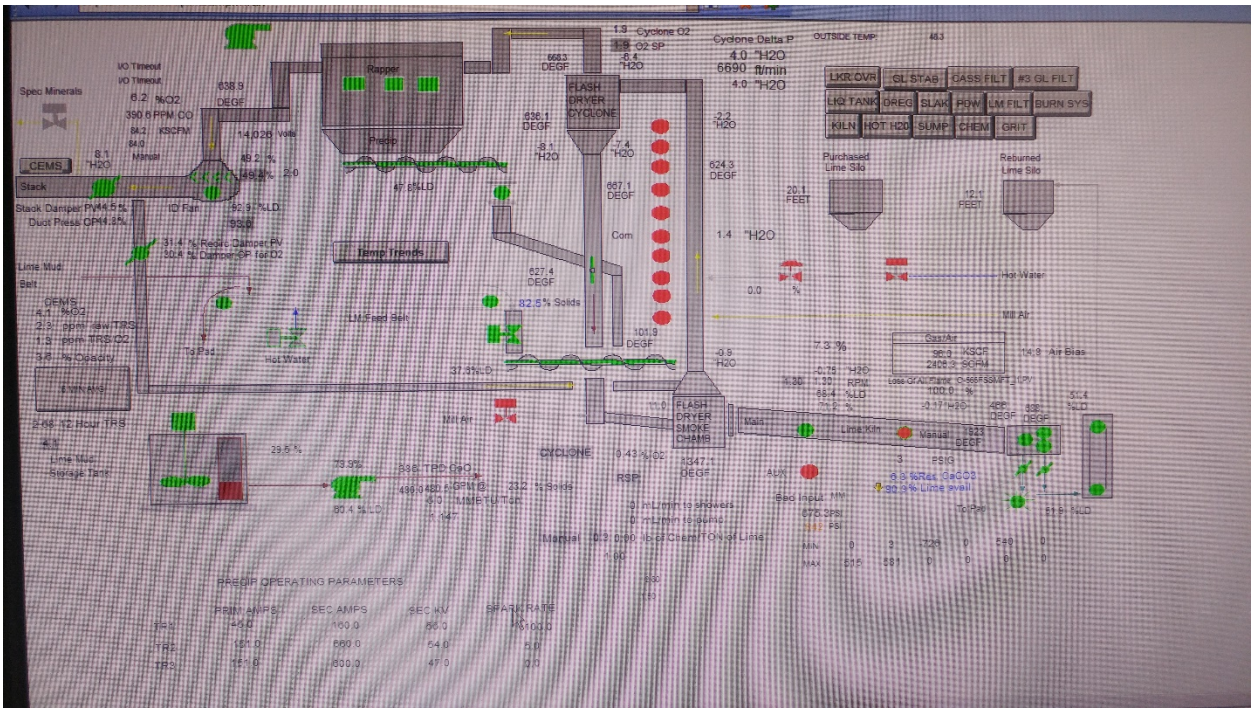
flowrate, etc. in the mill). Many times, (such as the kiln plugging incident, which will be covered later) problems that arise in the equipment simply cannot be explained by looking at a computer screen. This technique also helps each team member to visualize topics of discussion during meetings. This aided in troubleshooting of various issues throughout the project. The brick washing incident (in which the refractory brick inside the kiln began disintegrating at an alarming rate at the fire end of the kiln), was a perfect example of Genchi Genbutsu. In this incident, the fire end of the kiln's shell began heating above allowable levels (more than 900˚ F). This was not observable in Pi, and could only be seen/felt (because the radiation was so strong one could feel it on their skin from fifty feet away) by going out in the field.

