

A KNOWLEDGE-BASED APPLICATION OF A SIX SIGMA-DMAIC TYPOLOGY IN PROCESS IMPROVEMENT: A CASE OF CABLE MANUFACTURING IN NIGERIA

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Abstract

The case organization has, over the years, been plagued with a variety of production issues in the form of high rejection % of cable after extrusion owing to insulation surface faults, failed insulation thickness, low conductor diameter, and variability in cable dimensions, etc. Even though the case organization had previously employed several consulting firms to assist in resolving some of these issues, the problems continue to exist and threaten the business. This study examined the possible advantages of integrating the Knowledge Management (KM) approach into the Six Sigma-DMAIC (SS-DMAIC) implementation methodology in an organizational setting, even though hundreds of studies have already been done to examine different facets of Six Sigma. Descriptive and inferential statistics were used to analyze the collected data. Measurement System Analyses (MSA), Process Capability Analysis (PCA), Analysis of Variance (ANOVA), and Design of Experiment (DOE) with central composite design (CCD) were used in the study. The study's completion resulted in a peak improvement in process capability, with a significant reduction in Defects Per Million Opportunities (DPMO) from 13,900 to 10, improving the Sigma level from 3.7 to 5.2. The number of non-conformed cables rejected due to insulation surface flaws was reduced by 57% from the baseline value of 22,256 meters to 9,570 meters within the observed production quarters.

1. Introduction

Quality and productivity play an important role for any organization, especially for the manufacturing sector, where more profit is essential for the company to succeed (Kulkarni et al., 2021). The case organization faces several issues that can be divided into social and technical. Social issues include the organization's lack of an organic framework to create a knowledge spiral among its employees, which leads to issues like knowledge loss or inability to retain knowledge, as well as the inability to replicate best practices. Unacceptable variation in cable products contributes greatly to many defects, which leads to higher production costs, lower profit, and customer dissatisfaction. As a result, many organizations within this specialty are now capitalizing on their knowledge-based assets, searching for systematic ways to cut production costs, improve production rate, and quality in cable manufacturing. The acknowledged ability to retain, develop, organize, and utilize their employees' capacities is nonexistent since "Community of Practice" (CoP)-related techniques related to process improvement are not intentionally used. According to the organization's records, between January 2013 and February 2017, 46.5% of the length of 1.0 mm cables were rejected because of inadequate concentricity in the extrusion process. This equated to 46.5% of the overall cost of poor quality (COPQ) during the manufacturing period under observation.

Furthermore, during the same time, the percentage of cables rejected because of rough insulation surfaces reached 43.9%, resulting in a cost accrual of 44% of the entire cost. The two flaws accounted for 90.7% of COPQ and consistently happened every quarter. A design that eliminates the anomalies of having cables that are over- and under-dimensioned is also necessary due to the variability in cable dimensions. Low-dimensioned cables frequently fail the insulation thickness test.

In contrast, over-dimensioned cables indicate that more polyvinyl chloride (PVC) material is used in production than necessary. Our Six Sigma initiatives' primary goals were to minimize insulation material waste, decrease cable concentricity variances, and slow the occurrence of insulation surface defects. In technical terms, the pilot study revealed that the organization's use of statistical tools to track process improvement is still ill-conceived, and the application of the Five "Whys" to process/quality-related issues has proven ineffective in offering a measurable metric for evaluating product variation.

SS is a business strategy that seeks to identify and eliminate causes of defects or failures in business processes by focusing on outputs critical to customers (Snee, 1999). Its DMAIC method is rather general, and its original task domain was variation reduction, especially in manufacturing processes (De Mast & Lokkerbol, 2012). The essence of the SS method is to reduce variation in a process to achieve high conformance quality in the customer's terms. Six Sigma attempts to integrate the most powerful statistical and non-statistical tools and techniques in a well-disciplined manner (Antony, 2022). The SS is concerned about removing variability from the existing processes. SS methodology forces project leaders to capture problems regarding facts and measurable variables. However, research on the subject of Six Sigma (SS), despite its impressive track record in practice, is still low (Zhang et al., 2009). This results from divergent views and set perceptions on the SS subject. Some scholars understand SS simply as repackaging the well-known total quality management (TQM) (Beer, 2003), while others view it as a management fad. However, the ability of SS to achieve both efficiency and innovation has been challenged from different perspectives, and most researchers have argued that the utilization of process management methodologies favours exploitative innovation at the expense of eliminating explorative innovation. With much emphasis on process improvement and variance reduction, SS would impede product innovation and radical change (Parast, 2011), and many quality management proponents argued that Six Sigma projects focus primarily on understanding and identification of critical characteristics to the existing customers (Harry, 1998; Dasgupta, 2003; Evans & Lindsay, 2005), at the expense of threatening the ability of the firm to identify new customers and introduce new products and/ or services. Thirdly, as a spin-off of quality management, SS maintains a strong emphasis on setting specific goals (Linderman et al., 2003), and according to Pande et al., (2000) setting a clear goal is central to SS and as such, cannot address the core principles of quality management such as a culture of learning, continuous improvement of processes, and a system view of the organization. However, the ability of SS to achieve both efficiency and innovation has been challenged from different perspectives.

