

AUTHOR'S ORIGINAL VERSION

Submitted to **Journal of Advanced Manufacturing Systems (World Scientific)**

Evaluating Lean Six Sigma Tools for Welding Engineering Applications: An Engineering Perspective

Divyansh Srivastava¹, Utkarsh Chadha^{2*}, Ashrita Samantula², Pratyush Prakash³, Arshdeep Kaur², Molly Code², Gaurav Chhablani³, Sakshi Santosh Kumbhar³, Girish Yemul³, Vezhavendhan R³, Won-Chol Yang⁴

¹Technische Universitat Darmstadt, Darmstadt, Germany

²University of Toronto, Toronto, Ontario, Canada M5S E34

³Vellore Institute of Technology, Vellore, Tamilnadu, India – 632014.

⁴Faculty of Materials Science and Technology, Kim Chaek University of Technology, 60 Kyogu, Pyongyang, Democratic People's Republic of Korea

*Corresponding: utkarshchadha1302@gmail.com

Abstract. The Lean Six Sigma (LSS) Framework is a strategic approach to managing waste, reducing inefficiencies, and optimizing manufacturing processes, including those in welding. Its effectiveness lies in its ability to focus on minimizing waste and precisely directing processes. As industrialization progresses, it often leads to the depletion of natural resources such as water and land. Many welding industries have yet to fully implement effective waste control and process regulation strategies. This review explores how the LSS methodology can address and mitigate defects in industrial welding processes. Central to LSS is the DMAIC principle (Define, Measure, Analyze, Improve, and Control), which transforms problem-solving into a structured process with specific milestones to track progress. DMAIC has been widely applied in research for optimizing welding processes. This review examines how the LSS framework has been applied to welding processes, the improvements observed, and provides guidance on advancing sustainable welding practices.

Keywords: Lean Six Sigma; Welding; Manufacturing; Sustainable Practices;

1.0. Introduction

Welding is an intricate and prominent field of study most industrial applications rely on, being widely implemented within the industry. Welding processes in industries usually face issues or errors which can be solved on the ground level using current industry technologies. However, there is still a lack of mitigation strategies where Lean Six Sigma can actually help personnel follow a set of rules and guidelines to avoid errors and wastage during the process [1].

Lean Six Sigma (LSS), as shown in **Figure 1**, is a combination of 'Lean' emphasizing waste reduction, while 'Six Sigma' aims to reduce errors and defects. This synergy has revolutionized the manufacturing and welding industry, by not only quality and

waste, but also improving the operational conditions, constraints, or limitations of the process through the support of research [2-4].

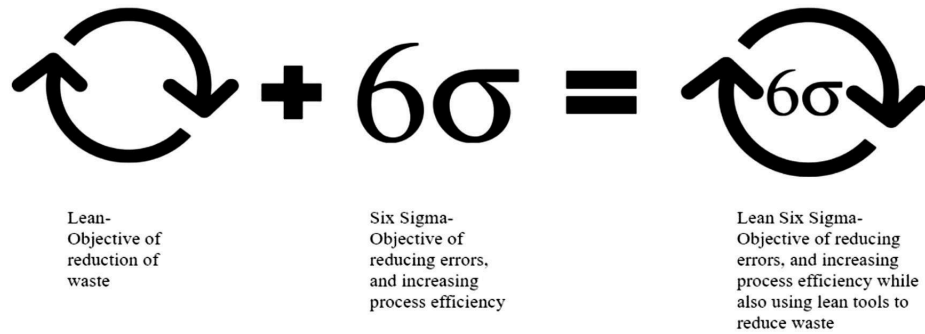


Figure 1. Lean Six Sigma [1]. *Adapted with Permission, © Elsevier B.V.*

Total quality management is adopted in the welding process to increase the efficiency and performance of the final welded materials at the industrial level. It has principles, rules, & regulations for standard and essential operations inside the industrial manufacturing process. Six Sigma is a six-level mechanism and system utilized to improve output efficiency. It is used to manufacture vital products and design processes to increase the reliability and compatibility of products at an industrial scale [5, 6]. The main objective behind Six Sigma practice in companies and industries is to improve manufacturing quality and efficiency to meet customers' demands and satisfaction. This process also helps minimize defects and directly impacts the failure of products at different testing phases and situations. This technology uses emphatical and statistical techniques for quality management and to reduce the multiple variabilities in production and regular business development processes. Additionally, the technology is famous for statistical modeling development and the growth of advanced materials manufacturing processes. Six Sigma technology requires a quality check that tests the Defects Per Million Opportunities (DPMO) for the betterment of the product to further show the long-term defects, problems and hazards that may occur in the future [5-7].

The DPMO calculates the level of variability and defects in the manufacturing product in ideology, basic design, and the product development phase. This process helps achieve quality improvement in a sustainable manner that requires commitment from working employees, companies, and organizations [5, 7]. The phenomena are known as LSS methodologies on the extensive use of Six Sigma in some groups or a particular bunch. It is a process in which every integral member's collective team effort, participation, and proper contribution must improve and make something performance efficient [1, 6]. This process depends upon the team effort and full participation of every member because the target is not achievable by a single or some members in the group. It only looks more realistic and achievable if it gets effort from every vital member [8-10]. All of the welding processes are an industrial-level complex work function, so the head of the team and the company's higher-level members always choose LSS methodologies in which they form many teams and assign them small pieces of the leading project plan so that on completion of small projects and their proper integration makes the main project half-way done and it gets

centralized by this step. Adopting the LSS methodology is that it distributes welding processes uniformly and gets the work done at a remarkably improving rate. This step also reduces variability in basic DMAIC and business plans, increasing the overall efficiency of manufacturing products [11-14].

This review provides insight into LSS implementation in welding processes and how such processes are impacted. Additionally, this study focuses on case studies in academia and the industry that have implemented Lean Six Sigma, and emphasize specific LSS tools that have been implemented in welding research.

2.0. Problems Associated With Welding Engineering

This section expands on the issues within the welding processes, associated standards, design and process challenges, human safety and workplace related concerns and costs. These factors then converge into the main argument of why Lean Six Sigma (LSS) is crucial and is the missing tool to be incorporated for a close-to-ideal output of the process while simultaneously reducing the inconveniences [15-17].

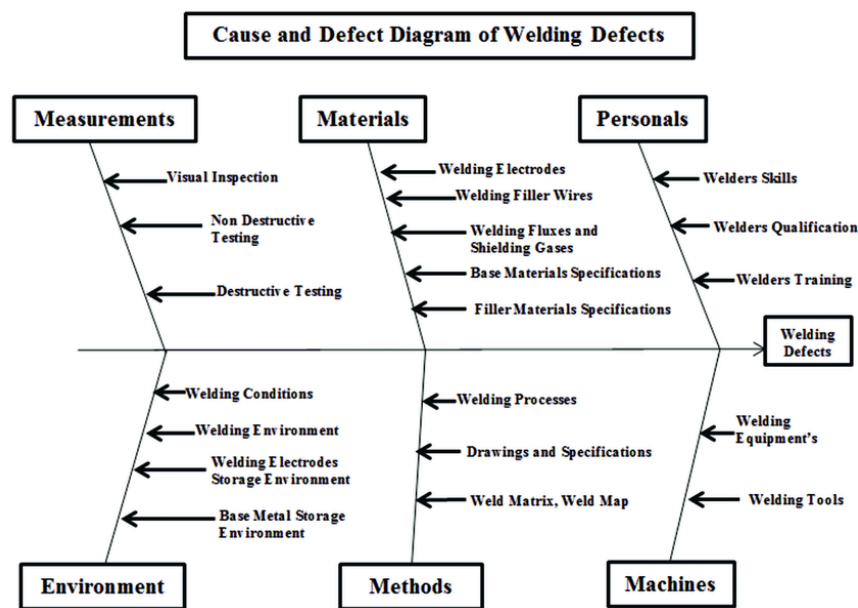


Figure 2. Cause and Effect Diagram of Problems Associated with Welding Engineering [17].

Figure 2 shows a fishbone diagram with the categorized causes of welding defects and problems associated with welding engineering as discussed above. The problems can be overarchingly categorized into design & problem challenges, human & safety challenges and cost & efficiency challenges. The challenges further have root causes which can be targeted and mitigated with the implementation of LSS methodologies, reducing welding defects to an ideal minimum.

2.1. Welding Defects

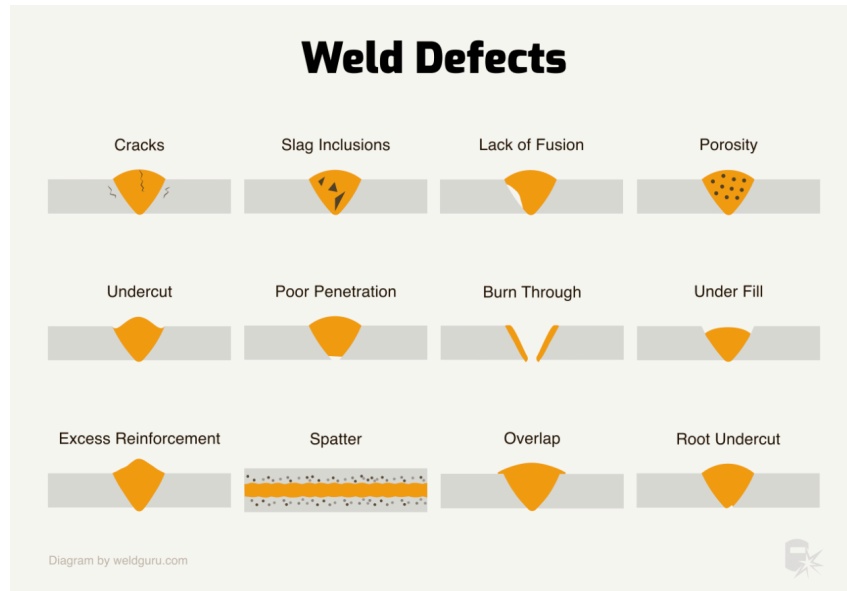


Figure 3. Common types of welding defects. *Image Credits:* <https://weldguru.com/common-welding-defects> [16].

Weld defects are faults and discontinuities in weld joints which can compromise joint strength, degrade manufacturing quality and compromise intended function, overall resulting in weld failure. Defects are common and inevitable occurrences in all welds and may be accepted or rejected in industrial practices, depending on three factors: type, size and location. It is when these discontinuities exceed their appropriate acceptance standards, that they become a true defect and make the weld unsuitable for use [15]. These defects can be classified as internal or external and have a variety of causes which include improper arc voltage, inconsistent weld speed, and overall poor welding skills [15]. Common welding defects are shown above in **Figure 3**. Internal defects are those which are invisible to the eye and occur in the base metal and grow rapidly, worsening the material over time. Cracks, Slags, Poor Penetration, and Lack of Fusion, as depicted in **Figure 3**, are classifications of internal defects that significantly weaken the welds. There are three main types of cracks; Longitudinal cracks - running parallel to the weld, Transverse cracks – along the width of a bead, and Crater cracks – often formed at the end of welds when arcs are terminated [17]. Slags involve impure welds with non-metallic materials trapped inside the weld; they commonly occur in flux-related processes, and form in brazing, stick, flux-cored, and submerged arc welding [17]. Poor penetration is when the weld fails to extend through the full depth of the joint, which occurs when weld beads do not fully penetrate the bottom of butt joints [17]. A lack of fusion results when the filler material does not bond properly with the base metal, further leading to structural weaknesses such as voids and gaps [17].

Contrarily, external defects are those which can be detected visually, or with surface based methods. Porosity, Undercut, Burn-Through, Under-Fill, Excess Reinforcement, Spatter, and Overlap are classifications of external defects, as shown in **Figure 3**. These defects make the materials more prone to cracks and failures, causing significant risk to structural integrity [17]. Porosity occurs when gas bubbles become trapped inside the weld bead, weakening the joint and impacting the weld's durability. Undercuts arise where grooves run along the toe of the weld [17]. Burn-Throughs are the result of excessive heat creating holes in metal that ruin the joint. Underfills are formed when the weld bead is lying below the surface of the base metal, while excess reinforcement is the occurrence of too much filler material in the weld [17].

