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Reducing Welding Defects in Turnaround Projects: A Lean Six Sigma Case Study

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ABSTRACT In the construction industry, successful project completion leads to customer satisfaction. Schedule delays, however, may be caused by unexpected downtime due to rework/repair. This case study describes how one specialty construction company used the Lean Six Sigma methodology to reduce welding defects in turnaround projects. As a result, they improved project performance and identified solutions that were implemented company-wide. From a broader perspective, this research demonstrates how Lean Six Sigma can be applied in service-based environments such as turnaround projects. It also provides evidence of the tangible benefits that can be achieved within specialty construction operations using process improvement strategies.

KEYWORDS case study, DMAIC, Lean Six Sigma, turnaround/construction projects, welding defects

INTRODUCTION

Because customer expectations are constantly changing and evolving, organizations must continuously improve their products/services to remain competitive (Flynn et al. 1995; Reed et al. 2000). Reducing or eliminating defects or errors associated with products or services is one way that organizations can set themselves apart from their competitors (Hinckley and Barkan 1996; National Institute of Standards and Technology 2011). In the construction industry, successful project completion leads to high customer satisfaction. Achieving this, however, requires cooperation between clients and contractors to deter budget overruns and/or schedule delays. To avoid schedule delays, construction companies need to implement structured project planning/management methods early in the project life cycle and clarify their understanding about the project environment, scope, and requirements (Casinelli 2005). For example, industrial process plants, such as petrochemical plants and refineries, require occasional scheduled shutdowns for inspection, repair, and/or maintenance (Bertolini et al. 2009). These events, or turnarounds, require services provided by specialty piping and welding construction companies to safely return process plants to normal operation. Due to the high opportunity cost of these plants being out of service for extended periods of time, avoiding schedule delays is a

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priority in turnaround projects (Megow et al. 2011).

Schedule delays caused by unexpected downtime in turnaround projects can result in significant financial losses due to the loss of production capability or rework/repair costs (Lenahan 2006). For example, the daily revenue loss for downtime at a refinery, such as a crude oil distillation unit with a capacity of 200,000 barrels per day, is approximately $2.47 million (Almazrouee et al. 2010). Direct shutdown and turnaround costs include the labor of pipe fitters and inspectors, along with the additional material costs associated with repairing welds and replacing defective pipes (Megow et al. 2011). Though welding repair costs are relatively minor in comparison to the loss of revenue associated with extended schedule delays for turnaround projects, a tremendous amount of pressure is placed on the company performing the turnaround work to deliver a high-quality service and stay on schedule. Downtime due to repairing defective welds may cause schedule delays and indirectly affect future business for welding construction companies. Factors such as decreased customer satisfaction, loss of company reputation, and/or inability to bid on future projects may contribute to a loss of revenue for these companies (Chatterjee et al. 2002). To retain current customers and gain new business, such organizations use performance and delivery guarantees to prove their reputation among their competitors (Chatterjee et al. 2002; Kumar et al. 2007).

This research specifically addresses the need to reduce welding defects in turnaround projects. Using an action research approach (Reason and Bradbury 2008), researchers worked closely with a specialty construction company located near Houston, Texas, to address an increase in the number of weld repairs that occurred during turnaround projects completed in 2011. To investigate this problem, the improvement project team used the Lean Six Sigma methodology, a well-known, structured problem-solving approach that helps to improve existing process performance and capability (George 2002; Kumar et al. 2007). Little documented research exists on the use of this methodology in the turnaround industry; hence, this research attempts to fill this gap in the literature by providing a case study that demonstrates how Lean Six Sigma can be applied in service-based environments such as turnaround projects. The next section provides further background on welding defects and describes some of their potential causes. Then, a brief discussion about the Lean Six Sigma methodology is presented. The subsequent sections describe the work conducted as part of this study, including a discussion of the project results. The final section suggests how the success of the project benefits the company where this project was conducted, as well as the turnaround industry as a whole, now and in the future.

BACKGROUND

Welding is commonly used to connect sections of pipeline during initial construction and later repair work for turnaround projects. Because welded connections, also called "butt welds," serve as a critical point of failure in pressurized pipeline systems, much time is spent on the process of welding sections of pipeline together. This work is done to ensure that stress concentrations on the welds do not result in connection failures (Lotsberg 2009). Butt welds are commonly inspected for internal defects through the use of a nondestructive form of examination known as radiographic testing. In this type of test, the quality of each weld is determined through the visual review of X-rays of welds by an expert (Qingming et al. 2010).

Some types of welding defects that are typically observed include lack of fusion and porosity. Lack of fusion occurs when the weld metal does not come into full contact with the base metal, such as the beveled edge surface of a carbon steel pipe (Souza et al. 2009). Porosity occurs in gas tungsten arc welding when gas that is captured during the welding process creates small internal voids in a weld (Nandhitha et al. 2009). For example, cross-air (i.e., wind) disturbances affect the gas shielding of the weld, increasing the chance of porosity occurring. This type of weld imperfection affects the quality of the weld, which may lead to connection failures once a turnaround project is complete (Zhiyong et al. 2009).

Additional causes of defects for butt welds include issues related to welder performance, such as inadequate training, poor execution of the required welding procedure, and poor eyesight/eye injury. To allocate welders to jobs by skill level, many organizations initially test and rank their welders by classifications that are standardized by the American Welding Society (Jeffus 2004). Unfortunately, the high cost of training welders in advanced techniques and restricted positions often deters companies from improving the classifications of their workforce (Stone et al. 2011). In addition to training issues, studies have shown that welding exposes workers to amplified amounts of radiant and thermal energy, increasing the chance of welding defects due to poor eyesight/eye injuries (Lombardi et al. 2005).

While Lean philosophies and the Six Sigma methodology have been used successfully for many years to generate significant financial savings for companies such as General Electric, Toyota, Caterpillar, and Bank of America (Holweg 2007; Montgomery and Woodall 2008), these approaches have only recently started being used in the construction industry (Ferng and Price 2005). For example, Pheng and Hui (2004) described how to apply Six Sigma in construction, specifically for building projects, and Stewart and Spencer (2006) discussed a case study that improves the construction of concrete beams for a raised railway station. More recently, it has been suggested that Six Sigma methods can be used in construction projects to reduce workflow variability and provide more concrete measures of project performance (Han et al. 2008).