Benner and Tushman (2003) overthink dependence on SS improvement methodology will only encourage exploitative innovation. However, Snee (2000) calls for research to help practitioners identify a robust set of improvement tools to be used in conjunction with the SS-DMAIC process. Any process can be improved to an infinite degree Through proper integration between SS methodology and other improvement/management initiatives. In recent time, a lot of studies that focused on the shared relationship between SS and other innovative management and practices were as follows; integrating and comparing principles and characteristic of SS with Total Quality Management (Uluskan et al 2017; Revere and Black, 2003;), integrating and comparing principles and characteristics of Six Sigma with human resource functions (Wyper and Harrison, 2001), integrating with the theory of constraints (Ehie and Sheu, 2005), integrating with lean production (Vincente et al., 2024; Daniyan et al., 2022; Gavagan et al., 2024; Hussain et al., 2024; Oliveira et al., 2023), Integrating with Business Process Management (Graves, 2014), integrating with value stream mapping (2016); integrating with Balanced score card SCOR model (Knowles et al 2005), integrating Six Sigma with ISO 9000 (Catherwood, 2002), Integrating with ISO 9001 (Dagleish, 2005), and integrating Six Sigma with the capability maturity model (Murugappen and Kenni, 2003) are all part of the quality community's effort to maximize the positive effect of the Six Sigma method. Martin (2006) incorporates an operations research technique in the analysis phase. Even with these numbers of Six Sigma Integration, there are still huge, reported cases of Six Sigma failures which most researchers (Kwak and Anbari, (2004); Antony (2004b); Parast, (2011); Alsagheer and Mohammed, (2011)) aligned to organizations inability to retain knowledge and sustain learning environment. Knowledge plays a crucial role in the success of DMAIC execution (Thanh Dat et al., 2016). Based on the experiences in the literature concerning many manufacturing companies that have implemented SS techniques without creating the underlying culture of learning, this has begot the era of shared relationship between SS and KM integration. Moosa and Sajid (2010) attributed most failures of the SS implementation approach to the lack of a standard model and to several social factors that prevail

in organizations. Few recent works on SS and KM integration have been reported in the literature by Gowen et al. (2008) and Baral et al. (2014). Few of the recently reported Six sigma-KM integration and proposed models, such as the Raytheon SS model, TEKIP model, Process-based knowledge creation and opportunities model, and knowledge flow model in Chinese SS teams, focused more on the technology aspect of KM enabler, and with less support on the organizational social structure/dimension.

2. METHODS

A uniform way to implement Six Sigma-DMAIC usually remains a myth (Moosa & Sajid, 2010), and its application, according to Tennant (2002), is still novel. In this study, the power of the generality trade-off was explored by augmenting the Six Sigma methodology with domain-specific adaptations, which include introducing additional Knowledge Management techniques in the existing method to make it more powerful for application. Six Sigma-DMAIC five-phase methodologies were followed emphatically, incorporating a lesson learning mechanism also within its approach to ensure that the eagerly sought improvements are well sustained and not short-lived.

2.1. Define Phase

The research aim at this phase was centered on identifying real-life problems, and the goal statement was to improve the extrusion process capability of 1.0mm single cable by reducing the rate of extruding cables with insulation surface flaws and cables with inconsistent dimensions. The Define phase of the Six Sigma-DMAIC provides the socialization environment, just like a reflection of the Nonaka SEIC model, where sharing experiences with other members aids in transferring tacit knowledge. At the define phase, the community of practice (CoP) was initiated, comprising of four heterogeneous mix of personnel from Quality Assurance Department (QAD) and Manufacturing Department (MD), The idea of initiating the Cop in this phase was as a result of informal knowledge representation in tacit order and core knowledge creation takes place at the group level as the team engages in improvement studies. A project charter was drafted containing necessary information about the project selected, see Appendix 1.

2.2. Measure Phase

The major activity in the measure phase is to understand the baseline condition of the system to be improved. Two sets of analyses are being conducted at this stage: Measurement System Analysis (MSA) and Process Capability Analysis (PCA). MSA was first conducted to validate that the measurement systems are good enough for the study. Under these MSA studies, two analyses were conducted: Attribute Gage repeatability and Reproducibility for attribute data (insulation smoothness), and Gage Repeatability and Reproducibility analysis for variable data (Cable diameter/dimension). Mathematically, the total variance in a quality characteristic of a process is described by Eqns. (1) & (2), while the percentage contribution of the measurement system to the total variance is calculated using Eqn. (6) The study's other useful Gage R & R metrics are also represented mathematically.

$$\sigma^2_{total} = \sigma^2_{product} + \sigma^2_{measurement} \quad (1)$$

$$\sigma^2_{measurement} = \sigma^2_{Repeatability} + \sigma^2_{Reproducibility} \quad (2)$$

Where, σ^2_{total} = total variance; $\sigma^2_{product}$ = variance due to product; $\sigma^2_{measurement}$ = variance due to measurement system; $\sigma^2_{Repeatability}$ = variance within operator/device; $\sigma^2_{Reproducibility}$ = variance between operators.

$$\sigma^2_{Reproducibility} = \sigma^2_{Operator} + \sigma^2_{Part*Operator} \quad (3)$$

$$\% \text{ contribution} = \frac{\sigma^2_{Repeatability} + \sigma^2_{Reproducibility}}{\sigma^2_{Total}} \times 100 \quad (4)$$

$$\% \text{ Study variation} = \frac{\sigma_{measurement}}{\sigma_{total}} \times 100 \quad (5)$$

$$\sigma_t = \sqrt{\sigma^2_m + \sigma^2_P} \quad (6)$$

$$\sigma_p = \frac{R_p}{d_2^*} \quad (7)$$

$$\text{Two-sided Spec\% \% P/T} = \frac{6\sigma_{\text{measurement}}}{USL - LSL} \times 100 \quad (8)$$

$$\text{NDC} = 1.41 \left[\frac{PV}{\sigma^2 \text{ Re peatability} + \sigma^2 \text{ Re producibility}} \right] \quad (9)$$

Where σ_t = total process standard deviation; σ_p = part-to-part standard deviation; PV = part-to-part variation; NDC = the number of distinct data categories that can be created with this measurement.

$$UCL = D_4 \bar{R} \quad (10)$$

$$LCL = \bar{X} - A_2 \bar{R} \quad (11)$$

$$UCL = \bar{X} + A_2 \bar{R} \quad (12)$$

A_2 , D_3 , and D_4 are factors obtained from tables of constants used in constructing control charts. From the graphical illustration in Figure 1, for the attribute data, we can see that the operators agreed with each other 90% of the time and agreed with the expected (standard) result 90% of the time. The Kappa Value for all appraisers versus the standard values was 0.90, indicative of excellent agreement between the appraised values and reference values.