2.1.1 Standards and Classifications of Welding Defects

The International Organization for Standardization (ISO) has multiple standards pertaining to common metals and alloys used in welding processes. These welding standards include ISO 5871 which assesses criteria for fusion-welded joints [18], and ISO 10042 which contains assessment criteria for arc-welded joints [19]. These standards are used to measure the degree of imperfections and defects a weld can possess before it is deemed unsafe. Additionally, these ISO standards sort welds into categories of B, C, and D, based on the amount and severity of defects detected within a certain area. Welds that are categorized as B-Level welds are of the highest quality, deemed as the minimal amount of defects [18].

2.2 Design & Process Challenges

Welding engineering may face challenges related to design and manufacturing processes which hinder the overall output and efficiency of production. Design problems are the ones that originate in the design of the product and impede on the result or efficiency of the welding process. They include joint design, weld accessibility, residual stress and distortion, incorrect material selection and metallurgical incompatibility [20]. Due to various physical phenomena, there must be a comprehensive understanding of design to effectively weld for design effectiveness. Joint design can pose challenges, as a poorly designed joint can lead to the failure of a product and inability to carry a load. Distortion of materials is experienced due to high temperatures and state change of materials and can create unexpected errors in the design. Welding parameters can be adjusted and optimized in order to reduce the distortion to a minimum [21]. Incorrect material selection and metallurgical incompatibility can compromise the integrity of a weld as materials are becoming more complex in their compositions and thus, a complete understanding of their functionalities and properties is required. The materials must be precisely selected to enhance their application in a manufacturing process and reduce inefficiency [22].

Process challenges originate in the process and can include equipment malfunction or inconsistencies, bottlenecks and improper heat input. Equipment malfunction halts process and production at a macroscopic scale and is a systematic error within welding engineering. This can lead to consistent issues common to all products of the process requiring a consistent maintenance of equipment and proactive detection. Process bottlenecks result from inefficiency during crucial stages, slowing down the

whole manufacturing process. Overall process reviews must be held immediately at detection of any inconsistencies to mitigate the effect of bottlenecks and production wastage [23].

2.3 Human & Safety Challenges

Welding processes may sometimes pose a safety hazard for the operators. Specific hazards include fume and gas exposure, electric shock and fire or explosion risks [24]. Due to the nature of welding activities, the risks are unavoidable but must be reduced through use of personal protective equipment (PPE), comprehensive personnel training and secure workplaces. Additionally, human involvement in manufacturing inevitably poses challenges due to human error, lack of sufficient training, fatigue leading to inconsistencies and non-compliance to procedures or standards [25, 26]. Inconsistencies and errors result in inefficient production and waste of materials and time due to defective products. Similar to risk mitigation, personnel training and appropriate work conditions is a priority to reduce human error.

2.4 Cost & Efficiency Challenges

Welding engineering faces quality limitations due to cost and efficiency as a result of prioritizations that must be made during manufacturing and design. Specific issues entail material cost versus quality, overwelding and ineffective quality assurance. Materials must balance both quality and cost to maximize effectiveness, possibly resulting in one being compromised for the other. This may result in drawbacks in budget allocation or quality of the final product. Overwelding is the overuse of time and materials in welds which are greater than required for the load of the product. Overwelding can allow for overloading of the product but can also be a wastage of materials increasing costs of production. According to a report from American Institute of Steel Construction's (AISC) from 2011, it claims that compared to a ¼-inch weld, a 5/16-inch fillet would consume 56% more metal. This leads to more metal-related costs and consumption, while also simultaneously increasing the labour costs for comparatively minimal benefits [27, 28]. Quality may be diminished during manufacturing as a result of the limitations of non-destructive testing (NDT). While limiting wastage, NDT can compromise the integrity of the output of a manufacturing process due to an incomplete detection of issues and lack of ultimate stress testing of the welded product [29-31].

2.5. What is the Need for LSS in Welding Engineering?

Lean manufacturing strives to reduce waste in eight key areas of manufacturing processes: defects, excess processing, overproduction, wait time, inventory, transportation, motion, non-utilized talent and skills [32]. Six Sigma's implementation in manufacturing processes utilizes teams that are assigned a well-defined project and problem. The team is trained in statistical thinking, and practices the DMAIC approach. The management environment is conducive to supporting these aforementioned initiatives [33]. Combining Lean manufacturing with the data driven Six Sigma strategies, the goal is a preventative approach to reduce the possibility for occurrence of defects and challenges, as opposed to traditional methods of defect

detection. LSS strategies could prevent these challenges from hindering an entire project, and allow for the project to reach the client with reduced time and cost [34].

ISO standards combined with having trained employees implementing these standards, align with the Six Sigma approach to welding. Equipping the highly trained employees for both high quality welds and immediate detection of errors, reflects the lean approach to welding. The integration of both approaches reduces manufacturing waste and increases quality production.

3.0. Understanding LSS Tools & Their Relevance for Welding Engineering

3.1 DMAIC

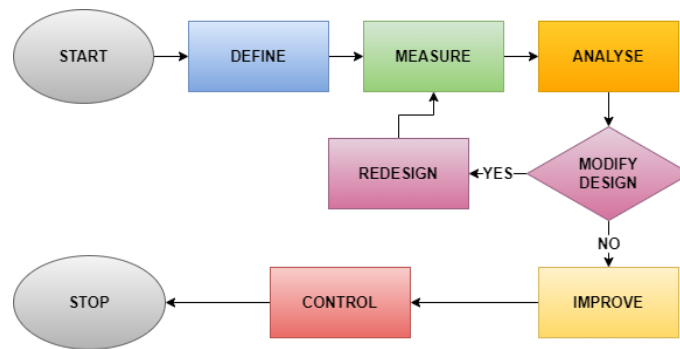


Figure 4. Flow of a generic DMAIC Process.

DMAIC, which stands for Define, Measure, Analyse, Improve & Control, is one of the most commonly used Six Sigma tools in welding (Figure 4). DMAIC is a methodology in LSS used to improve processes by identifying a problem or improvement opportunity. It can be specifically applied in welding engineering and can be explained in the following manner: The Define step consists of identifying a problem and an opportunity for improvement within a process. The issues in the welding process are initially identified, the personnel, after identifying the issues, must define a goal, i.e., reduction of welding defects by a certain percentage. The scope is defined to cater to the problem, avoid scope creep (unexpected deviation from the goal), and further involve the stakeholders from the initial step and transmit the progress information [35]. The measurement stage involves quantifying variables within the problem to be able to track progress and improvement and allow for detailed documentation. Baseline data must be collected and a measurement system must be standardized to maintain consistent data collection and analysis [36]. The next step, Analysis, is when root cause analysis is conducted, where the welding issues are detected, for example, operator skills, material issues, equipment settings or any calculation errors, etc., are accounted for. The problem is tracked back to the origin so it can be mitigated from a base level and the application of DMAIC can be sustainable [37]. The next step is improvement, the step where solutions are developed to eliminate or mitigate the root cause of the issue. The welding process

should be assessed for possible improvements, for which research work is conducted, and a new change or a new model is proposed accordingly. Further, the proposed idea is tested in multiple iterations before officially being implemented to test its commercial and technical viability. Once tested successfully, and if it is viable, the team must develop a plan to incorporate the new welding innovations throughout [38]. The final step is Control, once the improved model is approved and implemented, its performance and modifications should be documented to set a standard for the personnel to follow. Monitoring of this new, improved process is required to study the performance and utilize a benchmark study to compare the resulting outcomes for an opportunity to improve the process further. The improved process must be maintained, controlled and possibly improved once again if required [39]. Cases of DMAIC implementation are discussed below in Section 4.

3.2 The 5S (Sort, Set in order, Shine, Standardize, Sustain) Methodology

The 5S methodology is a workplace organization methodology, derived from the Japanese words for the acronym. The 5S method can be used to aid in continuous development and improvement of the welding process [40, 41]. The 5S method focuses on the workplace with a specific philosophy; if the workplace is well established, and workers are trained to follow the appropriate checklists and order of events, the likelihood of weld defects is significantly reduced [41]. **Figure 5** shows the application of the 5S process in Electric Arc Welding. The 5S methodology requires continuous review and improvement as shown in the flow chart.

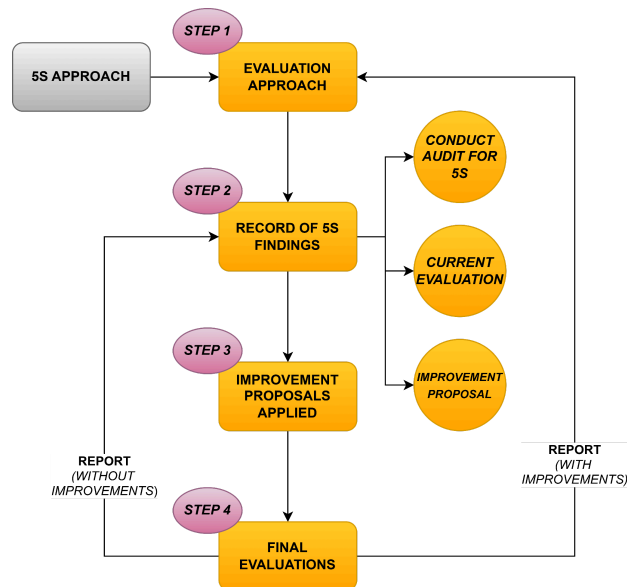


Figure 5. 5S Approach for Electric Arc Welding Process. *Adapted and Recreated from [41].*

The 5S methodology applies directly to the Lean aspect of LSS and aims to standardize the workplace. Seiri (Sort) pertains to eliminating unnecessary items in

the workplace. Seiton (Set in Order) refers to organizing necessary items so they are easy to find and use. Seiso (Shine) refers to the idea of cleaning the work area and equipment to maintain a safe, efficient environment and workplace. Seiketsu (Standardize) is the idea that routines and standards must be developed to maintain the first three steps of 5S. Finally, Shitsuke (Sustain) pertains to maintaining 5S as a habit within the workplace by training and discipline to ensure long-term use. **Table 1** addresses 5S's relevance to welding engineering in specific.

Table 1. 5S Relevance to Welding Engineering.

5S Process	Application [41]	Example 1 [40]	Example 2 [40]
Sort (Seiri)	Divide goods, material, and equipment based on requirements of welding team and facility	Disposing of items that are damaged and non-reusable	Organizing and returning misplaced items
Set in Order (Seiton)	Desired tools and goods are organized for efficient access	Safety items must be stored in an easily accessible space in case of emergency	Organize items based on frequency of use
Shine (Seiso)	Maintain cleanliness and hygiene in the work environment	Clean machines based on a predetermined schedule and checklist	Workplace and floors must be cleaned daily
Standardize (Seiketsu)	Ensure all steps (sort, set in order and shine) are regularly followed	Audit workers to ensure all steps are being followed	Educate workers on the standards of the 5S methodology
Sustain (Shitsuke)	Create a manageable 5S process that is sustainable for leaders and workers to follow	Leaders should center company values around 5S philosophy	Workers should have clear understanding of 5S and eagerness to uphold 5S principles

Implementing the 5S Philosophy ultimately optimizes the space and time of welding processes. Goods can be rearranged and grouped based on size and characteristics, ensuring that equipment is kept in correct order, and safety kits are placed in accessible areas. The reduction of searching, waiting and excess activities can improve the utilization of time and space during welding processes as well.