Lean encompasses practices for streamlining processes to create high-quality products/services with little or no waste (Shah and Ward 2003). The goal of Six Sigma is to “reduce variation in organizational processes by using improvement specialists, a structured method, and performance metrics with the aim of achieving strategic objectives” (Schroeder et al. 2008, p. 540). Since their inception, these approaches have evolved from manufacturing process improvement techniques into overall business strategies. Today, for companies to invest their time in implementing these methodologies, quantifiable long-term payoffs must be evident (Hahn et al. 2000). Used together, these methods help to streamline business processes by reducing/eliminating defects and waste, which effectively increases production capacity (Nonthaleerak and Hendry 2006).

The Lean Six Sigma methodology follows a five-phase approach, known as DMAIC (define, measure, analyze, improve, and control). The purpose of the Define phase is to identify the project goals and understand the potential value that the improvement project will generate for the organization. This phase includes obtaining approval of the project charter and developing a high-level map of the current process (George 2002). During the Measure phase, the measurement system is verified and data are collected to establish a baseline measurement for the current process (Erdmann et al. 2010; Hahn et al. 2000). In the Analyze phase, information about the problem and underlying process are analyzed to identify potential causes of the problem (Kumar et al. 2007). The objective of the Improve phase is to generate solutions for the vital few root causes found in the previous phase and implement these solutions to create an improved process (Gitlow et al. 1995). In addition, the performance of the improved process is measured and compared against the baseline established in the Measure phase to determine the degree of improvement achieved through the project (Kumar et al. 2007). The goal of the Control phase is to hold the gains made in the improved process. This includes developing a control/process management plan that documents, monitors, and controls the improved process (Rasis et al. 2002). The specific details regarding how this methodology was applied, using an action research approach, to reduce welding defects for one specialty construction company is discussed in the following section.

CASE STUDY

Company Background

JV Industrial Companies (JVIC), Ltd., is an industry-leading turnaround, construction, and fabrication services organization headquartered near Houston, Texas. This company provides complete construction solutions for industrial clients across the United States. The company's core values include superior safety, quality, service, integrity, personal responsibility, and personal accountability. JVIC's services for process plant turnaround projects include piping and specialty welding, tower revamp and reconfigurations, bolted connections for process equipment assembly, automated weld overlay, and customized fabrication facilities. The company-wide goal for the average weld repair rate (i.e., the total number of rejected butt welds divided by the total number of butt welds inspected by X-ray) on turnaround projects is 2% or less. When the weld repair rate exceeds an acceptable percentage on a given project, JVIC can be responsible for the cost of correcting these defective welds.

Unfortunately, JVIC experienced weld repair rates exceeding their customers' acceptance percentage for several turnaround projects completed in 2011. To address this issue, the company performed a Lean Six Sigma project to help identify the root cause(s) and develop solutions for addressing this problem. The company felt that reducing the weld repair rate for turnaround projects would help to keep projects on schedule, improve customer satisfaction, and generate a significant financial savings for the organization. Hence, the overarching question guiding this research was what solution(s) should JVIC implement to reduce the occurrence of defective welds in turnaround projects?

Action Research

JVIC conducted this Lean Six Sigma project through a participatory action research method of inquiry that involved employees and researchers working together to solve this problem (Reason and Bradbury 2008). This approach provided an opportunity for researchers to function as project participants through meetings with, and visits to, the company. Researchers, along with employees from the Turnaround and Quality Control departments at JVIC, were involved in analyzing the process to identify cause(s) of defective welds and together implemented changes to improve the welding process following the DMAIC approach. Within this framework, the action research process of planning, taking action, and evaluating the action, which leads to planning for further action was used to ensure that what was learned from one phase of the project was then used as the input to the subsequent phase (Coughlan and Coghlan 2002). The specific details regarding each phase of the DMAIC process for this project are described in the following sections.

Define Phase

At the beginning of this project, a project charter and a project management plan were developed by the project team. The project charter identified the responsibilities of the team members along with the business needs for the project. As stated in the problem and mission statements that follow, the overall objective of the project was to reduce the weld repair rate for turnaround projects conducted by one division of the company located in La Porte, Texas.

> Problem Statement: JVIC's butt weld repair rate for the La Porte division has averaged 3.66% over the last 9 months (January 2011–September 2011), resulting in increased repair costs.
>
> Mission Statement: Reduce the average butt weld repair rate for the La Porte division to 2.75% in the next 6 months (by April 2012), resulting in an estimated savings of $75,000-$100,000 per year.

The project team began their investigation of the problem using traditional Lean Six Sigma process mapping tools. To gain insight about the welding process and develop a high-level understanding of

Suppliers	Inputs	Process	Outputs	Customers
Pipe suppliers Weld rod suppliers Welding machine vendors Supplier engineers	Pipe Welders Pipe fitter Weld rod Engineering drawing Engineering specifications Weld procedure Pressure test Inspection equipment Welding machine	1. Verify materials received 2. Pipe fitter obtains pipe 3. Cut and fit pipe 4. Tack weld 5. Make weld 6. Inspect weld	Inspection reports Complete welded system	Plant facility End users

FIGURE 1 **High-level view of the pipe welding process.**

all the elements involved, the current process was mapped using a SIPOC (suppliers, inputs, process, outputs, and customers) diagram (Tague 2005). As shown in Figure 1, the tasks listed in the center column define the boundary points of the welding process. The first steps are to verify that the correct welding materials are procured for the project and for the pipe fitter to receive the pipe. Once the pipe has been beveled and fit in the desired location, the welder will make the required weld, which will be inspected as required by the customer. Inputs to the process include the welders, welding procedure, welding equipment and materials, along with any items needed for inspecting the weld once it is complete. These inputs are supplied by pipe and welding material vendors, equipment vendors, and design engineers. In addition to the completed welded system, other outputs for turnaround projects are inspection reports and detailed weld logs used for project status reports. The customers that use these outputs include the process plant facility owners and other end users of the facility.