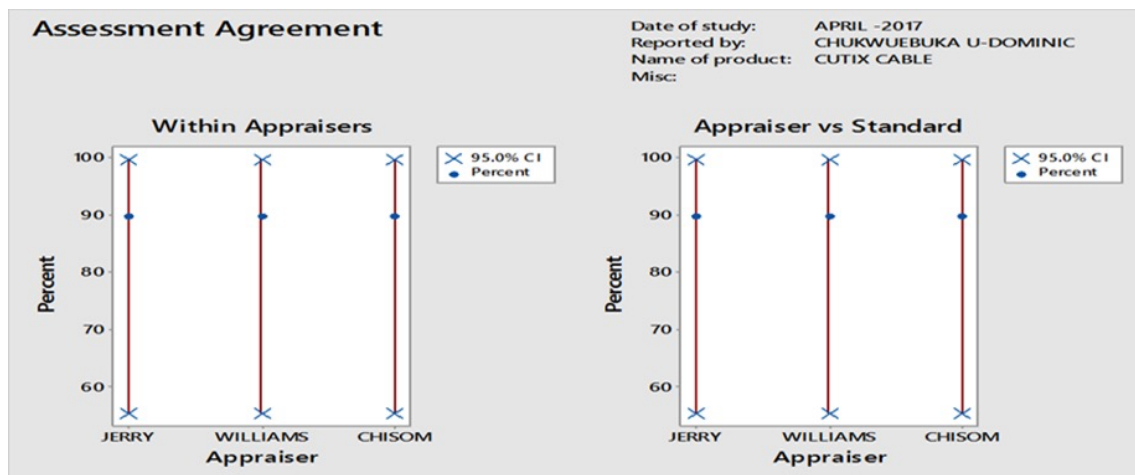


Figure 1. Measurement System Analysis results for the attribute data

The analytical results from Minitab-17 Software for the variable data show that the percentage contribution of Var Comp = 0.05%, percentage Study Var = 2.30%, percentage Tolerance = 2.92%, while the number of distinct categories NDC = 61. Comparing these results with the benchmark values in the Automotive Industry Action Group (AIAG, 2010) reference manual, we found the measurement system good enough for the study. After the measurement system had been validated and found reliable, the stability of the process was ascertained using the control chart, and then the process was established. Capability studies were conducted.

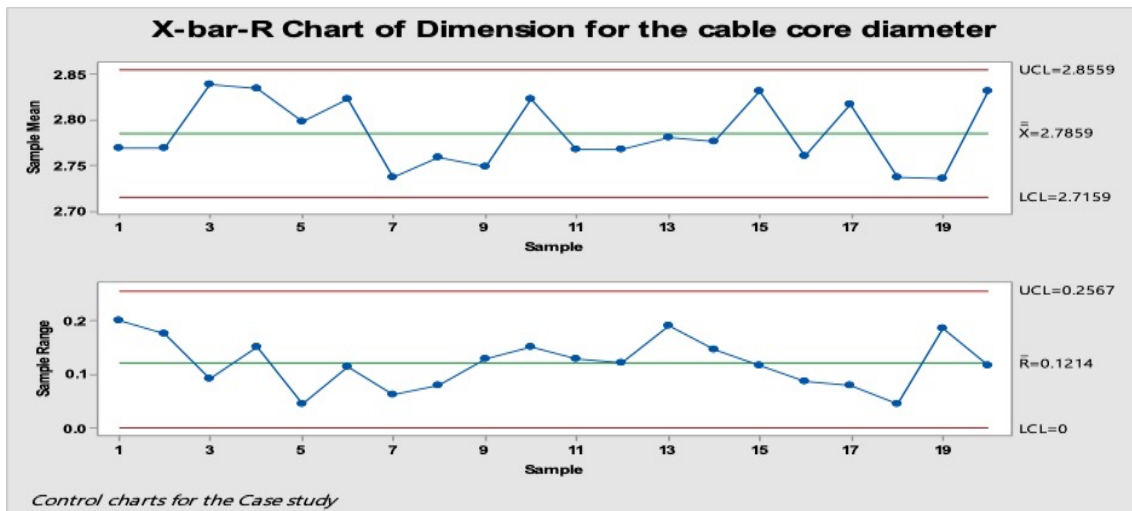


Figure 2. X-Bar-R chart of the Cable diameter data

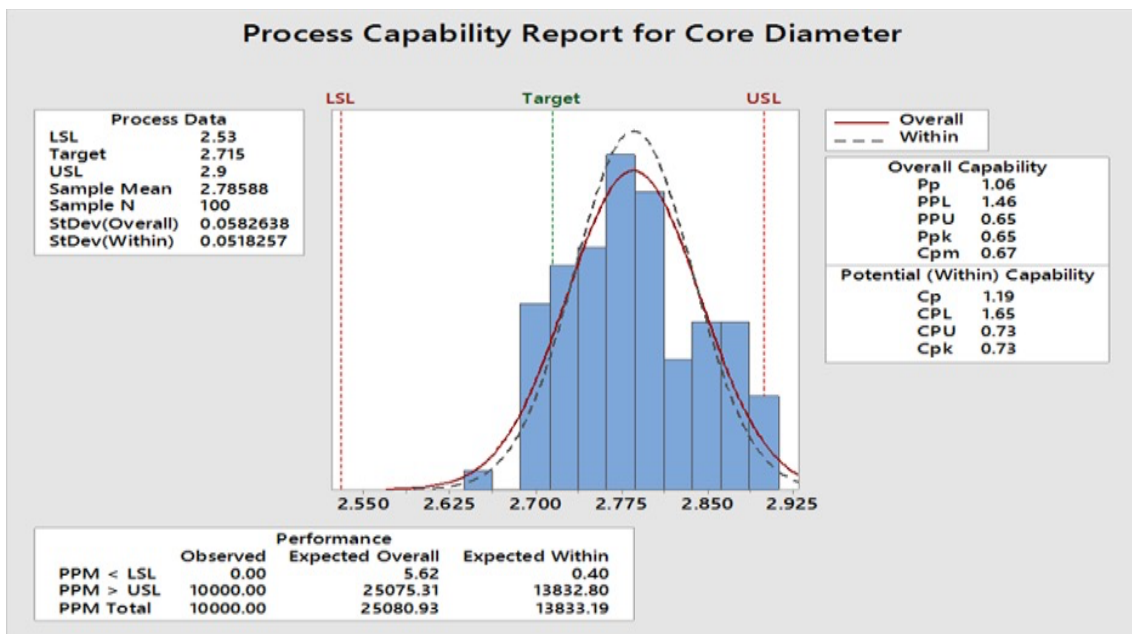


Figure 3. Pictures the baseline process capability report on the core cable diameter