3.3 Value Stream Mapping (VSM)

Value Stream Mapping (VSM) is a Lean Engineering Tool which helps solidify understanding of the problem, the solution, and the path to get there. It is a visual tool used to visualize and analyze the flow of materials and information needed to bring a product from start to finish. It is essential to identify problems such as waste, bottlenecks and areas for improvement in a production process. It is useful to be implemented in the Define and Control steps of DMAIC. **Figure 6** is an example of a VSM diagram which highlights the relationship between material and information flow. Additionally, **Figure 6** also depicts the process starting from material collection, welding, assembly, finishing, to checking and supplying the project to the client [42, 43].

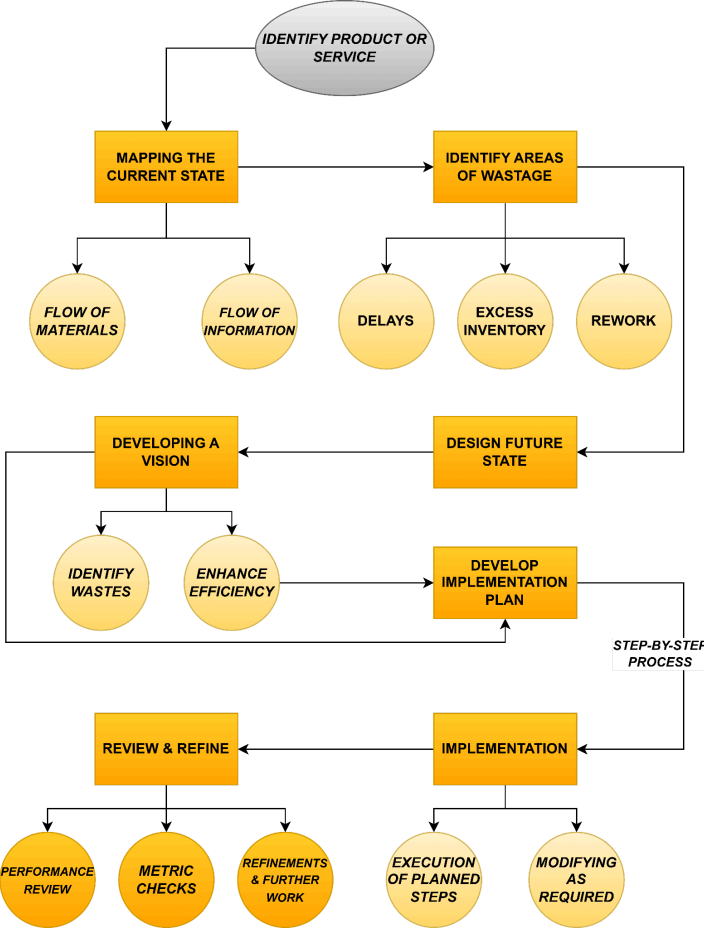


Figure 6. Value Stream Mapping for Welding.

The key components of a VSM diagram are the process steps, boxes to show actions within the process. Next are material flows which can be depicted as arrows to show the movement of parts in the process. Similarly, information flow is also depicted to show how scheduling, orders and data required in manufacturing are handled. The VSM diagram flows with time to highlight the cycle time, wait time and lead time that steps have in the process. Metrics must be denoted throughout the diagram for the

visual to be impactful and usable for process improvement. More data can be collected, such as the number of operators, available working time per shift, actual machine working time, and time taken to switch between producing products. Based on these inputs, several lean measurements such as lead time are taken, which involve the times taken by each part to move from starting to finishing processes [43, 44].

Table X: Relevance of VSM to Welding Engineering

VSM Functions	Applications in Welding	Benefits	Ref
Identifying Value-Added and Non-Value-Added activities	This allows for issues and inefficiencies to be identified and highlighted. Value adding time is also calculated which involves the actual time involved during the welding process which includes value added activities. The unnecessary waiting times may be identified and reduced by cross team collaboration amongst different departments to ensure that each worker is able to contribute adequately.	The unnecessary waiting times may be identified and reduced by cross team collaboration amongst different departments to ensure that each worker is able to contribute adequately. Welding process time will be reduced.	[44-46]
Reduces Defects and Rework	Pinpoints where weld defects are most likely to occur and enables improvements in inspection and quality checkpoints.	Costs of overproduction and waste will be cut down. Reworking and wasted time will also be reduced. Overall increasing yield percent and efficiency.	[47, 48]
Improves Material Flow	Maps how materials move between stations and can help visualize changes to improve material flow. Can suggest rearranging layout to reduce travel time and increase efficiency.	Will reduce travel time as well as effort required by employees to transfer material with better workplace layouts.	[49]
Visualizes Bottlenecks	Welding often gets bottlenecks due to equipment downtime or limited skilled labour. VSM makes it clear where delays	Increases efficiency and prevents slow points in processes before they can become a problem	[50]

	are and why they are happening.		
--	---------------------------------	--	--

3.4 Root Cause Analysis (RCA)

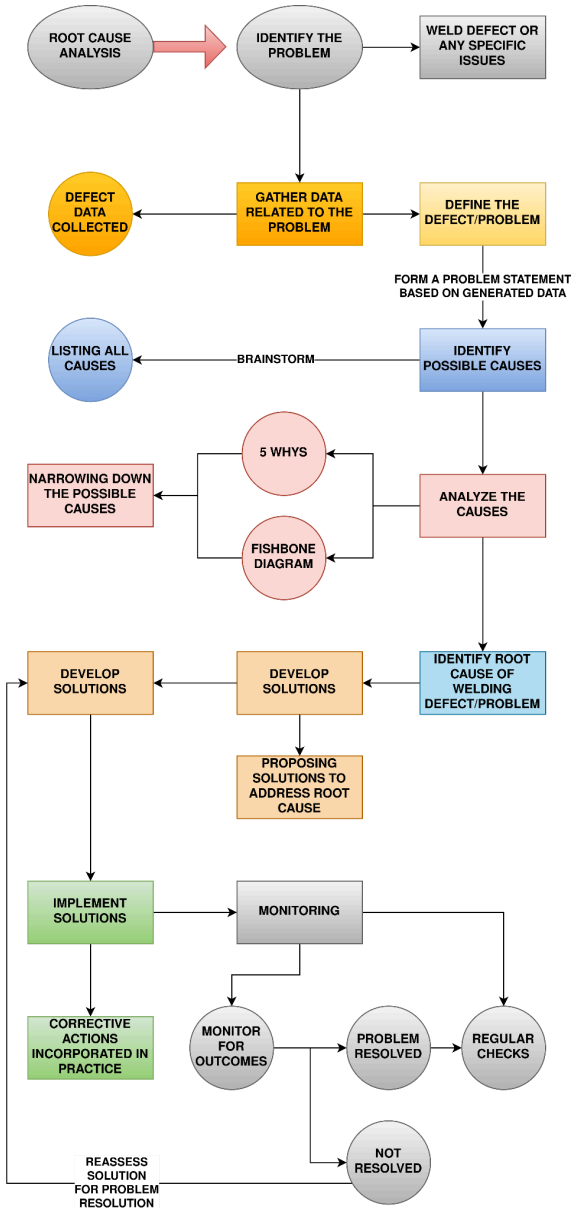


Figure 7. Root Cause Analysis for Welding.

Root Cause Analysis (**Figure 7**) is a problem-solving technique used to identify and mitigate the underlying causes of a problem rather than solving the resulting issues. In LSS and quality management, RCA ensures that corrective actions eliminate the source of the issue to prevent reoccurrence. This technique helps to find out the primary cause or the root cause of the problem occurring during the welding process. Symptoms of the root cause can include the defects in the joints, insufficient power supply & material flow, deposition of material, metallurgical properties of the material, atmospheric conditions, etc. According to **Figure 7**, firstly, the symptoms are checked to identify what kind of problem is occurring and a sufficient amount of data is collected to see the impact caused due to these problems. The below mentioned flowchart represents the workflow of this technique. The resulting problems are investigated using different tools to identify and analyze the root cause of the problem such as '5 Whys', Fishbone diagram (Cause & Effect Diagram), also known as Ishikawa diagram. These tools help to identify the technical parameters such as welding current, electrode design, amount of shielding gas, gap between the welding rod and metal piece, surface finish of the material, microstructural properties of the material, cooling time, etc. responsible for the welding defects and failure [51, 52]. Said parameters can be identified as problems and changed to optimize the process.

The Cause & Effect Diagram is an analytical tool and one of the seven quality control techniques which takes into account variations caused during the welding process and its parameters. This diagram can be plotted for various welding defects such as cracks, undercut, porosity, lack of penetration, excessive penetration, etc in the welding process. It is to understand which are the major defects occurring during welding and why as well as the parameters associated with it such as coating of electrodes with flux, size of electrodes, welding speed, shape of the plasma arc etc. The defects can be further analyzed by determining its causes such as problems occurring in machines, not using standard methods, faulty tools, inexperienced labors, man-made errors, measurement tools are not accurate, human fatigue, unclean area, incorrect welding parameters etc [53, 54]. Subsequently, appropriate solutions can be produced for these root causes, when discovered.

This type of statistical and investigative analysis can help the organization to further achieve high quality and reliable products meeting quality standards and customer demands. It can eliminate or reduce the deviations caused in the process by collecting and analyzing data and making sure that the cost involved is minimized. Identifying a problem at the root will mitigate the multitude of resulting problems and the overcoat and waste of the process. Due to this approach the welding process can also be redesigned and optimized based on the problem. '5 Why' approach can also be used as a brainstorming approach to find the appropriate root cause of the problem and further suggest ideas to prevent it. These solutions can then be monitored on a consistent basis to check whether the problem is resolved or not. This Lean Six Sigma framework takes into account the limitations occurring during other techniques such as Non destructive testing, Numerical analysis, etc. and is much more cost effective and easy to use [55, 56].

This type of analysis is quite reliable and can be taken into account during early development stages too which will prevent any problem occurring in future. The basic

steps involved are to identify the issue, its factors and why these factors are caused along with its effects. The level of importance can also be given to each factor to determine its criticality and a mathematical relationship can be developed between the input and output parameters to get the optimum weld quality. Once the critical parameters are found out they can be further optimized for further development of the welding process, and simulation plus experimental techniques can be modified too for better correlation between them [57].

3.5 Control Charts

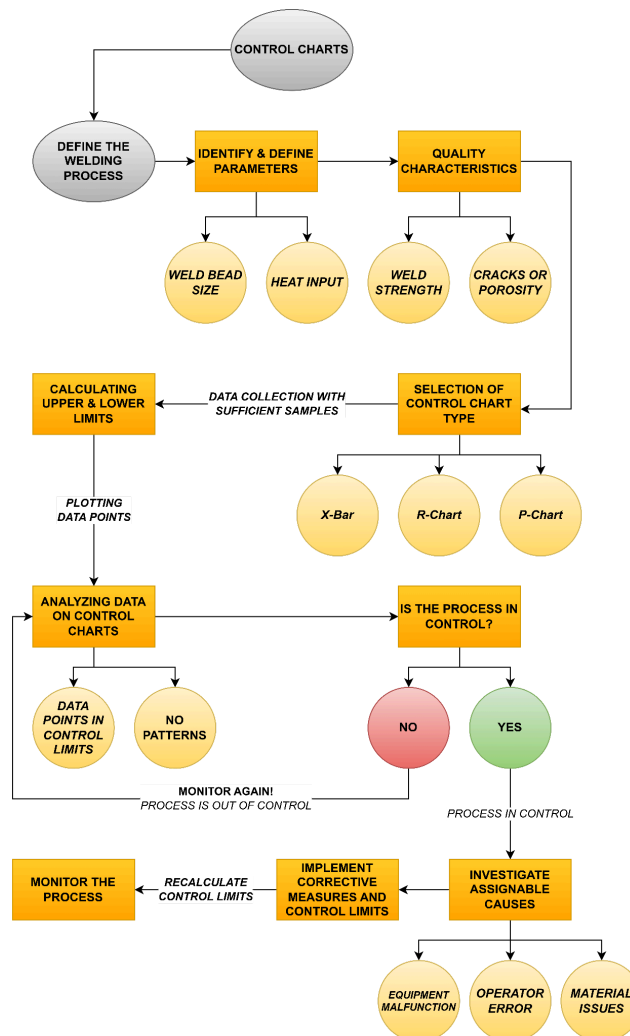


Figure 8. Control Charts in Generic Welding Engineering Scenario.

