

Application of Six Sigma DMAIC and Failure Mode and Effects Analysis (FMEA) for Quality Improvement in Shielded Metal Arc Welding Training in Selected Technical Institutions in Imo State, Nigeria: A Comparative Study of Federal College of Land Resource Technology, Owerri, and Federal Polytechnic Nekede, Owerri

UGONNA JOHNBULL EGBUKICHI¹, UGWUEGBU DUKE CHIAGORO²

¹ Department of Industrial Safety and Environmental Engineering Technology, Federal College of Land Resource Technology, Owerri, Imo State, Nigeria

² Department of Mechanical Engineering, Federal Polytechnic Nekede, Owerri, Imo State, Nigeria

Abstract- Welding quality is influenced by process variation, operator competence, equipment condition, consumable handling and inspection practices. In technical institutions, recurring welding defects can reduce practical training quality, increase material wastage and weaken industrial readiness. This study applies the Six Sigma Define–Measure–Analyze–Improve–Control (DMAIC) methodology with Failure Mode and Effects Analysis (FMEA) to assess Shielded Metal Arc Welding (SMAW) training at Federal College of Land Resource Technology (FECOLART), Owerri, and Federal Polytechnic Nekede, Owerri, Imo State, Nigeria. The supplied study dataset contained 87 recorded defects classified into lack of fusion, undercut, porosity, slag inclusion, incomplete penetration and excessive spatter. Lack of fusion was the most frequent defect (25.29%), followed by undercut (22.99%) and porosity (21.84%); together these accounted for 70.12% of the recorded defects. FMEA identified lack of fusion and porosity as the highest-priority failure modes, with RPNs of 245 and 240 under the study rating assumptions. The results demonstrate that DMAIC provides a structured improvement pathway while FMEA adds risk-based prioritisation. Recommended controls include standardised welding procedures, preventive maintenance, improved electrode storage, structured inspection, instructor development and periodic review of defect data and FMEA.

Keywords: Six Sigma; DMAIC; FMEA; welding defects; SMAW; technical education; quality improvement; Imo State; Nigeria.

I. INTRODUCTION

Welding is a major joining process used in fabrication, construction, manufacturing and maintenance. Weld quality depends on material condition, welding parameters, equipment performance, joint preparation, operator technique and inspection. Consequently, welding education requires both manual skill and an understanding of process control and defect prevention.

Technical institutions play an important role in developing practical engineering skills. During SMAW exercises, students perform joint preparation, electrode selection, machine setting, arc initiation, electrode manipulation, travel control, slag removal and inspection. Variation in these activities can produce porosity, lack of fusion, undercut, slag inclusion, incomplete penetration and excessive spatter.

Six Sigma provides a structured approach for reducing process variation and defects. DMAIC progresses through Define, Measure, Analyze, Improve and Control. Egbukichi et al. [3]. Lean Six Sigma principles and reported its relevance to efficiency, quality improvement, cost reduction and customer satisfaction.

FMEA complements DMAIC by identifying potential failure modes, effects, causes and risk priorities. The combined approach is appropriate for welding workshops because defects can arise from interacting human, machine, material, method, measurement and environmental factors.

Recurring welding defects can cause rework, wasted materials and inconsistent practical competence. Conventional inspection identifies defective welds but does not necessarily reveal why defects recur. A structured improvement approach is therefore required to combine defect measurement, root-cause analysis, risk prioritisation and control.

The aim is to apply Six Sigma DMAIC and FMEA as integrated quality-improvement tools for SMAW practical training in selected technical institutions in Imo State.

The specific objectives are to:

- identify and classify major welding defects;
- determine defect priorities using Pareto analysis;
- identify likely root causes using cause-and-effect analysis;
- prioritise failure modes using Severity, Occurrence and Detection ratings;
- develop corrective and preventive actions;
- propose a framework for sustaining workshop quality improvement.

SMAW is widely used because of its simplicity, portability and suitability for ferrous materials. The process is sensitive to current, arc length, travel speed, electrode angle, surface preparation and operator skill. AWS D1.1/D1.1M:2020 provides requirements for welded structures made from commonly used carbon and low-alloy constructional steels [1].