Because this case study focused on reducing the butt weld repair rate, a detailed flowchart was created to identify all steps in the welding process. This additional effort to document the process is illustrated in Figure 2, where, first, the welding material is received and proceeds through the welding process. Then, there are multiple decision points regarding weld inspections and repairs. If there is damage to the pipe upon initial inspection by the pipe fitter, the material is rejected and the process starts over. If the welder identifies that a windshield is needed in the welding area, this must be set up before the process can proceed. Once a weld has been completed, an inspection process will determine whether repairs are needed. Inspection documentation is completed when all welds have

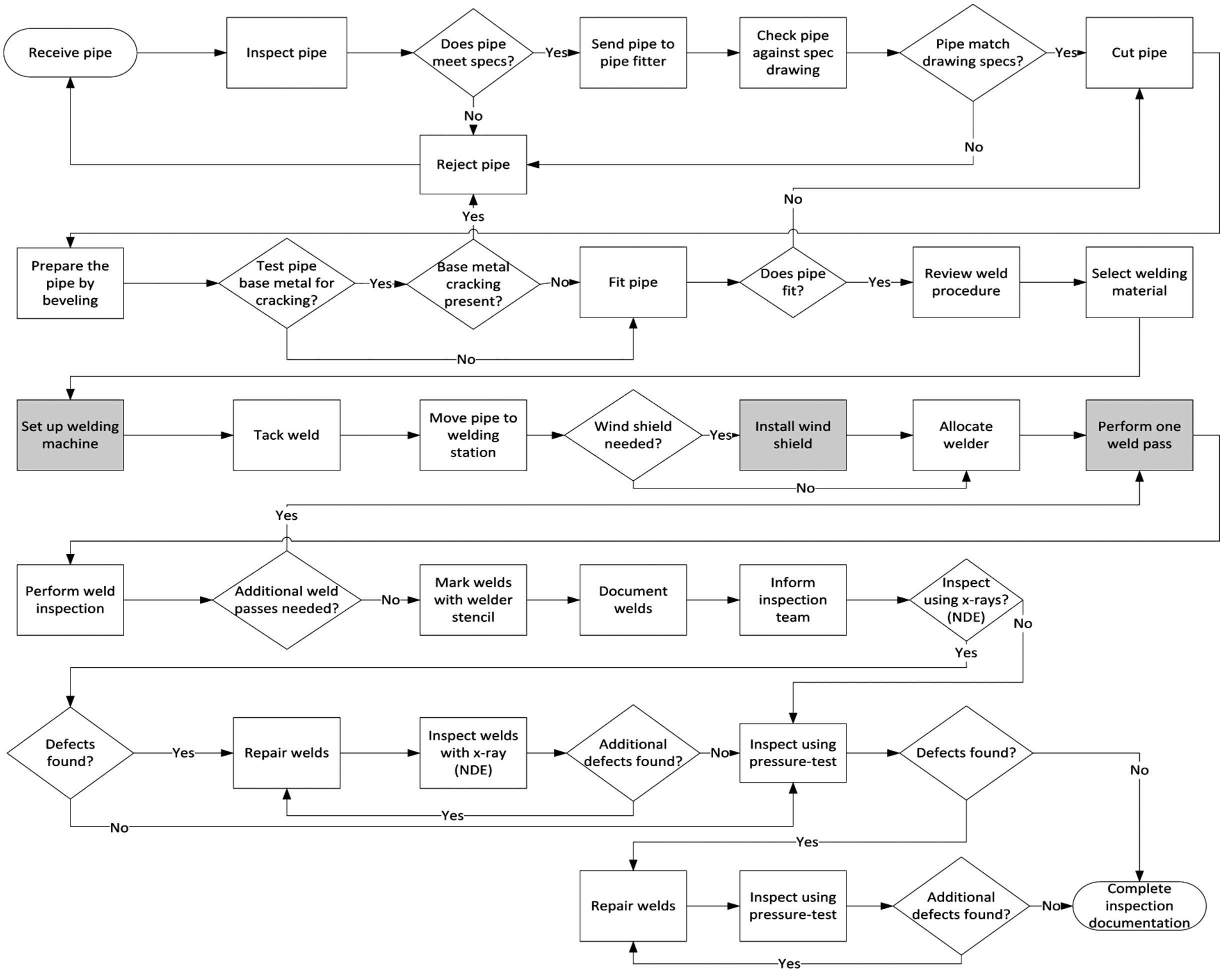


FIGURE 2 **Detailed view of the pipe welding process (boxes in gray denote process steps associated with the root causes identified in Figure 10).**

passed an X-ray inspection and/or a pressure test, as required by the customer or welding code/standard. The process steps in Figure 2 that are denoted in gray will be explained further in the Analyze phase of the project.

Measure Phase

During the Measure phase, information was gathered on the existing measurement system used by JVIC to quantify the weld repair rate. Again, the project team used traditional Lean Six Sigma process mapping tools, this time to document the measurement system. As depicted in Figure 3, first, the quality controller (QC) enters the initial project weld information into the electronic database based on the overall project weld map drawing they created. Once a weld has been completed, the QC enters the corresponding welder identification (ID) into the database. Then, the inspector performs a radiographic test or X-ray of the weld and analyzes it. Lastly, the weld inspection report is sent to the QC to be recorded in the electronic project database as part of the project documentation. If the X-ray analysis notes that a weld is defective, the repair is performed and the inspection process starts over.

The project team then used ad hoc process analysis and error proofing to improve the measurements system. The measurement system process flow was reviewed for accuracy, and it was identified that the QC inputs only the project weld information directly into the electronic project database. As a result, some information, such as the type of welding defect, is not recorded for all projects. The tasks denoted in Figure 3 by dotted line boxes indicate the improvements made to the measurement system to address this issue. Now, for each weld that is rejected, the two new steps in the measurement process require the QC to enter the welder ID and additional weld information (i.e., weld defect type) into the electronic database. As shown in Figure 4, the database has been error proofed using forced completion fields. That is, by configuring this database so that welder ID and defect type must be entered in order to access the next screen in the system, the amount of missing information found in the electronic project database is reduced/eliminated.