The calculated ZU for the process is 2.18, from the table (Area under the standard normal curve), $ZU = 1 - 0.9854$. According to this estimation, approximately 1.46% of the cable produced will exceed the upper specification limit. $ZL = 4.98$ and ZU value of at least +3 is desired (Pyzdek, 2003). Total reject rate = 1.46%, and projected yield = 98.54%.

2.3. Analyze Phase

This phase aimed to investigate reasons for the identified problems, and the data collected in this phase was analyzed to identify the root causes behind the gap between the current performance and the goals identified in the first phase. The selected community initiated the brainstorming session to stimulate and unlock the group's tacit knowledge of the process. This technique was potent in creating many solutions to tackle the poor extrusion performance. The brainstorming results were arranged in rational categories and used to construct a cause-and-effect diagram.

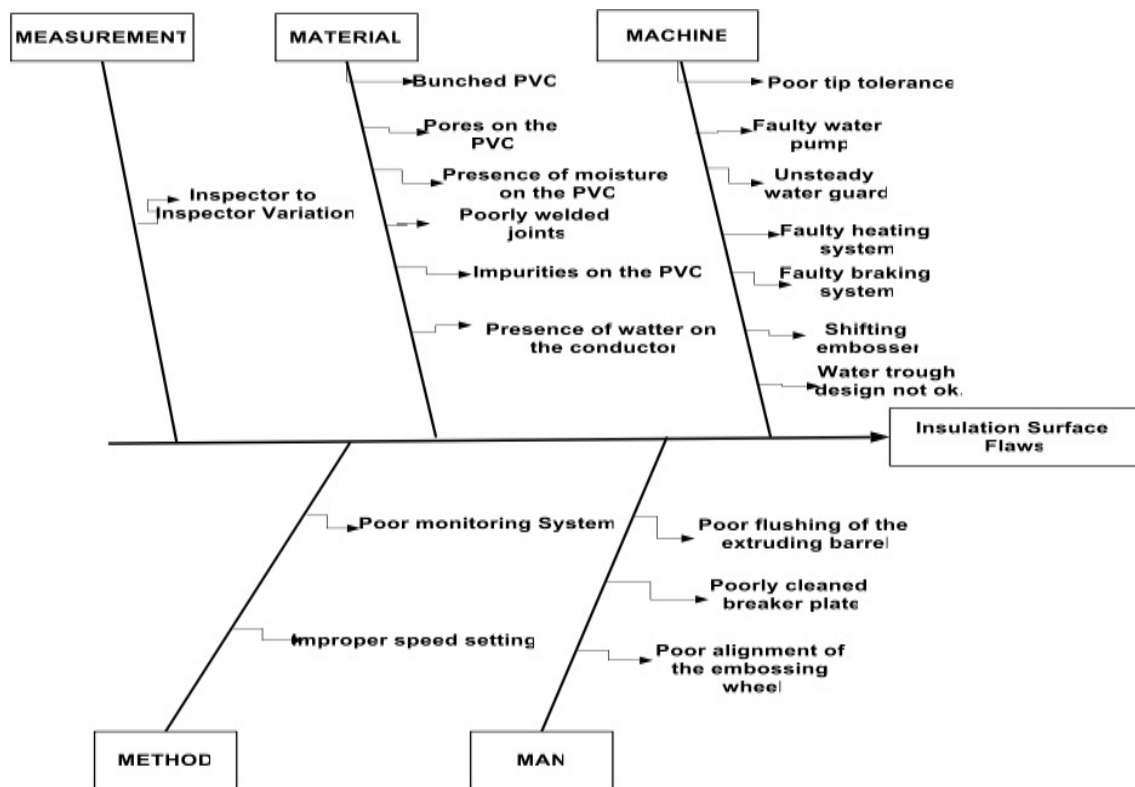


Figure 4. Cause and Effect diagram on the Cable Insulation Surface Flaws

A cause validation plan was also prepared; see Table V, which detailed the collected data type and the possible analysis for each of these causes. Further inquest was undertaken to identify the root causes of these quality defects, and this prompted the team to engage in a detailed discussion with the process personnel (machine operators & process engineers) in identifying the possible data that could be collected on the potential causes. Based on the CoP's interaction, a cause validation plan was prepared that detailed the type of data to be collected and the type of analysis possible for each of these potential causes. After listing the causes, every cause was validated, and the methodology for validation is shown in Table 3.

Table 3. Cause validation Plan on the cause-and-effect diagram

S/N	Causes	Confirmation Plan	Result
1	Faulty heating system	GEMBA	Root cause
2	Faulty water pump	GEMBA	Not a root cause
3	Presence of water on the input conductor	GEMBA/ Touch	Root cause.
4	Pores in the PVC	Microscope Visual inspection.	Root cause.
6	Poor monitoring system	GEMBA	Root cause.
7	Presence of moisture in the PVC	GEMBA	Not a root cause.
8	Improper setting of speed	DOE	Root cause.
9	Poor flushing of the extrusion barrel	GEMBA	Root cause.
10	Water trough design not ok.	GEMBA	Root cause.
11	Shifting embosser.	GEMBA	Root cause.
12	Poor tip tolerance	Measurement	Root cause.
13	Faulty braking system / Low tension	GEMBA	Root cause.
14	Inadequate skill/ negligence	GEMBA / Production yield	Root cause.
15	Bunched PVC	GEMBA	Not a root cause
16	Impurities on the PVC	GEMBA	Not a root cause
17	Poorly welded wire.	GEMBA	Root cause.
18	Management problems / lack of motivation	GEMBA / survey	Root cause.