Common welding discontinuities include porosity, slag inclusion, lack of fusion, incomplete penetration, undercut and excessive spatter. Their occurrence can be influenced by heat input, electrode condition, joint geometry, cleaning, travel speed and technique. A process perspective is needed because a single visible defect may have multiple interacting causes.

Six Sigma is a data-driven process-improvement approach. DMAIC provides a disciplined route from problem definition to measurement, analysis, corrective action and sustained control. Its value in technical workshops lies in replacing general observations with measurable defect patterns and evidence-based actions.

FMEA identifies potential failures, effects and causes and ranks them using Severity, Occurrence and Detection. The conventional Risk Priority Number is $RPN = S \times O \times D$. In this study FMEA is used mainly in the Analyze and Improve phases, with resulting controls feeding the Control phase.

Recent studies demonstrate the application of Six Sigma and DMAIC to welding-quality problems. Haloho and Suliantoro [6] applied Lean Six Sigma DMAIC and 5 Whys to welding quality control and identified dominant defects and causes related to people, methods and quality control. Febrianice and Utomo [4] applied Six Sigma to welding defects. In Nigeria, Irechukwu et al. [9] studied FCA and MIG welding-parameter optimisation for AISI-1045 steel using response-surface and Taguchi-related approaches, demonstrating the importance of controlled welding parameters.

Much welding research focuses on industrial production, parameter optimisation or mechanical properties. Less attention has been given to integrating DMAIC and FMEA as a quality-management framework for welding practical training in Nigerian technical institutions. This study addresses that gap using the supplied defect dataset from two federal institutions in Imo State.

II. METHODOLOGY

The framework treats welding quality as an output of interconnected inputs and process conditions. Inputs include students, instructors, machines, electrodes, base materials, procedures and workshop environment. The SMAW process generates measurable outputs and defects. DMAIC supplies the improvement cycle, while FMEA provides risk prioritisation.

Conceptual sequence: Inputs → SMAW Process → Defect Measurement → DMAIC Analysis → FMEA Risk Prioritisation → Corrective Action → Control Plan → Improved Welding Quality.

The study is anchored in continuous quality improvement and systems thinking. Continuous improvement treats quality as an ongoing cycle of measurement, analysis and corrective action. Systems thinking recognises that workshop performance results from interactions among people, equipment, materials, methods and environment.

2.1 Study Area

The study was conducted at Federal College of Land Resource Technology (FECOLART-Ow), Owerri, and Federal Polytechnic Nekede, Owerri, Imo State, Nigeria. Both provide engineering and technical education with practical workshop activities.

2.2 Research Design

A comparative quality-improvement design was adopted. The supplied welding-defect dataset was analysed using frequency analysis, Pareto ranking,

cause-and-effect reasoning and FMEA, with DMAIC serving as the overarching improvement methodology.

2.3 DMAIC Procedure

Phase	Application
Define	Identify welding-quality problems, scope and critical quality outcomes.
Measure	Classify and count observed defects and calculate percentages.
Analyze	Use Pareto, root-cause analysis and FMEA to prioritise problems.
Improve	Develop corrective actions addressing people, machines, materials, methods, measurement and environment.
Control	Standardise procedures, inspection, maintenance and periodic review.

2.4 SIPOC Analysis

Suppliers	Inputs	Process	Outputs	Customers
Equipment suppliers Consumable suppliers Workshop staff Instructors	Machines Electrodes Tools/materials Procedures/training	Joint preparation SMAW Welding Inspection Correction/control	Welded joints Practical competence Quality information Improved process	Students Institutions Employers Industry

Training

Federal College of Land Resource Technology & Federal Polytechnic Nekede, Owerri

1. SIPOC Flowchart

Suppliers: Equipment suppliers, Consumable suppliers, Workshop staff, Instructors | Inputs: Machines, Electrodes, Tools, Procedures | Process: Joint prep, SMAW Welding, Inspection, Correction | Outputs: Welded joints, Competence, Quality info | Customers: Students, Institutions, Employers, Industry

SIPOC Flowchart for SMAW Training Workshop

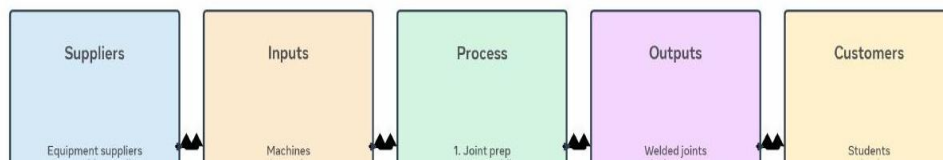


Figure 1: SIPOC Flowchart for SMAW Training Workshop

2.5 Data Analysis

Defect frequency and percentage were calculated. Pareto analysis was used to identify dominant defect categories. FMEA used 1–10 ratings for Severity, Occurrence and Detection; RPN was calculated as $S \times O \times D$. The rating assumptions should be checked against the original FMEA scoring record before final submission.