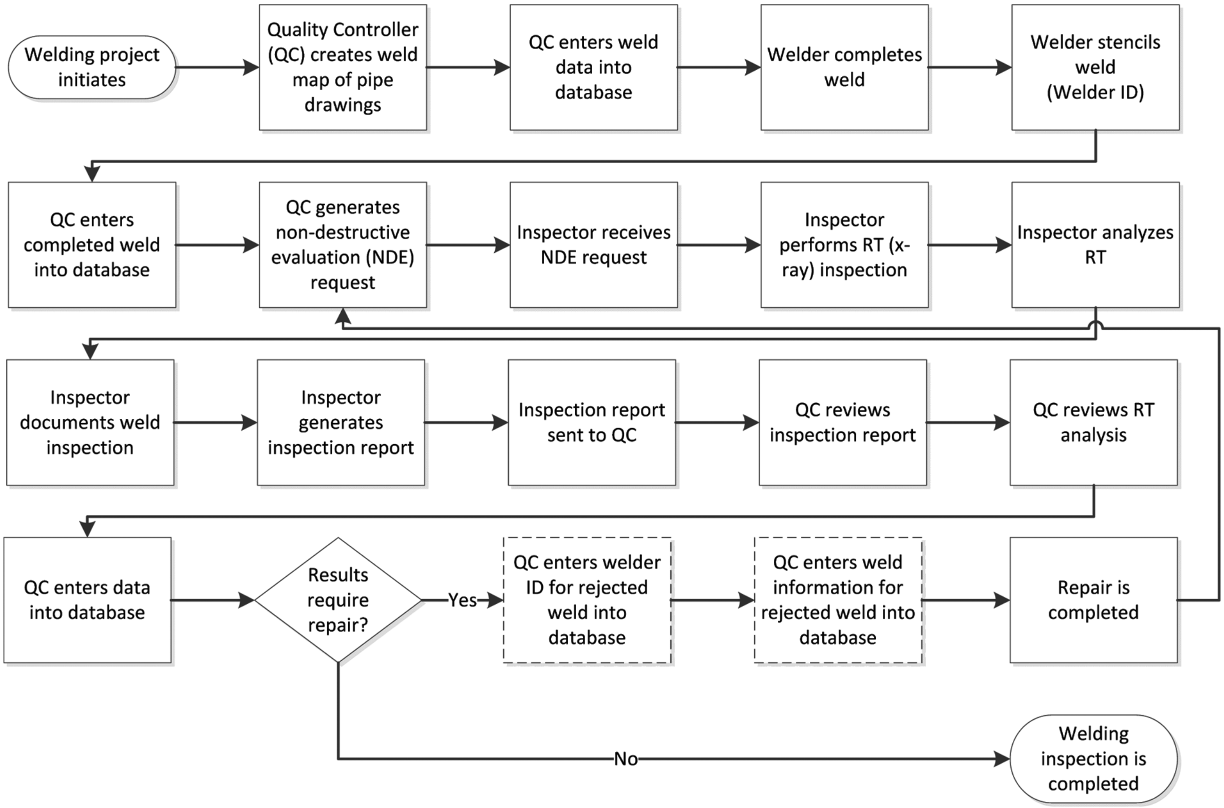
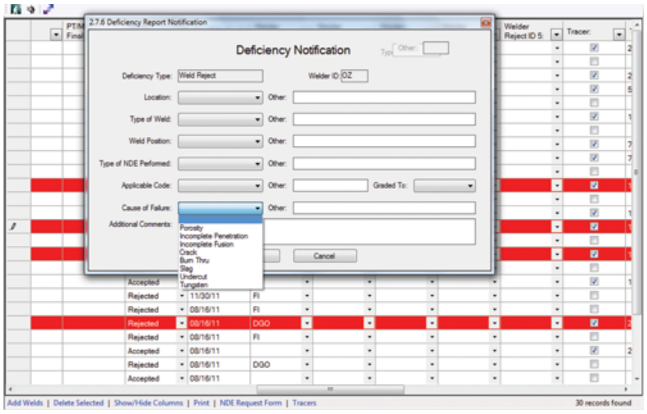


FIGURE 3 Measurement system flowchart (with improvements noted by dotted line boxes).


2.7.6 Deficiency Report Notification

Deficiency Notification

Deficiency Type: Weld Reject

Welder ID: OZ

Accepted		
Rejected	11/30/11	FI
Rejected	08/16/11	FI
Rejected	08/16/11	DGO
Rejected	08/16/11	FI
Accepted	08/16/11	
Rejected	08/16/11	DGO
Accepted	08/16/11	

30 records found

FIGURE 4 Examples of forced completion fields in the electronic project database.

To establish a baseline measurement that describes the current performance of the welding process and justify the focus of the project, data from detailed project weld logs for a 9-month period ranging from January through September 2011 were reviewed. This information was summarized by the project team using histograms and Pareto charts (Evans and Lindsay 2005). The horizontal axis of Figure 5 depicts the butt weld repair rate (i.e., the total number of rejected butt welds divided by the total number of butt welds inspected by X-ray) as a percentage for each project performed by the La Porte division over the past 9 months. The repair rate per project ranged from zero to 24% with an average of 3.66% and a standard deviation of 5.41%. It is interesting to note, however, that many projects had a repair rate that was higher than acceptable to the customer, which put JVIC in a position to be financially responsible for correcting the defective welds for these projects. As an additional consequence, JVIC's future business may be negatively affected because their customers might pursue JVIC's competitors to complete future turnaround projects. Though other divisions within the company may have had higher weld repair rates than the La Porte division, this Lean Six Sigma project was conducted at the La Porte division because it performs the most welds per project and has the second highest number of welds inspected per project compared with other divisions, as illustrated in Figures 6 and 7, respectively.