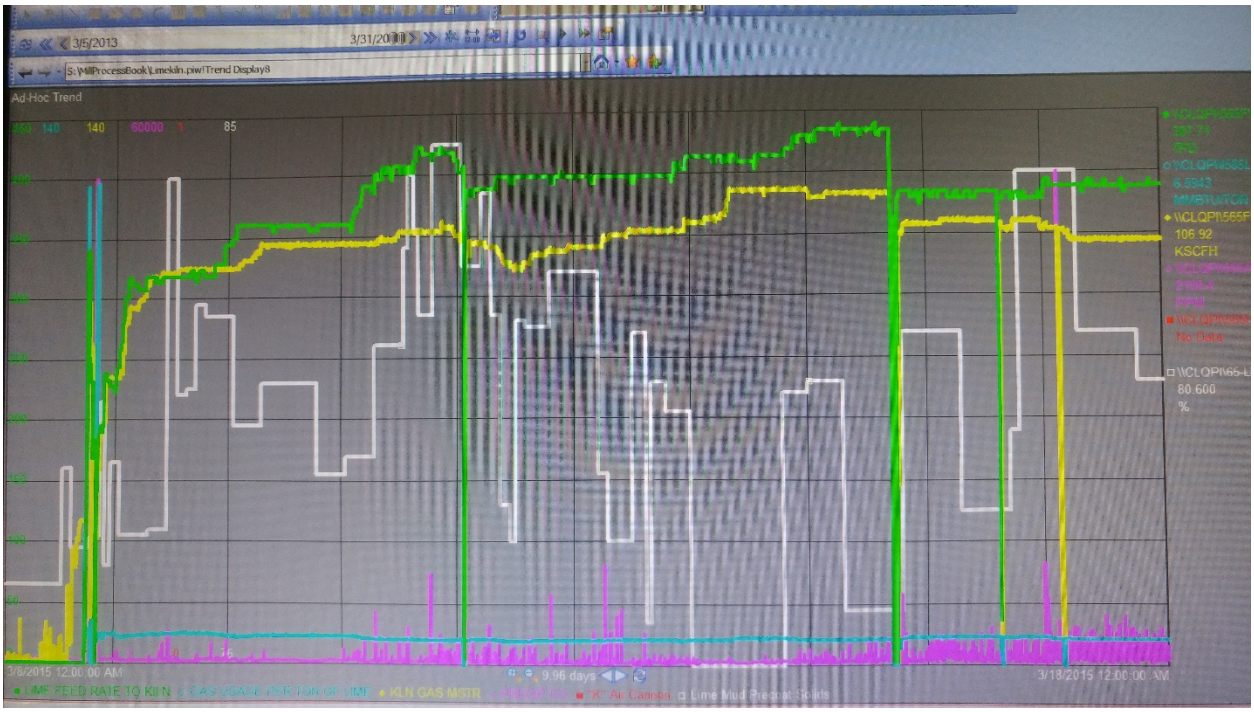
One last part of the predefine/define phases is the idea of "quick fixes". This is the idea that some problems are so blatant and visible that they can be identified easily and can be fixed quickly. One of these was the extending of the firing of air cannons on the cold end of the kiln. In what is called the "smokebox" or the area of the kiln that lime mud is introduced into the kiln, there are compressed air cannons that attempt to prevent mud buildup in the immediate area. There are six cannons in a very small area, and they were fired in rapid succession. This can sometimes overload the electrostatic precipitator that is designed to take lime mud particles out of the flue gas. Because this was a known issue, the firing succession was slowed so that each cannon was fired, the mud particles cleared, then the next cannon fired.

Once the team is assembled, goals established, knowledge shared, the problem defined, and any quick fixes attained, the team moves into the next phases of the PDMAICS process, measure and analyze.

Measure/Analyze

The measure phase does just what it says, measure. The word is simple, but one could argue this is the most important part of a LSS project. Without good data, any model or solution to a problem will never be good. With the kiln project, many variables were measured. Some of these included: kiln production rate, upset causes, carbon monoxide levels, landfilling costs, gas costs, makeup lime costs, etc. One of the most important tools in any LSS project is Minitab. Built with statistical analysis in mind, Minitab is a crucial tool to getting the job done. Although process data cannot be directly pulled into Minitab, it can be easily pulled into Excel, then copied into Minitab. During the entirety of the project, Minitab was used to monitor kiln production rate, and helped determine special causes and correlations with other process variables. Along with Minitab, Pi, or Plant Information Management Systems, was a crucial part in continuous process monitoring throughout the project. In Pi, one can build pages or trends to constantly monitor process equipment, and design personal pages so one can have only the information they need at the tips of their fingers. Below is an example of a Pi page looking at the entirety of the kiln system, as well as a trend that is monitoring production rate, burner gas flow, burner gas per ton of mud flow, carbon monoxide, and filtered mud solids consistency.