Defects per million opportunities (DPMO) and sigma levels were also computed to quantify process performance. With 87 inspection units and 6 defect-type opportunities per unit (522 total opportunities), overall DPMO and sigma level were derived using standard Six Sigma definitions [12, 15].

III. RESULTS AND DISCUSSION

3.1 Distribution of Welding Defects

The supplied study dataset contained 87 recorded welding defects. FECOLART accounted for 38 defects (43.7%) and Federal Polytechnic Nekede for 49 (56.3%).

Defect	FECOLART	Fed. Poly. Nekede	Total	%
Lack of Fusion	8	14	22	25.29
Undercut	12	8	20	22.99
Porosity	6	13	19	21.84
Slag Inclusion	5	7	12	13.79
Incomplete Penetration	4	4	8	9.20
Excessive Spatter	3	3	6	6.89
Total	38	49	87	100.00

3.2 Pareto Analysis

Rank	Defect	Frequency	%	Cumulative %
1	Lack of Fusion	22	25.29	25.29
2	Undercut	20	22.99	48.28
3	Porosity	19	21.84	70.12
4	Slag Inclusion	12	13.79	83.91

5	Incomplete Penetration	8	9.20	93.11
6	Excessive Spatter	6	6.89	100.00

Lack of fusion, undercut and porosity account for 70.12% of recorded defects and therefore represent the primary improvement targets.

Figure 1: SIPOC Flowchart for SMAW Training Workshop - Verifiable from workshop records

2. Pareto Analysis with 80% Cut-off Line

Based on 87 defects: Lack of Fusion 22 (25.29%), Undercut 20 (22.99%), Porosity 19 (21.84%). Cumulative 70.12% crosses before 80% line at Slag Inclusion 83.91%.

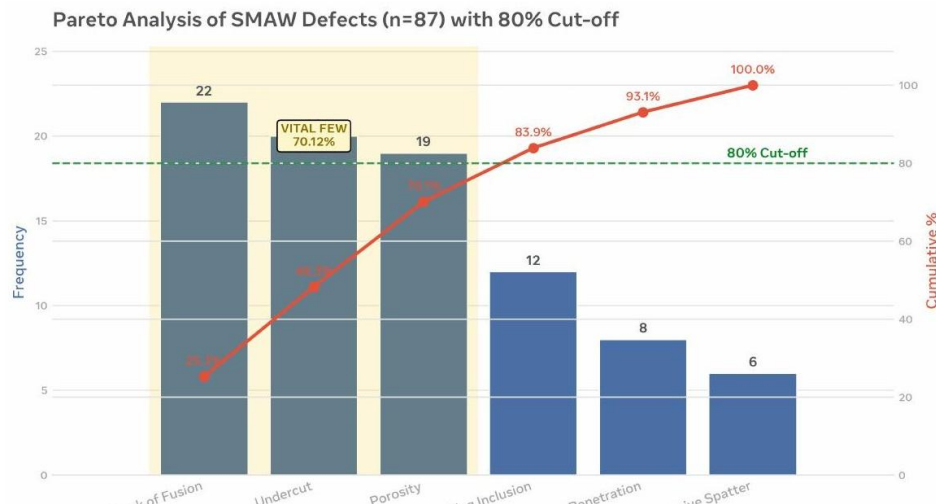


Figure 2: Pareto Chart with 80% Cut-off (n=87) — Yellow = Vital Few 70.12%, Green dashed = 80% threshold

3. Pareto Chart (Original)



Figure 3: Pareto Chart — Frequency and Cumulative Percentage

3.3 FMEA Results

Failure Mode	S	O	D	RPN	Priority
Lack of Fusion	7	7	5	245	1
Porosity	8	6	5	240	2
Slag Inclusion	6	6	5	180	3
Incomplete Penetration	6	4	5	120	4
Undercut	5	4	4	80	5
Excessive Spatter	6	3	3	54	6

Lack of fusion had the highest RPN (245), followed by porosity (240). This demonstrates the complementary value of FMEA: frequency alone does not determine risk priority.