2.4. Improve Phase

After the root causes were determined during the analysis phase, the DMAIC "Improve" phase aimed at identifying solutions to reduce and tackle the causes. The cause validation plan drawn in

the analysis phase has beneficially aided in identifying the root causes of these defects. Solutions to the identified causes for insulation surface flaws were proffered and followed to the desired specification, as shown in Table 4.

Table 4. Solutions for Reducing Insulation Surface Flaws in Cable Extrusion Process

S/N	Causes of cable Insulation Surface flaws.	Solutions for reducing the rate of cable failures due to Insulation surface flaws.
1	Faulty heating system	Use of high-quality heater bands. Temperature settings must be reduced while the machine operators are on break.
2	Presence of water on the input conductor	Use of oxyacetylene gas flame on every input conductor before extrusion and at intervals while extruding.
3	Pores in the PVC	Compromised quality must not be used
4	Poor monitoring system	Review monitoring strategy by ensuring that during extrusion that both process-based monitoring and product-based monitoring are used to achieve product improvement. [Process-based monitoring watches production process conditions such as melt temperature and pressure while Product-based monitoring follows properties of the product, such as clarity and thickness].
5	Improper setting of speed	Optimal parameter settings through experimental designs.
6	Poor flushing of the extrusion barrel	Proper flushing and adequate monitoring. The process engineer has to certify it ready before the next activities
7	Water trough design not ok.	Redesigning of the water trough guide, interval check on the cable guide.
8	Poor alignment of the embossing wheel or shifting embosser.	Interval check and proper tightening of the wheel.
9	Poor tip tolerance	Not to be used.
10	Faulty braking system	Maintenance/ Overhaul of the braking system.
11	Inadequate skill/ negligence	Adequate training, monitoring and to also make sure that the operators always adhere to standard operating procedure.
12	Poorly welded wire.	Careful filling of the welded joint (measure the welded point after weld)
13	Management problems / lack of motivation	Review the existing incentive programmed, improvise adequate resource planning system that will ensure needed parts and materials are readily available.

The outcome of the brainstorming session has linked the existence of a correlation between Capstan and Extruder speed with the inconsistency in the dimension of the cable produced. To achieve a global optimum for the control setting, statistical Software, Design Expert Version 11, was used to create the response surface design, specifically the Central Composite Design (CCD). The results of the optimization engineering are shown in Tables 5, 6, 7, 8, and 9, respectively.

Table 5. Experimental design using Central Composite Design and response value

Std	Run	Factor 1	Factor 2	Response 1	Response 2
		A: Capstan speed Rpm	B: Extruder speed Rpm	R1 Mm	R2 Mm
5	1	359.467	912.5	2.75	2.74
6	2	465.533	912.5	2.66	2.68
4	3	450	950	2.77	2.77
13	4	412.5	912.5	2.72	2.72
1	5	375	875	2.73	2.74
11	6	412.5	912.5	2.73	2.71
9	7	412.5	912.5	2.70	2.69
8	8	412.5	965.533	2.77	2.78
3	9	375	950	2.92	2.88
1	10	450	875	2.60	2.58
10	11	412.5	912.5	2.68	2.73
7	12	412.5	859.467	2.65	2.63
12	13	412.5	912.5	2.74	2.72

Table 6. Fit summary Response 1: Preheated PVC

Source	Sequential p-value	Lack of Fit p-value	Adjusted R ²	Predicted R ²	
Linear	0.0005	0.1115	0.7416	0.5666	Suggested
2FI	0.8133	0.0867	0.7148	0.2174	
Quadratic	0.7998	0.0468	0.6559	-0.2462	
Cubic	0.1585	0.0493	0.7694	-3.1115	Aliased

Table 7. Response 2: Non-preheated PVC

Source	Sequential p-value	Lack of Fit p-value	Adjusted R ²	Predicted R ²	
Linear	0.0002	0.1172	0.7792	0.6327	Suggested
2FI	0.7728	0.0918	0.7571	0.3515	
Quadratic	0.7402	0.0519	0.7134	-0.0299	
Cubic	0.0643	0.1237	0.8661	-0.7796	Aliased

The fit summary in Tables 6 and 7 shows that both the quadratic and cubic models are ruled out because their Prob > F falls below 0.05. Therefore, the linear model is the identified model, as it does not show a significant lack of fit.

Table 8. ANOVA table for cable dimension using preheated PVC

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	0.0558	2	0.0279	18.22	0.0005	Significant
A-Capstan speed	0.0207	1	0.0207	13.54	0.0042	
B-Extruder speed	0.0351	1	0.0351	22.90	0.0007	
Residual	0.0153	10	0.0015			
Lack of Fit	0.0130	6	0.0022	3.73	0.1115	not significant
Pure Error	0.0023	4	0.0006			
Cor Total	0.0711	12				

Table 9. ANOVA Table for cable dimension using Non-preheated PVC

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	0.0455	2	0.0228	22.17	0.0002	Significant
A-Capstan speed	0.0180	1	0.0180	17.49	0.0019	
B-Extruder speed	0.0276	1	0.0276	26.86	0.0004	
Residual	0.0103	10	0.0010			
Lack of Fit	0.0087	6	0.0014	3.61	0.1172	not significant
Pure Error	0.0016	4	0.0004			
Cor Total	0.0558	12				