A very important part of the measure phase was the discovery of the lime mud sensor error. This error was found to be responsible for significant overreporting of production on the kiln. This error would not have been discovered without the Measurement Systems Analysis (MSA) done on kiln

reporting. The lime mud solids sensor is an in-line process consistency sensor that measures the solids content of the lime mud slurry going to the mud filter. It gives a percentage reading (usually around twenty-two) of how high the solids content is in the slurry. This number is used, along with the mud flowrate and stoichiometry of the calcination reaction to determine the amount of calcium oxide produced by the kiln. Early in the measurement phase, the question "how is kiln production actually measured" was asked. After a few why's, it was discovered that this calibration was entirely determined by a hand test done by the operators, that was not an accurate representation of the actual calcium carbonate content of the mud. Being a slurry, there was dissolved salts in the slurry as well as the calcium carbonate. The test simply used a heat drying gravimetric measurement. Thus, both the dissolved salt, and the calcium carbonate were reported. This resulted in almost a ten percent overreporting of production! During the analyze phase, a new calibration was established (measuring only the calcium carbonate content), and during the improve phase, the sensor was recalibrated.

Along with production rate, there were almost a hundred different variables around the kiln in which historical data was pulled into excel, and analyzed in either excel or Minitab. This responsibility was shared amongst the team, and therefore was not a large burden on any one of the team members. Along with intracompany analysis, some of the data was sent out to third party consultants who had superior data analysis tools and experience.

During the analyze phase, the data that was collected is scrutinized and reviewed. This was a relatively short period in the project as the problems that had arisen were already visible and during the measure phase. The only real time that was spent in the analyzes phase was the reviewing of the downtime Paretos and making sure the topics that were being addressed were going to have the best impact on the project. Once these issues were addressed, the topic of special cause variation came front and center.

During any data analysis, there will be special cases that skew the data for a known reason. One example of this special cause idea was the kiln ringing incident. During the transition between the analyze and improve phases, a disaster came upon the project. In the cold end of the kiln (approximately fifteen feet towards the hot end), a "ring" of buildup became so severe that it was not allowing lime to pass through it. It was also causing differential pressures across the kiln to increase to dangerous levels unfortunately, this required a cold shut down of the kiln, and people had to venture into the kiln to clean it out by hand. This kind of incident is often called "special cause" and is omitted as a trip. Even though it was only one occurrence, it became a significant portion of downtime in the paretos. After three days of downtime, the kiln was back up and running. Although much investigation was done in the following days, no direct cause of the ring was identified. Instead, a method known as infrared kiln imaging became more common as a process monitoring technique. Using an infrared camera, one can take pictures of the kiln shell in its entirety to get a visual representation of shell temperatures. This can help identify rings or hot spots so maintenance and engineering can help mitigate them before catastrophe strikes. This imaging technique also helped later in the project when (after some bad burner angle adjustments) the insulating refractory brick in the hot end of the kiln began disintegrating. This resulted in the kiln shell getting dangerously hot. As the annual outage was coming soon, instead of shutting down the kiln to replace the brick, eight industrial sized fans were placed close to the shell using scaffolding. When turned on, they increased the heat convection coefficient on the shell's surface. This effectively cooled the shell temperature to a safe level until the outage could replace the refractory brick. When the outage finally came, there was only an inch and a half of brick remaining (there is supposed to be eleven inches). Without the increased monitoring of infrared shell images, this issue may not have been dealt with in time. Below is a picture of a full-shell infrared image of a kiln. After this unfortunate incident was resolved, the team was ready to head into the improve and control phases.