Control charts are used to visualize, control, measure and monitor the variations observed during the welding process, consistently helping to achieve proper quality welds (**Figure 8**). Control charts allow the visualization of fluctuations in a process and distinguish between natural fluctuations of a process and unusual fluctuations that

require intervention. Identifying these and intervening, enhances the stability of output for the process carried out. It is a statistical-based approach that plots graphs to visualize the variations observed in welding parameters, thus visualizing sources of defect. Productivity levels may be maintained as the mean, range and standard deviations are calculated and monitored over time for given welding parameters [58, 59].

The variations occurring during the welding process may be caused by natural occurrences such as environmental conditions, operators and material properties. Since the control limit values are defined for the same, the values plotted in the graph provide a sense of what process parameters are effective for welding arcs to ensure stability is achieved. This tool requires accurate and timely data collection. It is most useful when the process is not highly inconsistent and is stable. Operators must be trained to interpret and act on chart signals for ideal results. Furthermore, the welding process can be optimized through software such as Minitab, which is applicable for analysis and is cost-effective, thus saving large quantities of resources [60]. It becomes convenient to use these tools during quality inspection or checking of the welded joints of the product. If the sample points in the charts are falling outside of the control limits, this indicates that welding defects may be occurring. Generally, it is preferred to collect more data so that the results produced after analyzing them are more reliable. This technique may further prevent rework or repair action of welded parts as the problem occurring can be detected in the initial stage itself. Along with the X-bar, R charts for voltage and Moving Range, charts may also be plotted to check occurring process variations and their reasons due to which problem-solving steps can be made [61].

3.6 Failure Mode and Effects Analysis (FMEA)

Failure mode and Effect Analysis is a tool in LSS used to identify, prioritize, and prevent potential failures in a process, product or design before they occur. It is a structured approach which takes the following steps: first the possible failure modes must be predicted and identified. Subsequently the effects of each failure are analyzed. The causes and likelihood of occurrence are determined and finally actions will be taken to reduce risk. As shown in Figure 9, FMEA (Failure Modes & Effects Analysis) is an effective tool to note the potential problems and their occurrences in products. It indicates the severity of the problem alongside its motivating factors (i.e. current, voltage, weld speed) [62, 63].

The RPN, also known as Risk Priority Number, is calculated based on the severity of risk, occurrence and detection of the associated failures alongside the rating values given. The failure with the largest RPN value indicates the riskiest problem in the welding setup and is modified accordingly to meet safety standards [64-66]. The factors in the RPN, S, O and D, are ratings of severity, occurrence and detection on a scale of 1 to 10. Severity refers to the impact of the failure on the customer, occurrence is the likelihood of the failure occurring and detection is the likelihood of detecting the failure before it reaches the customer.

$$RPN = S(\text{severity}) \times O(\text{occurrence}) \times D(\text{detection})$$

The higher the RPN, the more urgent the need to address that failure. Solutions are developed from this tool to make more reliable welded products, by prioritizing risks and addressing them. By implementing these improvements in the development stages, further processes may be carried out at welding workshops and optimized process parameters to reduce defects.

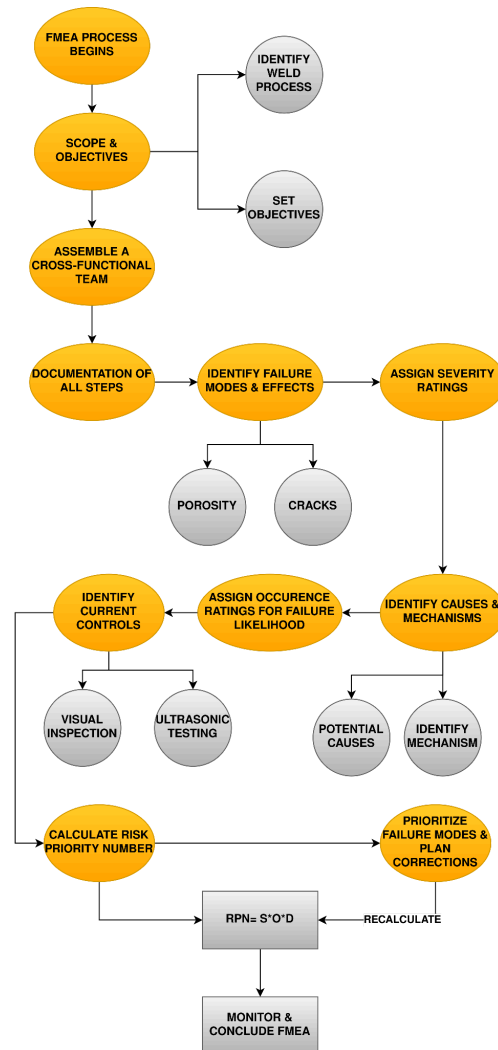


Figure 9. FMEA for Welding Engineering.

Generally, there are many products with complex welding and manufacturing systems, prioritizing and tackling risks as individual problems as opposed to attempting to address all risks is a more effective method of preventative improvements. FMEA can ensure that a process runs while meeting customer-specific demands. Analyzing the cause and effect of these factors may optimize equipment,

resources, time, wastage and expenses. Aside from defects, possible welding failures include short-circuiting, improper grounding, safety light detectors such as LEDs not working, welding rod eroded, issues with cooling, and welding arc stability [67-69].

These defects may be identified using the FMEA technique upon welding processes and as a checklist to meet the safety standard and customer-specific requirements of welded products. The significance of this tool is that it helps to create a feasible and sustainable method to tackle risks in processes to a level required by industry standards and prevents waste before experiencing problems altogether [69]. There are two types of FMEA - Process FMEA and Design FMEA (DFMEA) which deal with locating failure modes at process stages and design stages. These LSS tools can develop a correlation between design, simulation and welding to develop better simulation models that identify problems before physical tests.

3.7 Kaizen

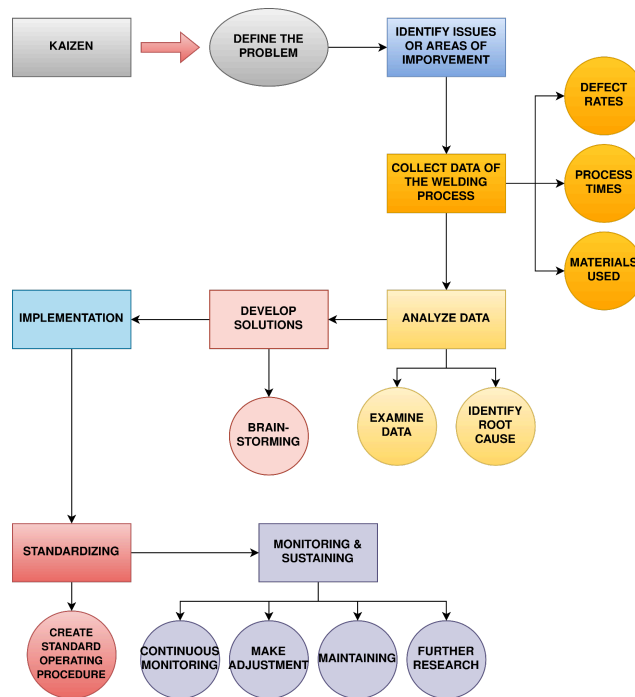


Figure 10. Kaizen in the Welding Process [70].

Kaizen is a Japanese term that indicates continuous improvement. This philosophy, while not a LSS tool, is parallel to the LSS methodology and refers to continuously adapting to the evolving demands within the welding process. It results in increased productivity while striving for zero defects in welding. Two of the most critical challenges that are faced in the industry are the limited availability of skilled labor and the increasing need for productivity and cost effectiveness. **Figure 10** visualizes the detailed methodology.

The Kaizen approach, implies reiterating the improvement process and this tackles this issue by distributing workloads based on skill set evaluations through statistical techniques. This allows for efficiency in welding processes and increased production that further contribute to cost and cycle-time reduction. In addition, the process addresses issues faced at welding lines, which include wastage of extra material, deposition, and reduction of joint strength due to material defects [70]. Addressing these problems in the design phase will allow space to implement appropriate modifications to optimize resources and production in comparison to traditional methods.

4.0. Implications of LSS Tools in Welding Engineering: Case Studies and Discussions

DMAIC is one of the most important tools of LSS as it is easily repeatable and a disciplined framework which allows it to be applied to various cases. Its structured nature allows it to solve a large variety of problems with the LSS approach and achieves the continuous improvement goals of LSS. This section discusses cases of DMAIC applications in welding processes.

4.1. Case Studies

There are cases where DMAIC was implemented successfully, with adequate results, as shown in Tables 6-9; the table is divided into components of DMAIC to explain the cases and their final outcomes.

Case 1: Applications of DMAIC to reduce weld defects in power plant component manufacturing processes. Wirani, A. P., Saroso, D. S., & Purba, H. H. [71]

The case focuses on power plant component welding and the fabrication process. The case was identified to have high instances of weld defects, specifically high porosity welds, resulting in reduced quality, productivity and safety. The LSS methodology was applied to systematically reduce the defects [71].

Table 6. DMAIC applications in Case 1 [71].

D	M	A	I	C
Improving the mechanical properties of pipes joined together by friction stir welding.	Pipe wall thickness (t), tool travel speed (s), and tool rotation speed (n) would be this experiment's variables.	Each parameter affects the sample joint's tensile strength and hardness. Analysis of Variance, or ANOVA, was implemented to this effect.	The optimal range value of the machine tool of certain rotation speed (n) and tool moving velocity(s) was calculated	The optimal mechanical tool rotates at speed, and the same tool moving speed values were 1800 rpm and 4mm/min, respectively.

In this research, there was a significant reduction in welds defects; primarily porosity, was significantly reduced through process improvements, better control of gas and improved welder techniques. The productivity and cost efficiency were increased with higher resource efficiency and cycle times. Standard operating procedures and regular quality controls were established to sustain the improvements. There was a Sigma Level increase as a result in this case from 4.1 to 5.0, indicating a substantial reduction in process variability and defects. The proportion of porosity related defects decreased significantly, contributing to overall quality enhancement. The reduction in rework and scrap led to lower production costs and increased productivity, which aligns with the project objectives [71].

The case validates the power of the DMAIC methodology when properly followed, it can be a disciplined and structured framework for identifying and solving quality problems. Collecting two years of defect data helped isolate patterns and root causes. LSS emphasizes measurement and analysis, which avoids assumptions and focuses on facts. Furthermore, it was discovered that a major root cause of welding defects was the skill of the welder, reminding us that LSS is not just about tools and machines, operator training and capability are equally critical. This case also shows that LSS is flexible enough to adapt to stringent, specialized processes. The drawbacks of this case are that it lacks specificity in the data; while key factors affecting weld quality are identified in the study, statistical analysis is lacking. The impact of each factor could have been quantified to demonstrate the effect on the problem and the results after applying LSS tools. The study also lacks in providing long-term data and explaining the long-term impacts of applying LSS methodologies to the process [71]. The effectiveness and sustainability of the control measures are not depicted over time. The study remains specific to the boiler fabrication process in a particular setting, limiting the applicability of the findings to other welding cases and contexts.

Case 2: Six Sigma as a tool to reduce Tungsten Inert Gas welding defects and underproductivity. Shinde, M. M. S., & Inamdar, K. H. [72]

This case focuses on weld defects, such as lack of fusion and improper shielding, in the aerospace industry which leads to reworking, increased cost, waste and delivery delays. The LSS tool was applied to identify and mitigate these defects [72].

Table 7. DMAIC applications in Case 2 [72].