The ANOVA in this study confirms the adequacy of the linear model, i.e., Model Prob > F is less than 0.005. The probability values for each term in the model can be seen from the ANOVA tables. The Model F-value of 18.22 and 22.17 from Tables (8) and (9) implies that the models are significant. The p-values for A and B for both responses are less than 0.0500, indicating that A and B are significant model terms. The lack of fit f-values of 3.73 and 3.61 are insignificant relative to the pure error. Fit statistics for R1 response as shown in Table 6 of Appendix L, the predicted R² of 0.5666 is in reasonable agreement with the adjusted R² of 0.7416; the adequate precision ratio is 12.460, an indication of adequate signal. For the response (R2) as shown in Appendix L, the predicted R² of 0.6327 is in reasonable agreement with the adjusted R² of 0.7792; with an adequate precision ratio of 13.7840, an indication of adequate signal. The factors are orthogonal as shown by the VIF value 1 in Table 9 of Appendix L. The models for the quality of extruded cable dimensions were developed to evaluate the relationship between extruding parameters and cable dimensions. These models can estimate experimental results of cable dimensions by any combination of extruding parameters. The developed mathematical models are listed below in terms of actual factors. Equations 13 and 14 are for the prediction of cable dimensions.

$$\text{Cable dimension} = 1.81243 + -0.00126332 * A + 0.00156569 * B \quad (13)$$

$$\text{Cable dimension} = 1.67344 + -0.0013576 * A + 0.00176569 * B \quad (14)$$

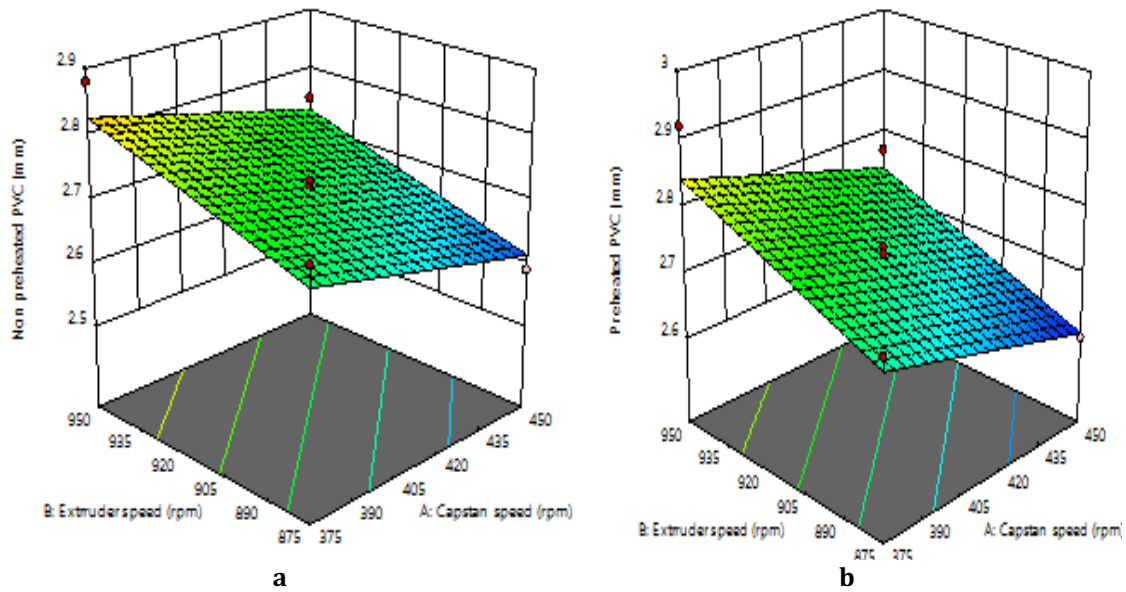


Fig. 4(a) 3D Contour Plot, (b) 3D Contour Plot

Figures 4(a) and 4(b) show the contour plot in three dimensions (3D) of cable diameter measurement values for the preheated and non-preheated PVCs, varying Extruder and Capstan speed. It shows that the cable dimension/diameter value tends to increase noticeably when the Extruder speed increases. Again, a decrease in the cable diameter values was also noticed when there was an increase in the Capstan speed. The point estimation method was conducted to optimize the level of each variable for a nominal response. The combination of different optimized variables to yield the expected response was determined to verify the model's validity. This study involves two responses, R1 for preheated PVC and R2 for non-preheated PVC.

Table 10. Optimization using the desirability criterion

Number	Capstan speed(rpm)	Extruder speed (rpm)	Preheated PVC (mm)	Non-Preheated PVC (mm)	Desirability	
1	416.992	906.790	2.715	2.710	1.000	Selected

From Table 10, the designed output shows that the optimal control settings that would lead to the attainment of the objective (nominal cable dimension) are A (Capstan speed) equal to 416.992 rpm and B (Extruder speed) equal to 906.790 rpm; these settings will yield a cable with a nominal dimension of 2,715mm. Therefore, it is recommended that the RSM (CCD) be used to obtain accurate optimization conditions and products.

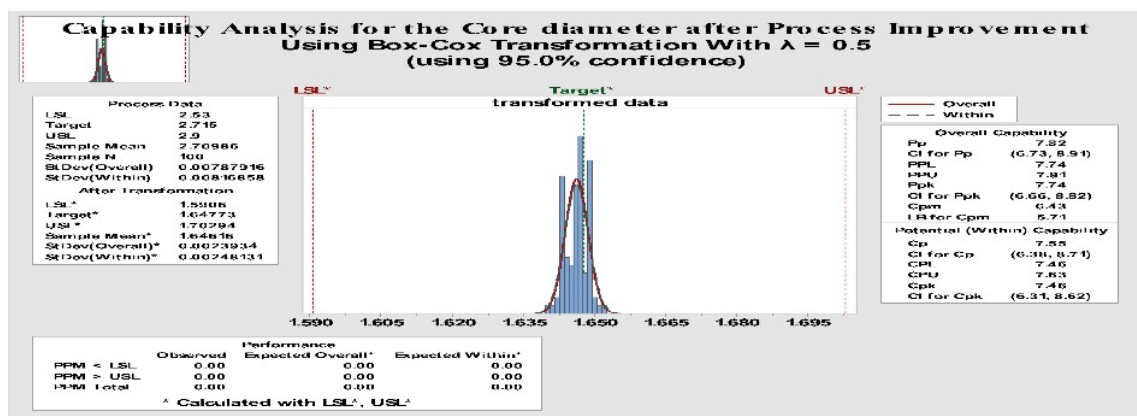


Figure 5. Capability analysis for the Cable diameter measurements after the process improvement