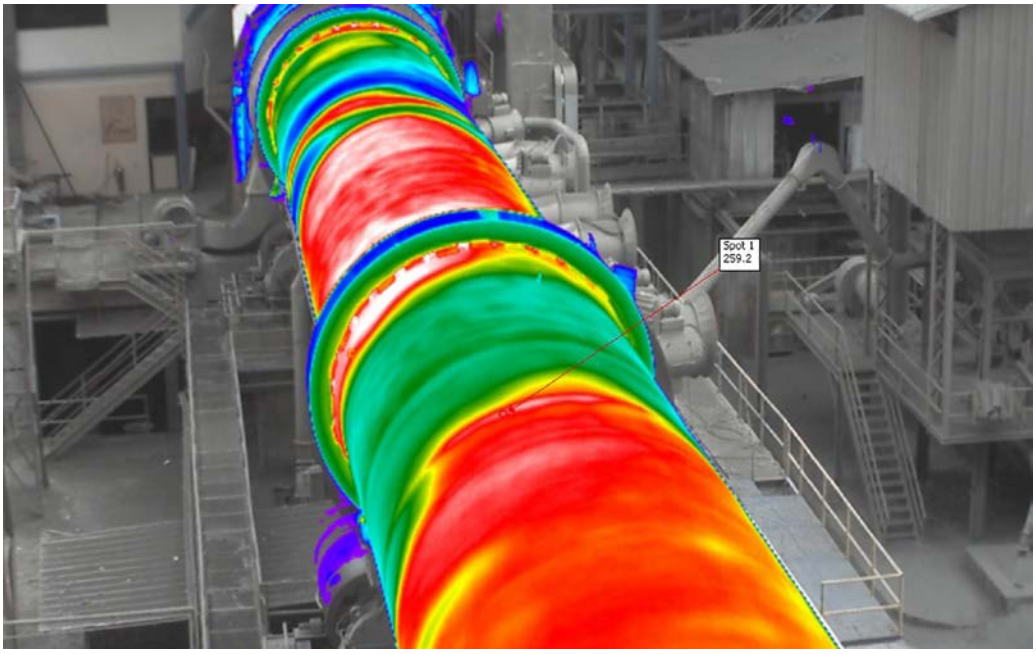


Figure 4: Infrared Kiln Image courtesy of i.ytimg.com

Improve/Control

This is arguably the most dangerous part of any LSS project, as it usually involves taking machinery where it has never gone before, or trying things that have never been investigated. To push processes to their limits of production and uptime, things often need to be done that could have adverse side effects. During the improve part of the kiln project at Sappi, there were many issues that arose. There were also a vast number of improvements made. It was at this time the original designer of the kiln, and a representative for the burner company were brought in as consultants. Representatives from other companies such as Andritz and Metso were also brought in. They helped the team through several issues documented in the measure and analyze phases such as burner angle and settings, a soda balance, refractory brick design, and air cannon sequencing.

A large part of the project was increasing throughput. The kiln was steadily bumped up in production a few tons per day (TPD) at a time. Gradually, the kiln went from 380 to 400 to 420 tons. This was done over a span of months, and did not happen in one week. Eventually, the kiln was pushing

440 tons per day of lime through the kiln steadily, and at the same quality specifications that the kiln was running beforehand. This resulted in a savings of approximately $1.4MM of makeup lime, and two hundred thousand dollars in landfilling costs. Unfortunately, there was also an associated cost increase in natural gas due to the increased heat requirement, but it was somewhat miniscule at around fifty thousand dollars. As the original goal for the project was $1MM in savings, the persons supervising the project were quite pleased when only one major aspect of the savings had surpassed this goal. Because the project was doing so well, the expected completion date would eventually be pushed back an incredible six months.

Another incredible aspect of savings was the increased uptime. By cutting down the amount of time the kiln was spending not adding value, an additional five hundred thousand dollars was added to the project savings (this included the same aspects of savings as the throughput increase did). This was done using the downtime Pareto in the analyze phase, so the team could tackle the issues that were causing the most hurt. One example of this was the carbon monoxide trips (a trip is when the kiln auto-stops production because of a dangerous process condition). This was by far the most important topic, as it caused many trips. When a carbon monoxide level of over ten thousand parts per million was detected in the electrostatic precipitator for over ten seconds, the kiln would trip, and ten to twenty minutes of downtime would ensue. Because of process safety rules, a flammable gas level that exceeds ten percent of its lower explosive limit (or LEL) is considered unsafe, and unacceptable. The problem here, was that carbon monoxide levels always spiked, and went from around five hundred to twenty thousand in the course of a few seconds. They usually dropped in the same fashion after a short time. This gave the operator little (if any) time to react and mitigate the issue. Instead of violating the ten percent rule, the electronics and instrumentation (E&I) department and the team came up with the solution to extend the trigger time to thirty seconds. This way, the operator had a significant amount of

time to react to the issue, and attempt to intervene before the trip occurred. This proved invaluable, as it cut the number of trips almost in half.