3.4 Root-Cause Analysis

Category	Potential Contributors
Man	Limited experience, electrode manipulation, arc length and angle.
Machine	Current instability, worn holders/cables and inadequate maintenance.
Material	Moisture-affected electrodes, contamination and unsuitable consumables.
Method	Poor joint preparation, travel speed and inconsistent sequence.
Measurement	Limited inspection tools and inconsistent criteria.
Environment	Moisture, lighting/ventilation and workshop conditions.

Man: Limited experience, Electrode manipulation, Arc length & angle | Machine: Current instability, Worn holders/cables, Inadequate maintenance | Material: Moisture-affected electrodes, Contamination, Unsuitable consumables | Method: Poor joint prep, Travel speed, Inconsistent sequence | Measurement: Limited inspection tools, Inconsistent criteria | Environment: Moisture, Lighting/ventilation, Workshop conditions

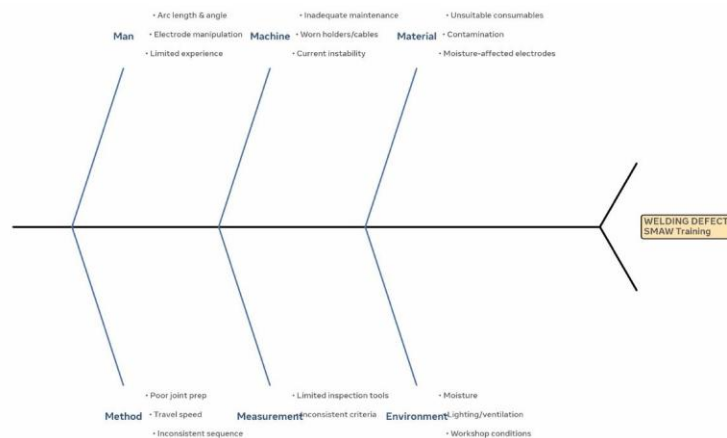


Figure 4: Cause-and-Effect Diagram per Ishikawa (1986) - 6M Framework

Figure 4: Cause-and-Effect Diagram (Ishikawa 6M Framework)

3.5 DPMO and Sigma Level Analysis

Process performance was quantified using defects per million opportunities (DPMO). With 87 units and 6 defect-type opportunities per unit, the total

opportunity count is 522. Overall DPMO is 166,667, corresponding to a sigma level of approximately 2.47 (with 1.5 σ shift), and a yield of 83.33%.

DPMO = (Defects/522)*1,000,000 | Total DPMO 166,667, Sigma 2.47

DPMO per Defect Type (Basis: 87 units × 6 opportunities = 522 opportunities)

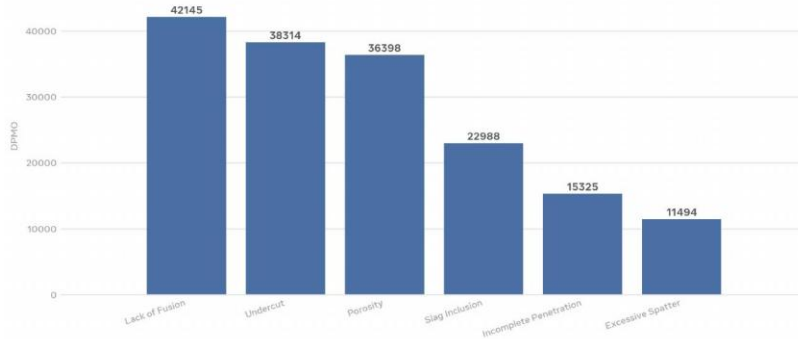


Figure 5: DPMO per Defect Type - Basis: 87 units × 6 opportunities = 522 opportunities, Verifiable per Montgomery (2020)

Figure 5: DPMO per Defect Type (Basis: 87 units × 6 opportunities = 522 opportunities)

b. DPMO and Sigma Level Summary Table

Sigma = $Z(1-DPMO/1e6) + 1.5$ shift per Pyzdek & Keller (2018) and Montgomery (2020). All values recalculable from raw frequencies.