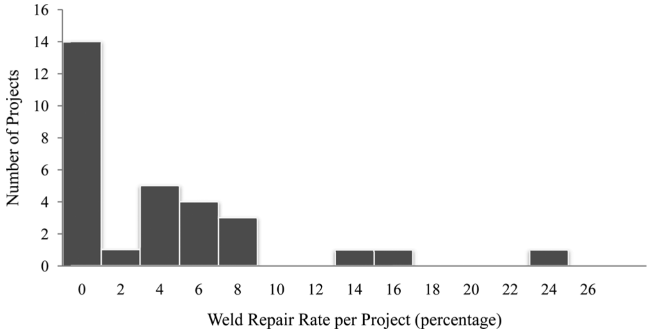


FIGURE 5 Weld repair rate baseline measurement for the La Porte division.

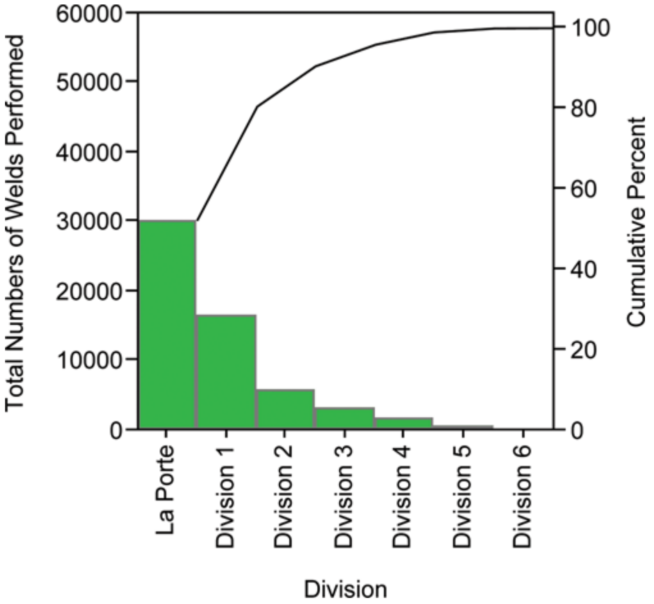


FIGURE 6 Total number of welds performed by JVIC division.

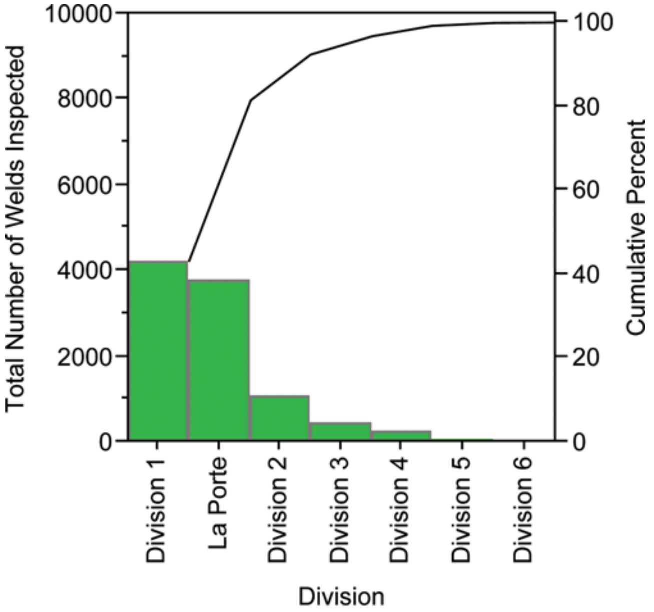


FIGURE 7 Total number of welds inspected by JVIC division.

Analyze Phase

In the Analyze phase, the project team identified potential causes of high butt weld repair rates through multiple brainstorming sessions using a five-why analysis. As shown in Figure 8, the results of this work were organized and recorded in the form of a cause-and-effect diagram (Kenett 2007). Potential root causes are listed in this diagram within categories that included machines (i.e., equipment), methods (i.e., how work is done), environment (i.e., buildings, logistics, space, etc.), materials (i.e., components, raw materials, etc.), measurement (i.e., calibration and data collection), and people (i.e., human elements). The way Figure 8 is structured indicates that, for example, one potential cause of high butt weld repair rate for La Porte projects that are due to the environment is the weather (listed in the upper right of the diagram). Various aspects of the weather, such as humidity, temperature, rain, or wind, could affect the quality of the welds performed at job sites. Specifically, improper wind breaks is a potential cause that explains how wind/weather may lead to weld repairs. The items in Figure 8 that are circled will be explained further in the Analyze phase of the project. The potential causes of weld repairs together with the steps of the welding process, shown previously in Figure 2, were used to further investigate the causes of defective welds.

Failure mode and effects analysis, or FMEA, is a well-known method for identifying and prioritizing potential failures (i.e., problems) in an existing process (Stamatis 2003). In this project, FMEA was used to analyze the process in order to determine the types of problems that could occur during the welding process for each process step. Using standardized 10-point rating scales from Tague (2005), the following were evaluated: (1) the severity of the effects of each problem, where 10 represents a catastrophic event and 1 represents an issue that is not noticeable to the customer; (2) the occurrence of potential causes of the problem, where 10 represents that the cause is almost certain to occur and 1 represents that it is highly unlikely the cause will occur; and (3) the ability of the current controls to detect whether a problem has occurred, where 10 represents that the control is nearly certain not to detect the problem/no controls and 1 represents that the control is almost certain to detect the problem. The issues identified through FMEA were prioritized based on their risk priority number, or RPN (i.e., the product of the ratings for severity, occurrence, and detection), in order to determine which problems represent the highest risk of failure (i.e., highest risk of causing defective welds). A portion of the FMEA for this project is shown in Table 1 for the items with the highest RPN. These items are related to the process steps denoted in gray in Figure 2 and the potential causes circled in Figure 8,