Unfortunately, with all this increased uptime and throughput, the kiln was running dangerously close to its environmental production limit. As the kiln puts out thousands of tons of carbon dioxide per week, one can imagine there are strict constraints regarding production. Because of the error in the lime mud solids measurement (from the measure phase) Sappi could back-calculate their reported production numbers to Minnesota Pollution Control Agency (MPCA), and show they were not in fact running up against their allowed limits. This again proved incredibly valuable, as limiting production because of the environmental permit would counter some of the gains made by the project. This was not cheating, or skirting around environmental regulations, it was simply adjusting the erroneous equipment to its true production values. It just so happened the calculation was erroneous in favor of Sappi. When the lime mud solids meter was calibrated to the correct values, many of the process engineers and operators were concerned, because the numbers on their operating systems did not line up with historical values. This was difficult for them to comprehend (or trust) because they were basing production (and venturing into uncharted territory) off the intern's testing. After the calibration, and associated reestablishment of "normal" process values, the kiln was back to increasing production.

In summary, the improvements made over the months-long timespan of the improve phase resulted in a savings of over $2MM. This was a home run for LSS at Sappi, and turned a process bottle-neck into a well-oiled piece of the pulp mill. The kiln went from 380 to 440 tons of calcium oxide produced per day, and achieved substantial gains in uptime. These gains were controlled by consulting all four operators on the new production norms, and ensuring that everyone involved in daily kiln operation was made aware of the improvements made.

Sustain

An important (and relatively recent) part of any LSS project is the sustain phase. This attempts to keep the gains that resulted from the project, and "sustain" them into the foreseeable future. A crucial part of this phase was the lime mud solids testing and calibration of the lime mud solids meter. Weekly testing, and as needed calibration was established to ensure the mud solids meter was reading correctly, and therefore production numbers were accurate. This testing was given to the pulp technical services department (separate from normal operations testing) to ensure results were consistent, and repeatable. The sustain phase is has a crucial role in keeping the gains from the project going. Team meetings that were intended for LSS talk turned into sustain meetings that involved only the key shareholders. This ensured that the people who were familiar with the project assisted in sustaining the gains made.

Lessons Learned (People, Equipment, Chemistry, Instrumentation, Meetings, Deadlines)

There are many take always from this project. First and foremost is the ability to improve upon one's soft skills. In a large team setting such as this, soft skills are as (if not more) important than hard skills. The list of examples is long and these skills translate to other aspects of the business world outside LSS. For instance, being able to hold and control a meeting is of utmost importance to get the most out of everyone's time. If there are fifteen people in a room, each getting paid seventy thousand dollars per year, a one hour meeting costs over five hundred dollars! Letting two people argue on a matter of subjective opinion (even for a few minutes) can start to cost serious money. This is ridiculous, and is in addition to the opportunity cost of constructive conversation that might have saved thousands! Companies like GE keep LSS meeting agendas down to the minute to ensure all time is used in the most efficient manner.

Second, it should be noted that machinery is never perfect. Things wear down, they drift from calibration, or they flat out stop working. This is learned quickly when working with a system one has experience with, as a human brain can recognize when things just do not add up. For instance, an oxygen sensor in the cool end of the kiln kept giving numbers that were physically impossible (as sensors downstream were giving a higher oxygen content). Upon further investigation, it was noted that this sensor is often plugged, and therefore cannot pass air through the sensor. After some tinkering by maintenance department, a new sensor inlet was designed that will not be subject to plugging as the opening is facing downstream. This correction helped to tune the burner better, and use less natural gas.

Third is chemistry. Through the course of this project, it became necessary to invent a totally new way to test lime mud. This was completely from the ground up with nothing to reference from. Operator manuals, standard operating procedures and conventional equipment were thrown out the window. After many hours of experimentation and running around the lab, a standard test (usually taking two hours) was completed, and a standard operating procedure was written. This is territory that one sometimes must venture into in a LSS project, and something that most engineers do not frequently encounter.

Last is deadlines. "Deadlines" are dates that one person imparts on another (maybe themselves) to complete a certain task or series of tasks. This project completely blew deadlines out of the water. The project was supposed to last three to four months, but ended up lasting more like ten. Depending on who is setting the deadline, they are often flexible. If the task is going extremely well but is behind schedule, it makes those deadlines easier to negotiate. This again ties back to the soft skills.

Summary

Everything said, this was a wonderful project, that resulted in over two million dollars in savings for the chemical recovery department of the pulp mill. These savings especially help in a varying specialized cellulose market, in which margins are thinner than projected. It seems as if a large portion of the strategies and aspects of LSS were employed within this project. Many lessons were learned, and many obstacles were overcome. In the grand scheme of things, two million is not that big of deal when it comes to a five hundred million dollar per year facility, but a few drops add up to a rainstorm.

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