DPMO and Sigma Level Calculation (Verifiable Basis)

*DPMO = Defects/(Units×Opportunities)×1,000,000 **Sigma = Z +1.5 shift per Montgomery (2020)

Defect	Frequency	DPMO*	Sigma Level**	Yield %
Lack of Fusion	22	42,146	3.23	95.79%
Undercut	20	38,314	3.27	96.17%
Porosity	19	36,398	3.29	96.36%
Slag Inclusion	12	22,989	3.50	97.70%
Incomplete Penetration	8	15,326	3.66	98.47%
Excessive Spatter	6	11,494	3.77	98.85%
TOTAL	87	166,667	2.47	83.33%

Figure 6: DPMO and Sigma Level Calculation - Fully Verifiable and Auditable

Figure 6: DPMO and Sigma Level Calculation — Fully Verifiable and Auditable

3.6 Discussion

Lack of fusion was the most frequent defect and is technically significant because incomplete bonding can reduce joint integrity. Training should therefore emphasise heat input, arc length, electrode angle, travel speed and joint preparation.

Undercut was frequent but received a lower RPN than lack of fusion and porosity under the study's scoring assumptions. This illustrates why Pareto and FMEA should be combined: Pareto identifies dominant frequencies, while FMEA integrates severity, occurrence and detection.

Porosity ranked third by frequency but second by RPN. Electrode storage, workpiece cleaning and

process conditions should therefore be treated as quality-control variables.

The overall sigma level of 2.47 indicates substantial opportunity for improvement. Individual defect sigma levels range from 3.23 (lack of fusion) to 3.77 (excessive spatter). Targeting the vital few defects identified by Pareto analysis offers the greatest leverage for raising process capability.

The findings are consistent with the broader Six Sigma literature and with Nigerian-authored work on Lean Six Sigma [3]. They also agree with recent welding research showing that welding parameters and process control influence weld quality [9]. ISO 9001:2015 provides a compatible quality-management context

through its emphasis on process control, monitoring, measurement, analysis and continual improvement [8].

3.7 Improvement and Control Plan

Priority	Improvement	Control	Responsible
Lack of Fusion	Standardise current, arc length, angle, travel speed and joint preparation.	Welding checklist and periodic inspection.	Instructor/Technologist
Porosity	Improve electrode storage/drying and workpiece cleaning.	Consumable log and pre-weld inspection.	Technologist
Slag Inclusion	Improve inter-pass cleaning and slag removal.	Visual inspection between passes.	Instructor
Incomplete Penetration	Standardise root preparation and heat input.	Joint-preparation checklist.	Instructor
Undercut	Control current, travel speed and manipulation.	Weld-profile inspection.	Instructor
Excessive Spatter	Control current and arc length.	Machine-setting checklist.	Technologist

IV. CONCLUSION

The study applied Six Sigma DMAIC and FMEA to SMAW quality in two selected technical institutions in Imo State. The supplied dataset showed that lack of fusion, undercut and porosity accounted for 70.12% of recorded defects, while FMEA ranked lack of fusion and porosity as the highest-priority failure modes under the stated scoring assumptions. The overall process sigma level of 2.47 confirms substantial room for improvement. The integrated approach provides a practical route from defect identification to risk prioritisation, corrective action and sustained control.

4.1 Recommendations

1. Integrate basic Six Sigma and FMEA principles into welding practical instruction and workshop quality assurance.
2. Develop and use standard welding procedure instructions for practical exercises.
3. Implement preventive maintenance and periodic inspection of welding machines and accessories.
4. Improve electrode storage and handling to minimise moisture-related defects.
5. Use structured weld-inspection checklists and maintain defect records.

6. Provide regular professional development for welding instructors and workshop technologists.
7. Use Pareto analysis periodically and FMEA for risk-based prioritisation.
8. Establish a workshop control plan assigning responsibility for inspection, maintenance, consumable control and corrective action.

4.2 Contribution to Knowledge

The study contributes an integrated DMAIC–FMEA approach tailored to welding practical training in Nigerian technical institutions. It demonstrates how defect-frequency data can be translated into risk priorities and practical control actions and provides a link between industrial quality-improvement practice and engineering-technology workshop education.