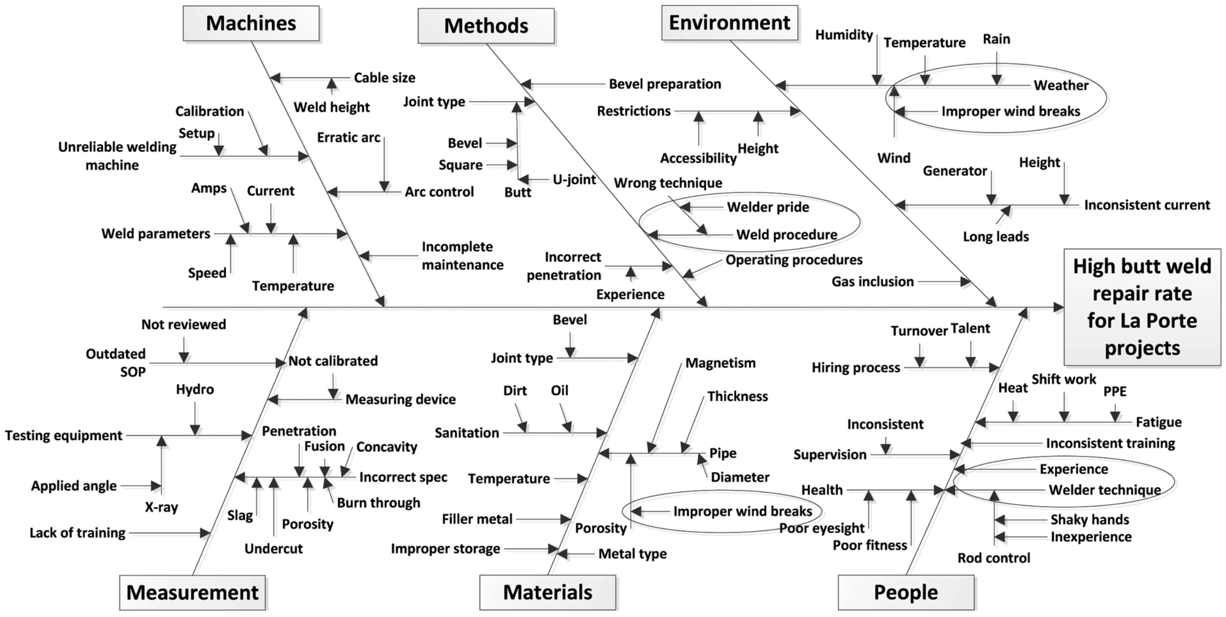


FIGURE 8 Potential causes of defective welds (items circled are associated with the root causes identified in Figure 10).

TABLE 1 **FMEA Items with the Highest RPN (i.e., root causes)**

No.	Process step	Potential failure mode	Potential effect	Severity	Potential cause	Occurrence	Current control	Detection	RPN
1	Install wind shield	Wind penetrates windshield	Defects—porosity	8	Windshield incorrectly installed	8	Inspected by supervisor	7	448
2	Perform one weld pass	Performing weld pass incorrectly	Defects—porosity	8	Wind	8	Windshield	7	448
3	Perform one weld pass	Performing weld pass incorrectly	Defects—porosity	8	Incorrect welding current setting	8	Weld procedure given	8	512
4	Perform one weld pass	Performing weld pass incorrectly	Defects—porosity	8	Moisture	8	Preheat	7	448
5	Perform one weld pass	Performing weld pass incorrectly	Defects—lack of fusion	8	Incorrect welding current setting	8	Weld procedure given, hard to detect	6	384
6	Perform one weld pass	Performing weld pass incorrectly	Defects—lack of fusion	8	Incorrect electrode angle	5	Weld procedure given	8	320
7	Set up welding machine	Welding machine set up incorrectly	Defects	7	Inexperienced welder/human error	5	Weld procedure given	9	315

shown previously. The issues associated with the highest RPN were identified as the root causes of defective welds. The first two rows of the FMEA indicate that root cause 1 is related to wind/incorrect windshielding and the five additional rows included in Table 1 suggest that root cause 2 is related to the use of incorrect welding techniques/inexperienced welders.

Improve Phase

In the Improve phase, the project team conducted additional brainstorming sessions to develop potential solutions for the two root causes of defective welds identified previously through FMEA: (1) wind/incorrect windshielding and (2) use of incorrect welding techniques/inexperienced welders. Prioritization matrices were then used to evaluate the solution ideas for each root cause (Tague 2005). In these matrices, solution options are listed across the top row and the desired characteristics (developed by the project team) are given in the left-most column. Solution options are then evaluated based on how well the solution fulfills each of the desired characteristics. In this project, these evaluations were completed using a 1, 3, 9 scale, where 1 represents that the solution option does not fulfill the desired characteristic very well and 9 represents that that the solution option does fulfill the desired characteristic. The total score is calculated by summing the scores down each column of the matrix, and the solution(s) with the highest score represent the most beneficial solution(s). For this project, four solutions were identified for reducing defective welds. To reduce the wind impact on the welding process, inspecting windshields (solution C) and training welders how to use windshields (solution E) were the highest rated solutions, as illustrated in Figure 9. To improve welder performance, developing standard welder training (solution F) and implementing annual eyesight tests (solution H) were the highest rated solutions, as shown in Figure 10.

The four top-rated solution ideas developed in this project were presented to and approved by JVIC management for implementation at the La Porte division. For solution C, inspecting windshields, a field fabrication shop design standard was created for use during installation of windshields by a third-party scaffolding company at the client's project sites where welding activities take place. To reduce the wind impact on the welding process, the new design standard shows elements such as required fabrication shop bay widths, appropriate roof slope for adequate rain drainage, and desired shop location in regards to northern wind direction. In addition, JVIC distributed a field fabrication shop

Desired Characteristics	Solution Options (Ways to Reduce Wind Impact on Welding Process)				
	A. Secure Lead	B. Design Better Wind Shield	C. Inspect Wind Shield	D. Use Wind Gauge	E. Train Welders on Proper Installation of Wind Shields
Ease of Implementation	●	□	●	○	□
Cost Effectiveness	○	○	○	○	○
Impact on Process	□	●	●	○	●
Staff Efficiency	○	○	○	○	○
Customer Satisfaction	□	●	●	□	●
Total	**17**	**25**	**33**	**13**	**25**

Legend: □ = 1 ○ = 3 ● = 9

FIGURE 9 **Solutions to reduce wind impact.**

standard to the La Porte division quality control managers (QCMs). For solution E, QCMs also provided additional training for welders at their site on the proper installation of personal windshields, which referenced aspects of the field fabrication shop design standard for comparison purposes. To improve welder performance by developing standard welder training, solution F involved the creation of a "Welder University." This is an extensive training program that offers guidance to help welders adhere to good welding practices/techniques during the welding process, including practice with welding in restrictive position environments and other mock plant facilities, as depicted in Figure 11. Welders are trained through this program in groups of eight, and the current goal is for welders to complete this training in 10 weeks. Skill evaluations are performed to assess welders' competencies as a result of this program. Finally, solution H involved the implementation of annual eyesight tests for welders company-wide. This test verifies that all welders have vision accuracy of 20/30 or better in each eye, and welders have the option to obtain corrected vision (i.e., through the use of corrective lenses) to achieve this requirement.