D	M	A	I	C
Investigating the manufacturing process	Process mapping, Data collection, Sigma-level	A Root Cause Analysis (i.e., fishbone diagram) was carried out to identify all possible sources of	1. Monitoring and reporting waste generation monthly 2. New control panel	A control plan was designed and circulated to the firm to sustain the
Constructing the SIPOC diagram	, and Downtime		3. Reaching out to a new supplier	improvements made.

Collecting preliminary data	measurements	waste, followed by the implementation of the Analytical Hierarchy Process (AHP) to find significant waste-generator	4. New glass mixing machine 5. Remodeling maintenance program 6. Installing the extra reclaiming machine 7. Creating a daily cleaning schedule with a checklist, worker responsible, area, machines, and signature box	Expectation setting is critical in eliminating ambiguities. Using the systematic methodology of DMAIC, the company could bring its waste ratio below 2%.
-----------------------------	--------------	---	---	--

This case demonstrated a significant reduction in welding defects, as the application of LSS tools led to improvements regarding issues such as lack of fusion and improper shielding. There were also improvements in process capabilities and an increase in sigma level. Productivity was enhanced due to minimal reworking and defects, leading to successful delivery according to schedules and expectations. Standard operating procedures and regular quality controls were established to sustain the improvements. There was a Sigma Level increase as a result in this case from 3.55 to 4.52, indicating a substantial reduction in process variability and defects. The study outlined an achievement of reducing the DPMO rate to 1,500, significantly surpassing the goal of 5,000. The reduction in rework and scrap led to lower production costs and increased productivity [72].

It was discovered through this case, that the structured approach of DMAIC proves effective in identifying and mitigating root problems in complex welding processes. The importance of root cause analysis and tools such as fishbone diagrams and FMEA were established. The use of these LSS tools allowed for a deeper understanding of the issues affecting the weld quality. The study also emphasizes the importance of collecting and analyzing data in order to make informed decisions when applying LSS. While this study effectively and systematically applied each phase of DMAIC and utilized various LSS tools, it also had a few drawbacks. The scope of this study was very limited and focused solely on TIG welding of Maraging Steel, reducing the generalizability and application of findings to different cases and welding processes [72]. The study also does not provide long-term data or findings or sustainability of the approach. Finally, the study identifies human factors as critical causes of defects in the welding process but does not elaborate on initiatives undertaken to mitigate this issue; ie. training, skill development, e.t.c..

Case 3: Friction Stir Welding mechanical properties improvement using LSS tools Sabry, I. et al. [73]

Before LSS methodologies were applied, the process of Friction Stir Welding for aluminum pipes was experiencing problems that negatively affected mechanical properties such as tensile strength, hardness and elongation [73]. The welds were inconsistent across batches and had many defects. variables in the process were not standardized or controlled leading to inconsistencies and poor quality. The goal in implementing DMAIC was to reduce process variability and enhance tensile strength and hardness.

Table 8. DMAIC applications in Case 3 [73].

D	M	A	I	C
Determination of Critical to Quality determine the SIPOC diagram for better knowledge of the issue preparation of the welding map WPS/PQR and weld joints	Exploration affirmed that with the execution of the FMEA technique, the industry gets an outline of the means to be taken for what is to come with the goal that the dependability of a steam generator heater framework can be enhanced.	Circumstances and logical results charts show the connection between issues confronted with reasonable causes just as components impact it. The elements that impact and become reasons for harm to welds can be named man/personals, material, estimation, strategies, machines, and climate.	The objectives of this stage are to choose the complex arrangement, do experimentations to approve arrangements and relations between the impacts and causes through Root Cause Examination (RCA) instruments, conceptualize, and conversation	The final period of DMAIC is administered, which guarantees the motion cycles on the functioning to design and produce expected result & stick with original quality levels. The apparatuses used in this stage are a control plan, check sheet, and observation.

The study successfully optimized welding parameters by identifying optimal ranges for rotation speed, travel speed and pipe wall thickness that enhanced the tensile strength of welded joints. By employing the DMAIC methodology, the research systematically analyzed the welding process, leading to data-driven improvements in weld quality. The optimized welding parameters led to improved tensile strength of the welded joints and products indicating a direct result of applying LSS to the process. Tensile Strength Cpk increased from 0.86 to 0.69. Elongation Cpk improved from 0.37 to 0.57. Hardness Cpk rose from 0.81 to 0.58. It was learned through this study that the DMAIC approach facilitated a structures analysis of the welding process, enabling the identification and control of variables affecting weld quality. The study also highlights the importance of collecting and analyzing process data to make informed decisions for process optimization. The adaptability of LSS tools was also demonstrated as the combination of Fuzzy Logic along with traditional LSS tools showed how versatile the methodology is in manufacturing processes. This study focused heavily on tensile strength and disregarded other issues that were identified

such as hardness and elongation. The study, while qualitatively analyzing the results of applying LSS, lacked in relaying quantitative results. Quantifying the results would have given concrete proof of improvement and before-after comparisons. Similar to the previous cases, long-term data is missing, leaving the sustainability of LSS unverified [73].

Case 4: LSS in manufacturing environments to reduce waste and production processes Hassan, M. K. et al. [74]

The manufacturing facility in question was dealing with excessive waste, low productivity, inefficiency, high operational costs and no standardized problem-solving methodology in place before implementing LSS. There was excessive waste, both materially and process-related. Overproduction, defective parts, poor layout and workflow as well as unnecessary rework and poor inventory management led to both low productivity and high operational costs. The lack of an approach to solve the problems allowed them to be persistent and left unaddressed [74].

Table 9. DMAIC applications in Case 4 [74].

D	M	A	I	C
The company understands the customer's issues using SIPOC, Voice of Customer, and Quality Capacity organization.	The nitty-gritty cycle planning, operational definition, information assortment outline, assessment of the current framework, appraisal of the current degree of measure execution, and so forth.	The third period of the DMAIC interaction incorporates the meaning of the fundamental driver of the imperfections and the main reason investigation utilizing apparatuses like the fishbone chart focusing on the significance or criticality of each cause utilizing apparatuses, for example, the FMEA, WHY-WHY Investigation.	The objectives of this stage are to choose the issue arrangement, perceive the dangers and carry out the chosen arrangement. This progression utilizes imaginative approaches to discover better approaches to improve, less expensive or quicker. Spontaneous creations in the process are done to keep the factors inside as far as possible.	The adjusted interaction is exposed to a vigil at standard time spans to guarantee that the key factors do not show unsuitable varieties.

The study resulted in a significant waste reduction and yield improvements from the manufacturing process. The process became more capable and reliable, with improvements in DPMO and sigma levels. By incorporating Analytic Hierarchy

Process, the research provided a structured approach to identifying the causes of waste and effective mitigations. There was a yield improvement of 2.49%. DPMO reduced from 42,500 to 17,600, demonstrating a significant decrease. The sigma level increased from 3.22 to 3.6, indicating process capability and reduced variability. The waste percentage of input material went from 4.25% to 1.76%, achieving the goal of less than 2% waste. It was learned through this study that the DMAIC approach systematically solves problems by identifying, analyzing and addressing quality issues in manufacturing processes.. The study also highlights the importance of collecting and analyzing process data to make informed decisions for process optimization. The adaptability of LSS tools was also demonstrated as the combination of Analytic Hierarchy Process along with traditional LSS tools showed how versatile the methodology is in manufacturing processes. This study also is limited in scope, resulting in a limited applicability of the findings to various cases in welding engineering. Similar to the previous cases, long-term data is missing, leaving the sustainability of LSS unverified. While the study identifies process improvements, it does not elaborate on training or skill development initiatives for operators [74].

4.2. Discussions: Progress & Critique of Current Implementation

The cases reviewed in the heading *4.1.*, and the implications in the welding and manufacturing industry, ranging from welding defect reduction to welding process efficiency. It was evident through these cases how structured methodologies such as DMAIC and other LSS tools can transform inefficient systems into streamlined, high performing systems. This following section discusses key insights, outcomes and recurring themes from the selected studies, with a focus on how LSS principles were adapted to real world challenges. The measurable impacts they had on productivity, quality and efficiency will be explored. Their implementations will also be critiqued, with suggestions for other methods. By comparing these implementations, their common success factors and the effectiveness of LSS in manufacturing environments can be understood as well as ideas for future steps and implementations.

Table X. Comparative Understanding of Performance of LSS in Welding Processes

Welding Process	LSS Tools Used	Defects Addressed	Key Measurable Outcomes	Implementation Challenges	Ref
TIG Welding	DMAIC framework, Pareto analysis Fishbone diagrams	Slag inclusion, Lack of fusion, Porosity	Current increased from 130A to 210A, voltage from 18V to 22V resulting in reduced	Need for operator training to handle parameter adjustments and maintain	[75]

			rejections.	consistency	
MIG Welding	DMAIC methodology, Pareto analysis, Cause-and-Effect diagrams, and Check Sheets.	Punctures, bead shifting, craters, blow holes, and wire sticking.	Enhanced weld quality by optimizing parameters such as gas flow (10–15 l/min), current (120–160A), and voltage (18–22V).	Variable operator skills and equipment settings required standardized procedures and training.	[76]
Resistance Welding	DMAIC approach, SIPOC diagrams, Cause-and-Effect matrices, and FMEA.	External leakages in welded joints, particularly in refrigerator manufacturing.	Achieved a 30% reduction in external leakage defects.	Identifying root causes of leaks required detailed analysis and process mapping.	[77]
Submerged Arc Welding	DMAIC and process optimization techniques.	Cracks and lack of fusion in valve components.	Achieved a 46% reduction in welding defects.	Adjusting process parameters and ensuring consistent quality across batches.	[78]
Automotive Exhaust System Welding	DMAIC framework, pareto chart, Ishikawa diagram and process capability analysis	Targeted defects in the muffler production line, focusing on issues that led to product rejections.	Sigma level improvement from 2.89 to 3.16. Increased process yield from 91.73% to 95.19%	-	[75]
Pressure Vessel Welding	DMAIC design of experiments and hypothesis testing	Die-casting and machining processes defects	Sigma level improved from 3.4 to 4.0.	Allocating sufficient time and personnel to conduct thorough analyses and	[79]

				implement improvements.	
--	--	--	--	-------------------------	--

Recurring Themes & Common Successes

Each case above emphasizes the value of DMAIC as an LSS tool and its versatility for problem solving. It can be learned that DMAIC is highly effective and useful for strategic problem solving, regardless of the issues identified. Data-driven Decision making is also highlighted as an important step of the problem solving process, as quantitative analysis is crucial for informed problem solving [80]. Metrics such as yield percent, DPMO, sigma levels and Process Capability Indices are useful tools in LSS problem solving. Visual tools and structured analysis such as Fishbone diagrams, VSM and Pareto Charts are also highly valuable in the problem solving process. Most cases succeeded in reductions of defects and waste as well as increased yield and sigma levels.

Gaps in Current Implementation

On the contrary, the cases shared a few common failures. While operator skill and training were listed as issues and root causes in many of the cases, they were not addressed when applying lean six sigma and the cases did not explore the effects and benefits of improving skill level and training. Many of the cases faced problems that were not solely caused by tools or design flaws, as operator skill and non-uniformity is a large cause of challenges in welding engineering, explained in section 2.3. These problems were overarchingly addressed through SOPs but lacked a comprehensive application of LSS principles to mitigate the issue. The cases also heavily relied on DMAIC. DMAIC is a commonly used methodology in relation to LSS principles but LSS is a large toolbox and has many facets within. Certain processes may benefit from FMEA or Statistical process control instead. The heavy reliance on DMAIC removes attention in the research works from other tools that could be explored, thereby reducing the support and reliability of other tools [80]. One of the largest issues that these studies face is that they lack long-term record and exploration of LSS implementations despite the theoretical sustainability of the philosophy. The lack of long term investigations and information on the saving and efficiency of process improvement in the long run is consistent with most studies. All case studies that have been mentioned, lack the use of AI or predictive or real-time tools such as digital twins, real-time SPC, or AI based Root cause analysis [81, 82].