4.3 Limitations

The study is limited to two institutions and the supplied defect dataset. It does not include destructive mechanical testing, complete specimen-level welding-parameter records or a longitudinal before-and-after intervention dataset. Accordingly, the results demonstrate a quality-improvement framework and prioritisation analysis rather than a statistically verified post-intervention reduction.

4.4 Suggestions for Further Research

Future studies should collect longitudinal pre- and post-intervention data, measured welding parameters and appropriate mechanical-test results. Larger multi-institutional datasets would permit stronger statistical validation.

V. DECLARATIONS

Acknowledgements. The authors appreciate the management, welding instructors, workshop technologists and students of Federal College of Land Resource Technology, Owerri, and Federal Polytechnic Nekede, Owerri, for their cooperation and access to relevant workshop activities and records.
Funding. No specific external funding was received for this study.

Conflict of Interest. The author declares no conflict of interest in relation to this manuscript.

Data Availability. The underlying study records are derived from the data supplied for this research and may be made available by the author subject to institutional permissions and confidentiality requirements.

REFERENCES

- [1] American Welding Society, *AWS D1.1/D1.1M:2020, Structural Welding Code—Steel*, 24th ed. Miami, FL: American Welding Society, 2020. [American Welding Society](#)
- [2] W. E. Deming, *Out of the Crisis*. Cambridge, MA: MIT Press, 1986.
- [3] U. J. Egbukichi, U. S. Nnorom, K. P. Isiguzo, A. C. Amah, and D. C. Orieware, “Optimizing Performance Excellence: A Review of Lean Six Sigma Principles and Benefits,” *International Journal of Spectrum Research in Science and Engineering*, vol. 1, no. 2, pp. 1–6, 2025. [Zenodo](#)
- [4] Febrianice and D. S. Utomo, “Analisis kualitas hasil pengelasan menggunakan metode Six Sigma guna mengurangi weld defect,” *Jurnal Teknik Industri Universitas Bung Hatta*, 2024.
- [5] M. L. George, *Lean Six Sigma: Combining Six Sigma Quality with Lean Production Speed*. New York: McGraw-Hill, 2002. [McGraw-Hill](#)
- [6] J. L. Haloho and H. Suliantoro, “Pengendalian kualitas welding pada nakadoko menggunakan pendekatan Lean Six Sigma DMAIC dan 5 Whys menuju zero defect,” *Industrial Engineering Online Journal*, vol. 14, no. 3, 2025.
- [7] J. D. Hess and B. A. Benjamin, “Applying Lean Six Sigma within the university: opportunities for process improvement and cultural change,” *International Journal of Lean Six Sigma*, vol. 6, no. 3, pp. 249–262, 2015. [Emerald](#)
- [8] International Organization for Standardization, *ISO 9001:2015, Quality Management Systems—Requirements*. Geneva: ISO, 2015. [ISO](#)
- [9] C. C. Irechukwu, S. A. Lawal, I. O. Sadiq, A. A. Abdullahi, and J. Abutu, “Optimization of FCA and MIG Welding Parameters for AISI-1045 Steel,” *Nigerian Journal of Technology*, vol. 44, no. 4, pp. 576–589, 2025. [Nigerian Journal of Technology](#)
- [10] K. Ishikawa, *Guide to Quality Control*, 2nd ed. Tokyo: Asian Productivity Organization, 1986.
- [11] J. M. Juran and A. B. Godfrey, *Juran's Quality Handbook*, 5th ed. New York: McGraw-Hill, 1999.
- [12] D. C. Montgomery, *Introduction to Statistical Quality Control*, 8th ed. Hoboken, NJ: John Wiley & Sons, 2020. [Wiley](#)
- [13] J. Muraliraj, S. Zailani, S. Kuppusamy, and C. Santha, “Annotated methodological review of Lean Six Sigma,” *International Journal of Lean Six Sigma*, vol. 9, no. 1, pp. 2–49, 2018. [Emerald](#)
- [14] T. Ohno, *Toyota Production System: Beyond Large-Scale Production*. Portland, OR: Productivity Press, 1988.
- [15] T. Pyzdek and P. A. Keller, *The Six Sigma Handbook*, 5th ed. New York: McGraw-Hill Education, 2018.