Once these improvements were in place for a several months, data were collected to quantify the degree of improvement achieved through this project. As shown in Figure 12, the butt weld repair rates per project for projects performed by the La Porte division from October 2011 to April 2012 ranged from zero to 26%. On average, this

Desired Characteristics	Solution Options (Ways to Improve Welder Performance)				
	F. Develop Standard Welder Training	G. Improve Welder Classification Levels	H. Implement Annual Eye Sight Test	I. Improve Welder Allocations to Projects	J. Provide Welders with Weld Parameter Check Sheet
Ease of Implementation	□	□	●	○	○
Cost Effectiveness	●	○	○	●	●
Impact on Process	●	○	○	○	○
Staff Efficiency	○	●	●	●	□
Customer Satisfaction	●	○	○	□	●
Total	**31**	**19**	**27**	**25**	**25**

Legend: □ = 1 ○ = 3 ● = 9

FIGURE 10 **Solutions to improve welder performance.**

FIGURE 11 **Welder University mock facilities used for training.**

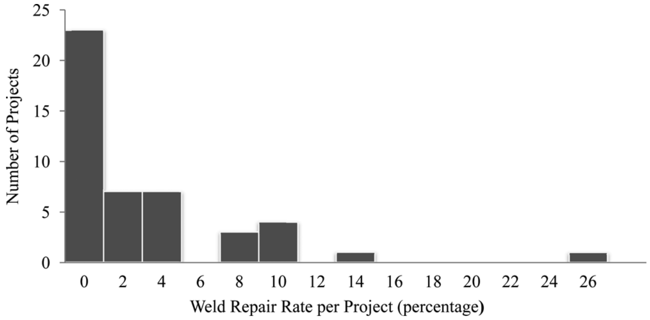


FIGURE 12 Improved process weld repair rate for the La Porte division.

division had a weld repair rate per project of 2.68% with a standard deviation of 4.78%. This result is approximately 1% less than the baseline measurement for the project established previously at 3.66% (see Figure 5), and it is below the original project goal of 2.75%. The improvements made as a result of this project generated an annual savings of $90,000 from direct labor costs for JVIC. Further revenue may be generated as a result of this project through continued business for JVIC from current customers and other potential new business.

Control Phase

During the Control phase, the project team created a plan to sustain the gains made through the project. The control plan for the project included (1) documenting the improvements made to the process, (2) training employees to properly perform the improved process, (3) monitoring the performance of the improved process, and (4) auditing aspects of the improved process to ensure it is performed properly. JVIC's corporate policies and procedures were revised/established to reflect the improvements made as a result of this project. These changes include requiring the use of field fabrication shop design standards for installing windshields at project sites, training welders on the use of personal windshields and on proper welding techniques through Welder University, and annual eyesight tests for welders company-wide.

To monitor performance related to some of the improvements made, the time to complete Welder University will be tracked by JVIC using a run chart, as shown in Figure 13. The current goal is for welders to complete this training in 10 weeks, but this will be adjusted if it is found that welders need more/less time to complete the training. Welders' performance on the skill evaluations administered as part of Welder University is also being monitored, as depicted in Figure 14. The goal is for all eight welders in a group to pass the evaluations with a minimum of six passing; however, if the pass rate drops below six, this will set off an action alarm that will cause the Quality Control Department to launch a root cause investigation to determine the underlying cause of the problem and correct it. Finally, the weld repair rate for welders who have and have not completed Welder University will be tracked using a run chart as illustrated in Figure 15, where the goal is for the weld repair ratio to be 2% or less. The benefits of tracking performance in this manner are twofold. First, JVIC can actively monitoring welder performance, which will enable them to take action to continue to improve welder performance as along as the weld repair ratio is less than 2%. Second, this run chart provides JVIC with measures that offer some indication of the impact that the Welder University training may have on welder performance.

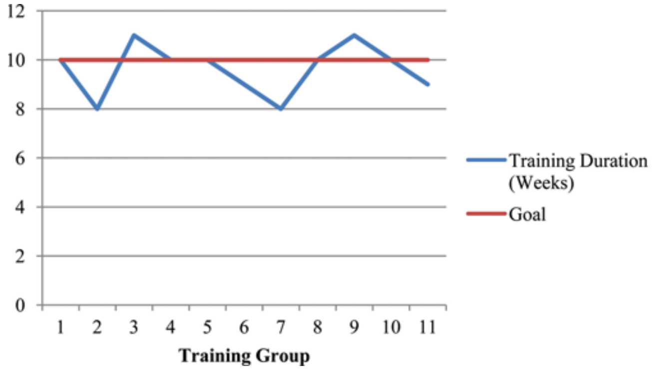


FIGURE 13 Welder University duration tracking.

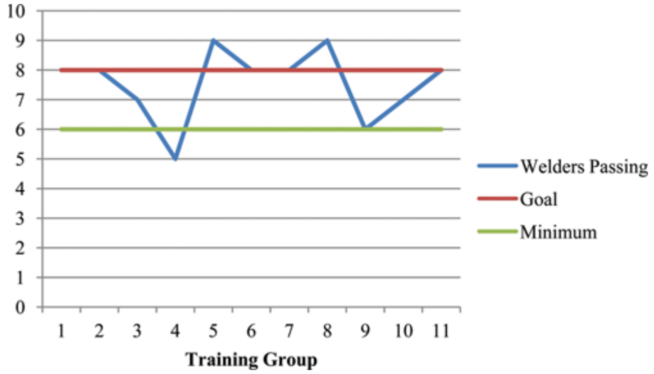


FIGURE 14 Welder University pass rate tracking.