Cross-Tool Effectiveness & Contextual Suitability

All LSS tools have their strengths, weaknesses and ideal situations to apply them. To apply LSS to a maximum effectiveness, it is essential to understand the facets of LSS tools as well as know the ideal situations to apply tools in collaboration to improve quality and efficiency at a high degree.

Table X. Cross-Tool Effectiveness in the Synergy of Welding-LSS.

Tools	Strengths	Limitations	Use Cases in welding	Ref
-------	-----------	-------------	----------------------	-----

DMAIC	Systematic approach to identifying and eliminating defects. Effective in structured environments, particularly when integrated with advanced analytics. For example, integrating predictive quality analytics into DMAIC enhances process improvement.	In high-mix, low-volume settings, traditional DMAIC methods may have limited applicability unless combined with predictive modeling or simulation to account for variability.	Manufacturing environments with stable, repetitive processes seeking to reduce defect rates. DMAIC can be applied in welding processes seeking to reduce defects and improve efficiency as well as rework the manufacturing process.	[83]
FMEA	Effective for early-stage risk detection and prevention. Prevents wastage before possibility of occurring. Mitigates risk before they manifest. Comprehensive method to identify and classify risks.	May not capture unforeseen failure modes if the analysis is not comprehensive. Required a high degree of attention to detail and skill to predict as many failure modes as possible.	Design and development phases of products or processes where early identification of risks is crucial.	[84]
Control Charts	Visual tool. Helps maintain high quality in high-output production by distinguishing between common and special variations. Provide real-time monitoring, enabling immediate corrective actions when processes deviate from	Less effective in environments with low production volumes or highly variable processes. Requires high volume of data collection to be effective.	High-volume manufacturing settings where consistent product quality is essential. Often used to visualize the process and consistently used during the lifetime of a process.	[85]

	control limits.			
Kaizen	Creates positive and disciplined work environments and provides structure involving all employees. Engages employees of all levels and promotes sustained improvements.	Requires cultural buy-in since without it, initiatives may face resistance or fail to sustain momentum. All employees must be actively participating.	Repetitive production environments where ongoing, small-scale improvements can lead to significant gains over time.	[86]

The LSS methodology is one that can be applied regardless of the presence of a defect in processes in order to improve and optimize manufacturing. As mentioned in the above sections, all LSS tools have strengths as well as ideal situations for implementation. Being aware of the facets of the tools as well as how to utilize them in combination will give the best results. Some tools may be more valuable than others in certain environments and would produce more effective results as compared to using another. Combining these tools can address their individual limitations and leverage their strengths. Most effective process improvement can only take place when multiple tools are used in unison to tackle the problems at hand. In high-mix, low-volume settings, integrating predictive analytics with DMAIC can enhance its applicability by accounting for variability and enabling more accurate process improvements. Using FMEA to identify potential failure modes and then monitoring those specific areas with control charts can proactively manage risks and maintain process stability. This could be done before process implementation. Implementing Kaizen within the DMAIC framework can promote a culture of continuous improvement, ensuring that process enhancements are sustained over time. It is also common practice and encouraged to use other tools within one another such as using Fishbone diagrams during the define step of DMAIC or RCA. By understanding the specific advantages and limitations of each LSS tool, organizations can strategically apply them in combination to optimize process improvements, enhance quality, and foster a culture of continuous enhancement.

5.0. Benefits

The implementation of the Lean Six Sigma framework in welding has several benefits that current industries value highly in order to increase their competition and expand their businesses.

Quality Control and Defect Reduction

LSS focuses on improving the quality of the product by defect identification through intense analysis. The applications of this philosophy will minimize waste products that are the cause of defects, resulting in higher quality production. The use of LSS in welding has reduced the occurrence of defects to 3.4 per million products made [87]. It helps fix problems in earlier stages, reducing initial costs and production time.

Organizations have experienced significant improvements in quality and efficiency. For example, Johnson Controls reduced defects by 70% and saved \$800,000 per year at their Ohio manufacturing plant [35, 88].

Relying on Data

The statistical data and analysis that LSS collects improves the quality of products and their cycle time. Additionally, the data collected may be used to determine accurate prediction rates of future errors, allowing for organizations to foresee drawbacks ahead of time. The data pertaining to wastage and failure are kept for future reference in production [89]. Consistent data collection promotes organization, measurable quality control and as a report card for workplaces. A study conducted by the Institute for Supply Management (ISM) in 2022, compared current and past contracts that consisted of data pertaining to manufacturing methods. The implementation of suggested improvements reduced the average contracting cycle time (number of days between the beginning and end of the contracting process) by 30 % [89].

Increase in Revenue

The increase in manufacturing and decrease in wastage will result in the increase of company revenue. The high standard products will contribute to a stronger market, improving the business's revenue generation. The reduction in defects will also result in the decline of waste management costs, as they will be converted into sales and a reduction of material and time wastage. For instance, Linde Group, a gasses and engineering organization, conducted process revamping at several North American facilities in an attempt to improve process efficiency [90]. These LSS projects were composed of processes being standardized to improve the ability of workers to transport between sites. The improvements implemented as a result of this method increased productivity by approximately 20 % and reduced production costs by roughly 13 % [90]. Companies implementing LSS have reported substantial financial benefits. For example, General Electric added \$2 billion in 1999 and \$2.4 billion in 2000 to their bottom line through LSS initiatives [102]. Similarly, Motorola saved more than \$15 billion in the first ten years of Six Sigma implementation [103].

Improve Customer Satisfaction

The application of LSS in manufacturing will improve customer satisfaction through better product performance. By focusing on defect reduction and process optimization, LSS contributes to higher quality outputs, thereby increasing customer satisfaction. In comparison to hearing customer feedback, LSS proves to be a proactive approach towards satisfying customer needs [65]. LSS implementation reduces product rejection as shown in research work by J. Singh et al. [75].

6.0. Limitations of the LSS as a Philosophy for Welding Engineering

Despite the growing popularity of LSS in Welding, the philosophy poses several limitations that hinder the efficiency of production and workplace if not approached correctly.

Time-intensivity

Implementing LSS into workplaces involves a large investment of time and resources to train employees, conduct data analysis and implement improvement projects. Companies must be prepared to allocate the appropriate amounts of time to ensure successful implementation. A study found that it takes roughly 2-3 years for companies to fully adopt LSS practices, indicating that the journey to full adoption is a gradual process, which does not reflect direct results [91, 92].

Organizational Resistance

During the implementation of LSS, the need for highly skilled and experienced laborers arises, with the call for employees to quickly adapt to Six Sigma training. For the effective implementation of LSS, employees of all levels must be actively participating and adapting practices. However, many organizations find difficulty in implementing such practices on larger scales. A survey revealed that 15% of companies encounter LSS resistance at executive levels during lean implementation [91].

Focus on Quality Only

LSS implementation in the welding industry only focuses on quality of production, with little attention towards production and efficiency rates as well as operator skill level and training. The overemphasis on defect reduction prevents companies from allocating attention towards other important factors such as customer experience, employee satisfaction and organizational growth [91, 92]. The project-centered strategy of Six Sigma through Green Belt and Black Belt improvements may create successful products, but do not iteratively improve their process [92].

Critical quote from Klefsjo et al (2006), stated they see *“a risk that the belt-based infrastructure has an unavoidable tendency to glorify some people and, hence, not sufficiently support the TQM value of everybody’s commitment”* [91].

Increase in Production Costs

Due to the additional LSS techniques, in certain cases of process rework, labor costs, materials usage and time of manufacturing, production costs are expected to increase. Increases in the production rate may further lead to increases of product costs as well. As a result, it is predicted that customers may search for lower-priced products that are not suitable for LSS manufacturing [93-95].

7.0. Future Directions

The scope of this study will play a vital role in improving existing processes in the future by analyzing and summarizing existing LSS implementations in the real world. Further research will provide more solutions to welding problems, where optimization is anticipated to provide level 6 quality according to the six-sigma requirement from the existing 3 to 4-sigma. This will lead to better productivity, lesser rejection, less material wastage, and higher profits for the organization [96].

Future prospects of LSS technologies and welding involve the use of Artificial Intelligence (AI) in various aspects. For instance, DMAIC stages can be augmented

by AI which can accelerate processing speed and reduce labor intensive tasks of improvement projects [97, 98]. Process improvement teams tend to use process maps and “five whys” root cause analysis. However, AI is able to perform these tasks faster and with higher accuracy, reducing labor and simultaneously enhancing worker safety by reducing human involvement [99]. Robotic technologies can be used for repetitive processes within welding activities to be completed with higher precision and accuracy. Many companies have already begun to implement AI into their welding processes [99, 100]. One example is Johnson & Johnson, a pharmaceutical, biotechnology, and medical technology company that has executed an “intelligent automation” initiative that implements AI tools to automate processes and enhance productivity. Their cost analysis resulted in \$500 million in savings [101].

However, as AI grows in importance for processing improvement, these new strategies will challenge current standards and philosophies. For example, current approaches rely on scripted routines that permit workers to utilize them. By using AI, the importance of these standardized tools can deteriorate, and may be resisted by Black Belts/consultants who are strong believers of the original LSS philosophy [99, 101]. Moreover, the skills required to leverage AI in welding are not currently taught in LSS training, indicating that leaders need to promote updated training. One niche application of AI has been to further explore virtual reality (VR) and augmented reality (AR) for upskilling welders without wasting the materials and allowing better training to acquire essential skills as a welder [100].

The industry requires more optimization for manufacturing processes, especially in the automotive industry, where components like engines consisting of an air intake, pistons, cams, etc., require exceptional precision. Other elements like disc brakes, nuts, bolts, wheels, etc., have to undergo extreme variations in temperature and pressure, meaning any minor defect can result in a significant catastrophe. Hence, it is vital for the automotive industry and has enormous opportunities for development and research for various implementations of LSS methodologies.

Observing the capability of LSS in the industry reveals many domains where implementing this methodology can enhance productivity and provide revolutionary ideas that can change the face of mass production in the industries. Hence, it is vital for heavy and consistent research on various tools and methods of LSS. Optimization of welding as a process can also be enhanced using artificial intelligence, machine learning, or deep learning algorithms, and the implementation of LSS tools in such cases can be considered vital and groundbreaking.

8.0. Conclusions

This review investigated how the LSS methodology can help reduce or eliminate defects observed in the industrial welding process. The fundamental and primary tool of LSS is known as DMAIC, which stands for Define, Measure, Analyze, Improve, and Control. The process works by converting problem-solving into steps and setting milestones to monitor progress by applying LSS methodology in these commonly used welding methods. Even though LSS and its tools, like DMAIC, Root Cause

Analysis, etc., can optimize various processes and cycles, it is still bound by many limitations.

What stands out most is the sheer versatility of LSS as a problem-solving methodology. From DMAIC to RCA, FMEA to SIPOC, we see how LSS is packed with tools that can remedy all shapes and sizes of problems. It was seen that LSS is used to reduce waste caused by welding defects like slag inclusion, lack of fusion, and porosity issues. This was remedied by applying RCA, where the root cause was ultimately the lack of cleaning of raw materials. This was achieved by running the problem through the DMAIC process, where it was found that tensile strength can be maximized by optimizing two welding parameters: tool travel speed and tool rotation speed. Whether improving dismal process efficiency by minimizing uncontrolled variation or reducing customer complaints through properly training welding operators, LSS has proven itself to be a powerful ideology all organizations should consider adopting to optimize their processes. Due to the significant implication of LSS, this ideology can be extended to any process in terms of optimization or rectification.

Furthermore, this study also assessed and analyzed the benefits and limitations of LSS as a methodology and highlighted improvements and changes for future implementation, serving as a comprehensive guide for industry application. The challenges of past implementations can be taken as teachings for future implementations.