After running the capability analysis on the transformed data, the index results were all high and above recommended Six Sigma value, values like; Cp = 7.55, against the Six Sigma recommended Cp of 2, Cpk = 7.46, Cpm = 6.43, CR = 13.25%, ZU = 22.88, ZL = 22.39, $\sigma_{Overall} = 0.0281477$, $\sigma_{Within} = 0.0314975$ an indication that the existing engineering tolerance is far apart from each other with a large standard deviation. An appropriate tolerance interval was designed from the process to clearly depict the Six Sigma Process. The tolerance intervals design in Six Sigma, according to Pyzdek (2003), is typically of the form:

$$\bar{X} \pm Ks \quad (15)$$

$$s = \sqrt{\frac{\sum(x - \bar{x})^2}{N - 1}} \quad (16)$$

K is a constant determined so that the interval will cover a proportion P of the population with confidence Y, s is the sample standard deviation, x = each value in the sample, \bar{x} = the mean of the values, and N = the sample size. Twenty samples were selected from the stable population to compute in the equation. (4). From the calculations, $s = 0.0087977$, $\bar{x} = 2.7114$, $2.7114 \pm K(0.0087977)$. Finding K value for two-sided limit in tolerance interval factor table for $n=20$, $P = 0.99$, and $Y = 0.95$, then $K = 3.615$. Substituting $k = 3.615$, then $2.7114 \pm 3.615(0.0087977) = 2.7114 \pm 0.32$. $USL = 2.74$ and $LSL = 2.67$ for the new derived engineering tolerance.

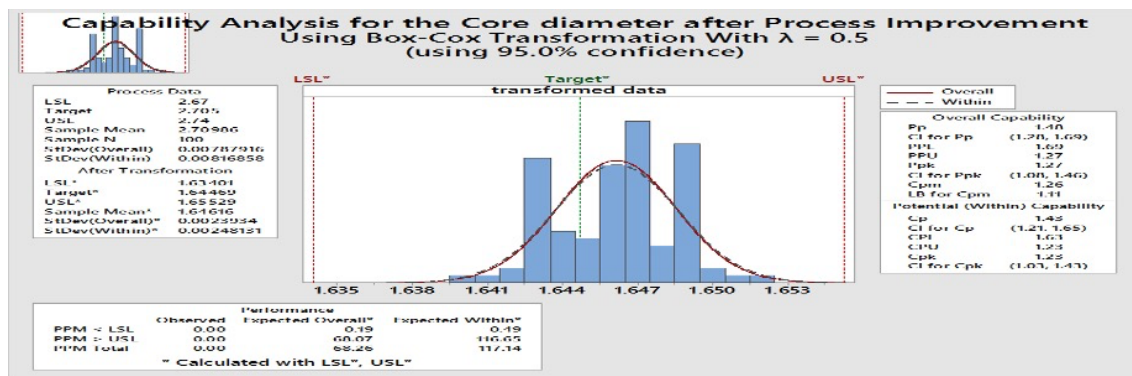


Figure 6. Capability analysis for the Cable diameter measurements after the process improvement with the new engineering tolerance.

The calculated ZL = 4.89, ZU 3.68, and are both above +3, which is quite acceptable, but not up to the Six Sigma process of ZL ZU +6. Checking from the area under the standard normal curve, ZU (3.68) = 1-0.9999. By this estimation, approximately 0.01%. Total reject rate= 0.01%, and projected yield = 99.99%.

2.5. Control Phase

The control phase is about creating and implementing monitoring and response plans to sustain improvements. Control charts were used to monitor the process, and the main reason for using them is to detect the special causes of course variation so that examination and corrective action will be carried out to eliminate them before having an excessive number of non-conforming cables produced. A detailed control plan (see Appendix 2) was drafted, listing necessary measures, the target for each measure, how the measure will be checked, how often the measure will be checked and who will check the measure, as well as actions that will be taken for an out-of-control event, etc. Part of the process control is to identify causes of process variation and categorize them into special and common causes. It is believed that eliminating the special causes of variation will stabilise the process into a state of control. Obvious characteristics of special and common causes of variation are contained in Table 13, and Table 14 categorizes special causes and common causes of variation as were identified in the projects.

Table 13. Characteristics of Common Causes and Special Causes of Variation

S/N	Common Cause of Variation	Special Cause of Variation
1	Present all the time.	Not always present
2	Have a small effect individually	Have a large negative impact on product quality.
3	Result in random variation	Result in between variations across subgroups.
4	Its effect can be tolerated	Its effect cannot be tolerated.

As part of the monitoring regimen for the improved process, I-MR-R/S (Between/within) chart consisting of an individual chart, a moving range chart, and an R/S chart was used to assess the stability of the process location, the between-sample component of variation, and the within-sample component of variation.