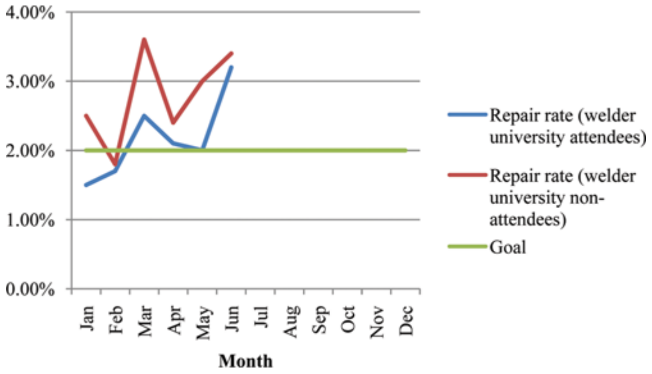
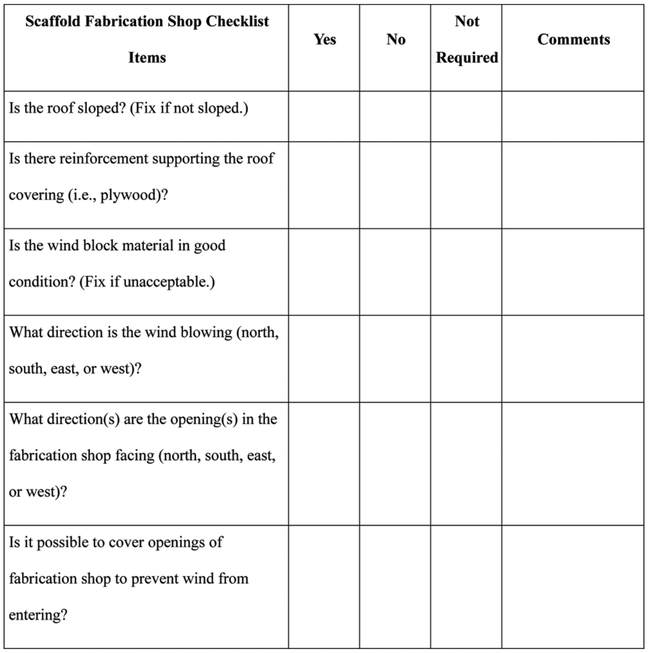


FIGURE 15 **Welder performance tracking.**

Finally, to audit some aspects of the improved process, QCMs were tasked with periodically conducting a visual inspection of the field fabrication shop constructed by the third-party scaffolding company at their project sites. The checklist shown in Figure 16 was developed to assist with these audits. This checklist contains items listed in the design standards that QCMs must check for compliance. Adherence to each item will depend on the client's specific project requirements, environmental conditions, and location of the fabrication shop site. In some cases, JVIC does not have control of the location of the fabrication shop because the client has strict space limitations at the project site.



Scaffold Fabrication Shop Checklist Items	Yes	No	Not Required	Comments
Is the roof sloped? (Fix if not sloped.)				
Is there reinforcement supporting the roof covering (i.e., plywood)?				
Is the wind block material in good condition? (Fix if unacceptable.)				
What direction is the wind blowing (north, south, east, or west)?				
What direction(s) are the opening(s) in the fabrication shop facing (north, south, east, or west)?				
Is it possible to cover openings of fabrication shop to prevent wind from entering?				

FIGURE 16 **Field fabrication shop checklist.**

CONCLUSION

This case study demonstrates how the Lean Six Sigma methodology can be applied successfully in the turnaround industry to address issues such as reducing defective welds. The use of an action research approach helped the project team reflect on what was discovered in each phase of the project and use what they learned to guide the next step of the project. Using this approach, this project achieved a substantial reduction in the weld repair rate as a result of the solutions implemented to reduce the wind impact on the welding process and improve welder performance. By implementing windshield standards, training welders through Welder University, and instituting eyesight tests for welders company-wide, the weld repair rate decreased by more than 25%, which translated into a savings of $90,000 for this company.

As a result of this project, JVIC will request third-party scaffolding companies at project sites to use the field fabrication shop design standard and accompanying checklist. They will also implement the Welder University training program across all divisions within the organization. Hence, the horizontal deployment of solutions developed through this project across the organization is likely to generate additional financial savings/revenue for JVIC in the future. JVIC also plans to continue improving the welding and other related processes to obtain additional benefits. For example, based on the Lean case study described by Garrett and Lee (2011) that achieved measurable improvements in process cycle time using electronic paperwork, JVIC may wish to convert their field fabrication shop checklist into an online form.

During the course of this project there were a few factors noted that may have affected the outcome of this study. Though the researchers were intimately involved in this project from beginning to end, they had little input regarding the specific focus of this study. As is typical in action research projects, the company selected the problem they wanted help to solve (Schein 2008). In addition, some members of the project team may have had preconceived notions about solutions to the problem being investigated. It is not uncommon for those involved in structured problem-solving efforts to jump to solutions at the start of a project, especially if they are new to formal, analytical approaches to problem solving and/or their previous experience has mostly involved firefighting/quick fixes (Bohn 2000; Hughes 2003). In this case, however, the use of Lean Six Sigma may have helped those involved in the project understand and analyze the problem thoroughly so they could implement appropriate solutions (MacDuffie 1997; Tucker et al. 2002). Finally, a limitation to this research is that this study was conducted at only one company. Hence, further research is needed to confirm whether the use of the Lean Six Sigma methodology could generate similar benefits for other service providers, especially in specialty construction applications.

Despite these limitations, this research provides an example of how one specialty construction company used the Lean Six Sigma methodology to reduce the occurrence of a problem that traditionally contributes to budget overruns and schedule delays in turnaround projects (Casinelli 2005). This study was important for this organization due to the financial losses that resulted from not strictly adhering to the project quality and schedule performance required by their customers. As a result of this project, however, JVIC was able to improve the performance of their welding process, which facilitates the retention of current customers and the acquisition of new business in the future (Chatterjee et al. 2002). The positive impact to JVIC from the successful use of the Lean Six Sigma approach suggests that other specialty construction companies may benefit in the future by conducting similar process improvement projects.

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