Acknowledgments

The authors acknowledge the support from Dr. Vishvesh Badheka from Pandit Deendayal Energy University (PDEU), Gandhinagar, for providing vital inputs for the study to be improved.

References

1. Sharma, A., Chouhan, A., Pavithran, L., Chadha, U., & Selvaraj, S. K. (2021). Implementation of LSS framework in automotive component manufacturing: a review, current scenario and future directions. *Materials Today: Proceedings*, 46, 7815-7824.
2. Yousef, M. A., Al-Omairi, K., Al-Shehri, A. I., & Kakpovbia, A. E. (2014, July). Improvement of the Welding Inspection Process for Projects in the Oil and Gas Industry Using Six Sigma Methodology. In *Engineering Systems Design and Analysis* (Vol. 45851, p. V003T14A012). American Society of Mechanical Engineers.
3. Selvaraj, S. K., Raj, A., Dharnidharka, M., Chadha, U., Sachdeva, I., Kapruan, C., & Paramasivam, V. (2021). A Cutting-Edge Survey of Tribological Behavior Evaluation Using Artificial and Computational Intelligence Models. *Advances in Materials Science and Engineering*, 2021(1), 9529199.

4. Mongan, P. G., Hinchy, E. P., O'Dowd, N. P., & McCarthy, C. T. (2021). Quality prediction of ultrasonically welded joints using a hybrid machine learning model. *Journal of Manufacturing Processes*, 71, 571-579.
5. Adin, M. Ş. (2024). A parametric study on the mechanical properties of MIG and TIG welded dissimilar steel joints. *Journal of Adhesion Science and Technology*, 38(1), 115-138.
6. Desai, T. N., & Shrivastava, R. L. (2008, October). Six sigma—a new direction to quality and productivity management. In *Proceedings of the World Congress on Engineering and Computer Science* (pp. 22-24). San Francisco, CA: Elsevier.
7. Pepper, M. P., & Spedding, T. A. (2010). The evolution of lean Six sigma. *International Journal of Quality & Reliability Management*.
8. Mira-Aguiar, T., Leitão, C., & Rodrigues, D. M. (2016). Solid-state resistance seam welding of galvanized steel. *The International Journal of Advanced Manufacturing Technology*, 86(5), 1385-1391.
9. Sun, X. (2001). Effect of projection height on projection collapse and nugget formation—a finite element study. *Welding Journal*, 80(9), 211s-216s.
10. Wang, X., & Zhang, Y. (2017). Effects of welding procedures on resistance projection welding of nuts to sheets. *Isij International*, 57(12), 2194-2200.
11. Kumar, R. K. M. A. N. (2017). HHO Generation & Its Application on Welding. *Int. J. Sci. Res. Dev.*, 5, 2321-0613.
12. Santiago Nieves, I. (2015). Cost Reduction in the Accumulator Process in Welding Operations. *Manufacturing Engineering*.
13. Saryanto, S., Purba, H., & Trimarjoko, A. (2020). Improve Quality Remanufacturing Welding and Machining Process in Indonesia Using Six Sigma Methods. *J. Eur. Systèmes Autom*, 53, 377-384.
14. Yousaf, F., Butt, D., & Ikramullah, S. (2014). Reduction in repair rate of welding processes by determination & controlling of Critical KPIVs. *International Journal of Production Management and Engineering*, 2(1), 23-36.
15. Technoweld. (2019, November 13). The most common welding defects: Causes and remedies. Technoweld. <https://technoweld.com.au/2019/11/13/the-most-common-welding-defects-causes-and-remedies/>
16. Grill, J. (2024, January 4). 13 common types of welding defects & how to prevent them. WeldGuru. <https://weldguru.com/common-welding-defects/>
17. Yousaf, F., & Butt, S. I. (2014). Reduction in repair rate of welding processes by determination & controlling of Critical KPIVs. *International Journal of Production Management and Engineering*, 2(1), 23-36.

18. International Organization for Standardization. (2023). ISO 5817:2023 – Welding — Fusion-welded joints in steel, nickel, titanium and their alloys (beam welding excluded) — Quality levels for imperfections [PDF]. <https://cdn.standards.iteh.ai/samples/80209/8c36b0ac8b8543bdf704329da39262c/ISO-5817-2023.pdf>
19. International Organization for Standardization. (2018, June). ISO 10042:2018 – Welding— Arc-welded joints in aluminium and its alloys — Quality levels for imperfections [PDF]. <https://cdn.standards.iteh.ai/samples/70566/7db54c321472490f97ecf856495f3ab9/ISO-10042-2018.pdf>
20. Xpress Mobile Welding. (2025, January 13). Common welding problems & solutions. <https://xpressmobilewelding.com/welding-tips/common-welding-problems-solutions/>
21. Liu, S., Wu, Z., Liu, H., Zhou, H., Deng, K., Wang, C., ... & Li, E. (2023). Optimization of welding parameters on welding distortion and stress in S690 high-strength steel thin-plate structures. *Journal of Materials Research and Technology*, 25, 382-397.
22. Kah, P., & Martikainen, J. (2012). Current trends in welding processes and materials: improve in effectiveness. *Rev. adv. mater. Sci*, 30(2), 189-200.
23. Uludağ, F., Olabi, Y., Günay, E. E., & Kremer, G. E. O. (2019). Mitigating the effects of bottlenecks in wagon manufacturing. *Procedia Manufacturing*, 39, 1010-1019.
24. Salvador, D. C. (2023). Welding Safety and Health: Occupational Hazards and Risk Mitigation. *Int. J. Adv. Res. Sci. Commun. Technol.*, no. July, 993-997.
25. La Fata, C. M., Adelfio, L., Micale, R., & La Scalia, G. (2023). Human error contribution to accidents in the manufacturing sector: A structured approach to evaluate the interdependence among performance shaping factors. *Safety science*, 161, 106067.
26. Torres Medina, Y., Nadeau, S., & Landau, K. (2019). Application of human errors analysis in manufacturing: a proposed intervention framework and techniques selection.
27. American Institute of Steel Construction. (2011, July). Control costs: Avoiding overwelding [PDF]. *Modern Steel Construction*. https://www.aisc.org/globalassets/modern-steel/archives/2011/07/2011v07_ccontrol_costs.pdf

28. YesWelder. (n.d.). Welding efficiency: Strategies for welding cost optimization. YesWelder. <https://yeswelder.com/blogs/yeswelder/welding-efficiency-strategies-for-welding-cost-optimization>
29. Juengert, A., Werz, M., Gr Maev, R., Keller, M., Labud, P., Scott, R., ... & Dobler, M. (2025). Nondestructive Testing of Welds. In Handbook of Nondestructive Evaluation 4.0 (pp. 1-43). Springer, Cham.
30. Dwivedi, S. K., Vishwakarma, M., & Soni, A. (2018). Advances and researches on non destructive testing: A review. *Materials Today: Proceedings*, 5(2), 3690-3698.
31. Stenberg, T., Barsoum, Z., Åstrand, E., Öberg, A. E., Schneider, C., & Hedegård, J. (2017). Quality control and assurance in fabrication of welded structures subjected to fatigue loading. *Welding in the World*, 61, 1003-1015.
32. Gay, C. (2025, May 21). 8 wastes of lean manufacturing. MachineMetrics. <https://www.machinemetrics.com/blog/8-wastes-of-lean-manufacturing>
33. American Society for Quality. (n.d.). Six Sigma. ASQ. <https://www.asq.org/quality-resources/six-sigma>
34. KAIZEN™. (n.d.). Lean Six Sigma for cost reduction. Kaizen Insights. <https://kaizen.com/insights/lean-six-sigma-cost-reduction/>
35. Anderson, N. C., & Kovach, J. V. (2014). Reducing welding defects in turnaround projects: A lean six sigma case study. *Quality Engineering*, 26(2), 168-181.
36. Snee, R. D. (2010). Lean Six Sigma—getting better all the time. *International Journal of Lean Six Sigma*.
37. Kifta, D. A. (2018). WELDING DEFECT RATE ANALYSIS AND ITS (Intelligent Transportation System) RECTIFICATION USING SIX SIGMA METHOD DAN FMEA AT PT XYZ.
38. Akca, E., & Gürsel, A. (2016). Solid state welding and application in aeronautical industry. *Periodicals of Engineering and Natural Sciences (PEN)*, 4(1).
39. G.A.R. Krishna, G.S. Dangayach, Six Sigma implementation at an auto component manufacturing plant: a case study, *Int. J. Six Sigma Competitive Advantage* 3 (3) (2007) 282
40. Rizkya, I., Syahputri, K., Sari, R. M., & Siregar, I. (2019, May). 5S implementation in welding workshop—a lean tool in waste minimization. In

IOP Conference Series: Materials Science and Engineering (Vol. 505, No. 1, p. 012018). IOP Publishing.

41. Manzanares-Cañizares, C., Sánchez-Lite, A., Rosales-Prieto, V. F., Fuentes-Bargues, J. L., & González-Gaya, C. (2022). A 5S Lean Strategy for a Sustainable Welding Process. *Sustainability*, 14(11), 6499.
42. Matt, D. T. (2014). Adaptation of the value stream mapping approach to the design of lean engineer-to-order production systems: A case study. *Journal of Manufacturing Technology Management*, 25(3), 334-350.
43. Chen, J. C., Li, Y., & Shady, B. D. (2010). From value stream mapping toward a lean/sigma continuous improvement process: an industrial case study. *International Journal of Production Research*, 48(4), 1069-1086.
44. Aksoy, B., & Orbak, Â. Y. (2009). Reducing the quantity of reworked parts in a robotic arc welding process. *Quality and Reliability Engineering International*, 25(4), 495-512.
45. Vinodh, S., Devarapu, S., & Siddhamshetty, G. (2017). Application of Lean approach for reducing weld defects in a valve component: a case study. *International journal of lean six sigma*.
46. Wang, C. C., Chien, C. H., & Chang, C. W. (2020). Six Sigma Case: The Improvement Welding Strength of LED Soft Board Process.
47. Dagmar, A. V., & Tarigan, Z. J. H. (2021). The application of the Six Sigma method in reducing the defects of welding on the steel material. In *IOP Conference Series: Materials Science and Engineering* (Vol. 1010, No. 1, p. 012044). IOP Publishing.
48. Desai, T. N., & Shrivastava, R. L. (2008, October). Six sigma—a new direction to quality and productivity management. In *Proceedings of the World Congress on Engineering and Computer Science* (pp. 22-24). San Francisco, CA (Controller Applications): Elsevier.
49. Rohac, T., & Januska, M. (2015). Value stream mapping demonstration on real case study. *Procedia Engineering*, 100, 520-529.
50. Wongso, R. (2010). An application of Value Stream Mapping to reduce lead time and WIP in a make-to-order manufacturing line (Doctoral dissertation, Massachusetts Institute of Technology).
51. Karthikeyan, M., Naikan, V. N. A., & Narayan, R. (2017). Root cause analysis and reliability improvement methods for orbital TIG welding process for propulsion feed system of satellites. *International Journal of System Assurance Engineering and Management*, 8, 910-924.

52. Taghipour, M., Bahrami, A., Mohammadi, H., & Esmaili, V. (2021). Root cause analysis of a failure in a flange-pipe welded joint in a steam line in an ammonia plant: Experimental investigation and simulation assessment. *Engineering Failure Analysis*, 129, 105730.
53. Rao, U. A., Elapanda, S., Raju, I. B., & Kumar, M. A. SIX SIGMA APPLICATION IN MANUFACTURING SPECIAL PROCESS: A CASE STUDY ON RESISTANCE WELDING.
54. El-Kassas, A. M., Sabry, I., & ElWakil, M. (2017). An implementation of Six sigma in aluminum pipe welding. *International Journal of Advance Research and Innovation*, 5(2), 192-195.
55. Rezaei, A., Ehsanifar, M., & Wood, D. A. (2019). Reducing welding repair requirements in refinery pressure vessel manufacturing: a case study applying six sigma principles. *International Journal on Interactive Design and Manufacturing (IJIDeM)*, 13(3), 1089-1102.
56. Saryanto, S., Purba, H., & Trimarjoko, A. (2020). Improve Quality Remanufacturing Welding and Machining Process in Indonesia Using Six Sigma Methods. *J. Eur. SystèMes Autom*, 53, 377-384.
57. Pawan, P. R., & Kumar, D. (2016). Reduction in Repair rate of Welding Processes by using DMAIC. *SSRG International Journal of Mechanical Engineering*, 3(1), 12-15.
58. Thekkuden, D. T., Santhakumari, A., Sumesh, A., Mourad, A. H. I., & Rameshkumar, K. (2018). Instant detection of porosity in gas metal arc welding by using probability density distribution and control chart. *The International Journal of Advanced Manufacturing Technology*, 95, 4583-4606.
59. Tabim, P. M., & Ferreira, M. L. R. (2015). Productivity monitoring of land pipelines welding via control chart using the Monte Carlo simulation. *Journal of Software Engineering and Applications*, 8(10), 539-548.
60. Cook, G. E., Maxwell, J. E., Barnett, R. J., & Strauss, A. M. (1997). Statistical process control application to weld process. *IEEE Transactions on Industry Applications*, 33(2), 454-463.
61. Thekkuden, D. T., I. Mourad, A. H., Christy, J. V., & Idrisi, A. H. (2018, July). Assessment of weld quality using control chart and frequency domain analysis. In *Pressure Vessels and Piping Conference* (Vol. 51685, p. V06BT06A004). American Society of Mechanical Engineers.

62. Aumpiem, A., & Prateepasen, A. (2017). FMEA for risk assessment in discoloration pipe welding. In *International Conference on Recent Trends in Engineering and Technology* (pp. 232-237).
63. Aravinth, P., Kumar, M. T., Dakshinamoorthy, A., & Kumar, A. N. (2012). A criticality study by design failure mode and Effect analysis (FMEA) procedure in LINCOLN V350 PRO welding machine. *International Journal of Advances in Engineering & Technology*, 4(1), 611.
64. Abhilash, C. R., & Thakkar, J. J. (2019). Application of Six Sigma DMAIC methodology to reduce the defects in a telecommunication cabinet door manufacturing process. *International Journal of Quality & Reliability Management*.
65. Shinde, M. M. S., & Inamdar, K. H. (2014). Reduction in TIG welding defects for productivity improvement using Six sigma. *International Journal of Technical Research and Applications*, 2(1), 100-105.
66. Sharif, M. M., Anwar, Z., Ayub, Y., Abbas, A., & Ahmed, M. (2019). Optimization in MIG welding by using Six Sigma tools. *Ind. Eng. Manag.*, 8, 1-9.
67. Singh, T., Kumar, D., & Ram, P. (2015). An implementation of Six sigma in steel tube welding: a case study. *International Journal of Innovative Science, Engineering and Technology*, 2(9), 60-64.
68. Soni, S., Mohan, R., Bajpai, L., & Katare, S. K. (2013). Reduction of welding defects using Six Sigma techniques. *International Journal of Mechanical Engineering and Robotics Research*, 2(3), 404-412.
69. Sreedharan, V. R., & Raju, R. (2016). A systematic literature review of Lean Six Sigma in different industries. *International Journal of Lean Six Sigma*.
70. Singh, V., & Shah, S. (2014). Implementing Kaizen in a job shop industry through multi-skilling of labour. *International Journal of Emerging Technology and Advanced Engineering*, 4(3), 289-291.
71. Wirani, A. P., Saroso, D. S., & Purba, H. H. (2020, July). Innovation of quality improvement to reduce weld defect through six sigma methods in the fabrication process of power plant component. In *IOP Conference Series: Materials Science and Engineering* (Vol. 852, No. 1, p. 012064). IOP Publishing.
72. Shinde, M. M. S., & Inamdar, K. H. (2014). Reduction in TIG welding defects for productivity improvement using Six sigma. *International Journal*

of Technical Research and Applications, 2(1), 100-105. *Technology*, 2(9), 60-64.

73. Sabry, I. (2020). Six sigma methodologies used to improve the mechanical properties for friction stir welding of aluminum pipes. *Management and Production Engineering Review*.
74. Hassan, M. K. (2013). Applying lean six sigma for waste reduction in a manufacturing environment. *American Journal of Industrial Engineering*, 1(2), 28-35.
75. Singh, J., Singh, H., Singh, D., & Singh, V. (2017). Six Sigma methodology for reducing defects in manufacturing industry-a case study. *International Journal of Indian Culture and Business Management*, 15(4), 397-419.
76. Dhamija, A., Saini, N., Shukla, O. J., & Misra, A. K. (2014). Sigma level improvements in MIG welding using DMAIC approach. *Sop Transactions on Statistics and Analysis*, 1(1), 23-37.
77. Rao, U. A., Elapanda, S., Raju, I. B., & Kumar, M. A. SIX SIGMA APPLICATION IN MANUFACTURING SPECIAL PROCESS: A CASE STUDY ON RESISTANCE WELDING. *International Journal of Advanced Research in Engineering and Technology (IJARET)*.
78. Vinodh, S., Devarapu, S., & Siddhamshetty, G. (2017). Application of Lean approach for reducing weld defects in a valve component: a case study. *International journal of lean six sigma*, 8(2), 181-209.
79. Condé, G. C. P., Oprime, P. C., Pimenta, M. L., Sordan, J. E., & Bueno, C. R. (2023). Defect reduction using DMAIC and Lean Six Sigma: a case study in a manufacturing car parts supplier. *International Journal of Quality & Reliability Management*, 40(9), 2184-2204.
80. Chadha, U., Abraham, A., Anilkumar, K., Kuriyakkattil, V., Singh, H., Bane, S., ... & Patterson, A. (2024). Synergizing Lean Six Sigma Framework Using Artificial Intelligence, Internet of Things, and Blockchain for Sustainable Manufacturing Excellence. *Authorea Preprints*.
81. Pongboonchai-Empl, T., Antony, J., Garza-Reyes, J. A., Tortorella, G. L., Komkowsky, T., & Stemann, D. (2025). DMAIC 4.0-innovating the Lean Six Sigma methodology with Industry 4.0 technologies. *Production Planning & Control*, 1-22.
82. Pongboonchai-Empl, T., Antony, J., Garza-Reyes, J. A., Komkowsky, T., & Tortorella, G. L. (2024). Integration of Industry 4.0 technologies into Lean

- Six Sigma DMAIC: A systematic review. *Production Planning & Control*, 35(12), 1403-1428.
83. De Mast, J., & Lokkerbol, J. (2012). An analysis of the Six Sigma DMAIC method from the perspective of problem solving. *International Journal of Production Economics*, 139(2), 604-614.
 84. Wu, Z., Liu, W., & Nie, W. (2021). Literature review and prospect of the development and application of FMEA in manufacturing industry. *The International Journal of Advanced Manufacturing Technology*, 112, 1409-1436.
 85. Thekkuden, D. T., I. Mourad, A. H., Christy, J. V., & Idrisi, A. H. (2018, July). Assessment of weld quality using control chart and frequency domain analysis. In *Pressure Vessels and Piping Conference* (Vol. 51685, p. V06BT06A004). American Society of Mechanical Engineers.
 86. Vazquez-Hernandez, J., Martínez-García, R., González-Aleu, F., Verduzco-Garza, T., & Granda-Gutierrez, E. M. (2023). Application of industry 4.0, digital transformation, and lean six sigma to detect cold weld defects. In *Lean Six Sigma 4.0 for Operational Excellence Under the Industry 4.0 Transformation* (pp. 76-92). CRC Press.
 87. Rodriguez, D. (2025, May 21). Six Sigma in manufacturing: Advantages and disadvantages. Invensis Learning. <https://www.invensislearning.com/blog/six-sigma-in-manufacturing-advantages-disadvantages/>
 88. Dumitrescu, C., & Dumitrache, M. (2011). The impact of Lean Six Sigma on the overall results of companies. *Economia. Seria Management*, 14(2), 535-544.
 89. Bai, H. (2023, April 3). Measuring success of Lean Six Sigma efforts. *Inside Supply Management*. <https://www.ismworld.org/supply-management-news-and-reports/news-publications/inside-supply-management-magazine/blog/2023/2023-04/measuring-success-of-lean-six-sigma-efforts/>
 90. Waite, P. J. (2013, May). Save your steps: How one organization increased productivity and improved efficiency using Lean and Six Sigma [Case study]. *Six Sigma Forum Magazine*, 12(3), 20–24. American Society for Quality.
 91. Klefsjo, B., Bergquist, B., & Edgeman, R. L. (2006). Six Sigma and Total Quality Management: different day, same soup?. *International Journal of Six Sigma and Competitive Advantage*, 2(2), 162-178.

92. Wyatt, F. J. (2018, February 9). The demise of Six Sigma: The right-sizing of a problem-solving methodology. On Business Process Management and Workflow Automation (Medium). <https://medium.com/business-process-management-software-comparisons/the-demise-of-six-sigma-the-right-sizing-of-a-problem-solving-methodology-4e49b4442bf7>
93. M. Singh, R. Rathi, A structured review of Lean Six Sigma in various industrial sectors, *Int. J. Lean Six Sigma* 10 (2) (2019)
94. H.S. Sodhi, D. Singh, B.J. Singh, A conceptual examination of Lean, Six Sigma and Lean Six Sigma models for managing waste in manufacturing SMEs, *World Journal of Science, Technology and Sustainable Development* 17 (1) (2020) 20–32
95. G. Muthukumaran, Impact on integration of Lean Manufacturing and Six Sigma in various applications - a review. *IOSR Journal of Mechanical and Civil Engineering*, 6 (1) (2013) 98–101.
96. R.G. Schroeder, K. Linderman, C. Liedtke, A.S. Choo, Six Sigma: Definition and underlying theory, *J. Oper. Manage.* 26 (4) (2008) 536–554
97. Chadha, U., Selvaraj, S. K., Gunreddy, N., Sanjay Babu, S., Mishra, S., Padala, D., ... & Adefris, A. (2022). A survey of machine learning in friction stir welding, including unresolved issues and future research directions. *Material Design & Processing Communications*, 2022(1), 2568347.
98. Raj, A., Chadha, U., Chadha, A., Mahadevan, R. R., Sai, B. R., Chaudhary, D., ... & Hadidi, H. (2023). Weld quality monitoring via machine learning-enabled approaches. *International Journal on Interactive Design and Manufacturing (IJIDeM)*, 1-43.
99. Khurram, M., Zhang, C., Muhammad, S., Kishnani, H., An, K., Abeywardena, K., ... & Behdian, K. (2025). Artificial Intelligence in Manufacturing Industry Worker Safety: A New Paradigm for Hazard Prevention and Mitigation.
100. Huang, C. Y., Lou, S. J., Cheng, Y. M., & Chung, C. C. (2020). Research on teaching a welding implementation course assisted by sustainable virtual reality technology. *Sustainability*, 12(23), 10044.
101. Holweg, M., Davenport, T. H., & Snyder, K. (2023, November 9). How AI fits into Lean Six Sigma. *Harvard Business Review*. <https://hbr.org/2023/11/how-ai-fits-into-lean-six-sigma>

102. GE said Six Sigma would save it more than \$2 billion in 1999” (The Washington Post, 1999)
https://www.washingtonpost.com/archive/business/1999/11/26/six-sigma-energizes-ge/d56fc73a-e740-43af-b895-eeec703979fb/?utm_source=chatgpt.com

103. Six Sigma Online. (n.d.). The history of Six Sigma: From Motorola to global adoption. Six Sigma Online.
<https://www.sixsigmaonline.org/six-sigma-history/>