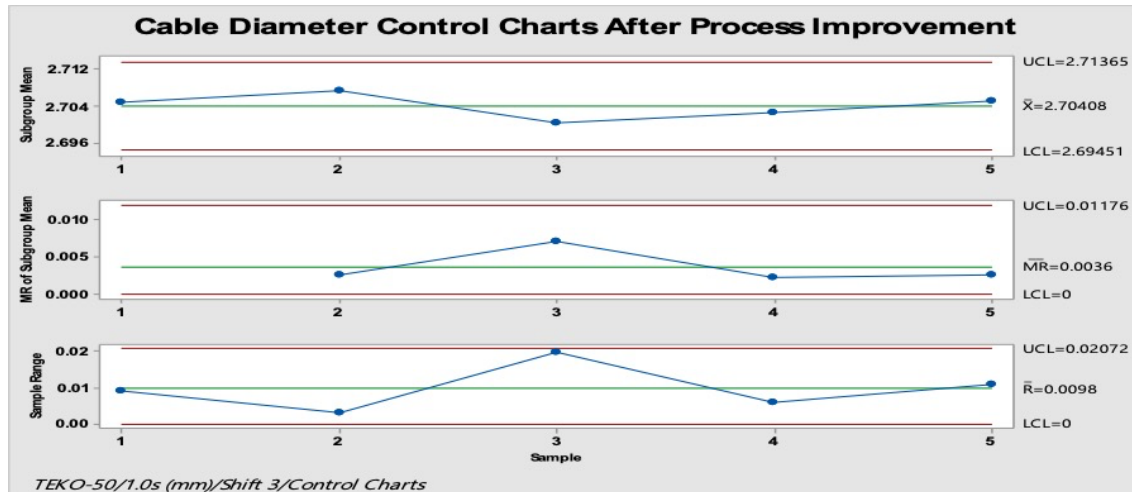


Figure 7. I-MR-R/S chart for the cable diameter after the improvement studies

During the assessment period, the process engineer measured five parts randomly from the extruding cable at 30-minute intervals using digital calipers. The assessment lasted for three days and included nine consecutive operational shifts. The stability of the process, as represented in Figure 7, clearly signifies a stable process, devoid of any special cause.

Table 14. Categorization of Special and Common Causes of Variation in Cable Extrusion Process

S/N	Special Cause Variation	Common Cause Variation
1	Over-dimensioned tips	Unsteady wire guard
2	Over dimensioned dies	Bunched PVC pellet stringing together
3	Use of un-annealed copper conductor	Faulty water Pumps
4	Use of low temperature yielding tips	Operator to Operator variation
5	Worn-out Centering Bolts/Nuts	Impurities on the PVC
6	Improper Parameter settings	Use of non-preheated PVC
7	Poor Monitoring System	Poor tip Tolerance
8	Presence of water on the Input conductor	Poor water trough design
9	Unaligned- embosser	Use of poorly annealed Conductor
10	Faulty measuring tools	
11	Faulty Heating system	
12	Faulty braking system	
13	Poorly welded joints	
14	Management Interference	
15	Poor flushing of the extrusion barrel	
16	Inadequate operators' skills	
17	Poor fitting of the tip to the core tube	

3. RESULTS

This paper presented a successful case study of defect reduction in a cable manufacturing company, where the Six Sigma methodology was complemented with a knowledge Management

approach. After the analysis carried out in the “analyze” and “improve” phases of Six Sigma DMAIC, the improvement project presented in this paper found that the Capstan speed and the Extruder speed had a statistically significant impact on the production of cables with varying dimensions. The root causes of insulation surface flaws were eliminated after the confirmation plan was validated through work study and other consolidated process improvement strategies. Table 15 contains the capability index results obtained from the project before and after the process improvement, as well as the Six Sigma outlook of the process. The tightened tolerance interval has saved and will continue to save production costs for the company, as the quantity of PVC material needed for extrusion drops from the initial quantity. The capability Cp of the extrusion process has shown a remarkable increase of 20.16%, and a 68.5% increment in Cpk, indicating that much was achieved in the design to meet the nominal value. The natural tolerance CR of the process utilizes 69.96% of the engineering requirement after improvement, against the initial 84.67% value. In general, the smaller the CR value, the better; for a six-sigma process, the value of CR is 50% (Pyzdek, 2003). So the 14.71% CR reduction after process improvement means that the natural tolerance of the process uses 69.96% of the engineering requirement, indicating that the process values now cluster around the nominal value. With the reduced process CR, it will be difficult to produce cables with core dimension values exceeding the two specified bounds. With this CR range, the possibility of producing out-of-range cables is minimal, except if there are special or assignable causes of variations in the process.

Table 15. Results -Capability Analysis.

S/N	Index	Before Improvement (2.715±0.185)	After Improvement (2.715±0.185)	After Improvement (With tightened Tolerance intervals of 2.7085±0.039)
1	Cp	1.19	7.55	1.43
2	Cpk	0.73	7.46	1.23
3	Cpu	0.73	7.63	1.23
4	Cpl	1.65	7.46	1.63
5	Cpm	0.67	6.43	1.26
6	CR	84.67%	13.25%	69.96%
7	Zu	2.18	22.88	3.68
8	ZL	4.98	22.39	4.89
9	σ _{Overall}	0.0582638	0.0281477	0.0023934
10	σ _{Within}	0.0518257	0.0314975	0.00248131
11	σ _{level}	3.7	-----	5.2

4. CONCLUSION

The study was conducted in a cable manufacturing industry in Southeast Nigeria that specialized in manufacturing cables of different sizes and colours. The organization’s production Plant was studied and improved through implementing the Six Sigma-DMAIC methodology, and with the supportive aid of the Knowledge management tool “CoP” over a six-month duration. A significant improvement was observed after the projects. Although one of the objectives was to reduce the quantity of non-conforming cables due to insulation surface flaws by 70% from the baseline, at the end, 57% reductions from the baseline value of 22,256 was achieved at the end of the observed quarter, which is even far better than the entitlement value of 18,990m gotten within the accounted quarters. In this study, a knowledge-based tool was developed from the Project using Microsoft Excel 2010 software to circumvent the cost of not knowing. The project activities were hyperlinked in an Excel spreadsheet detailing the improvement processes and launched as a blog for easy access and information retrieval. It is important to understand that informal knowledge representation in tacit form led to the notion of starting the CoP.

Like the Nonaka SEIC model, the formation of socialization is provided by the Define phase of the Six Sigma process. Meetings, brainstorming sessions, and tollgate evaluations offer the necessary socialization framework for knowledge tapping, which allows members' tacit information to be revealed. Individual team members revealed their inherent, untapped potential during this team activity. The third DMAIC phase contains knowledge externalization platforms used to investigate the subject problems. The fishbone diagram illustrates members' knowledge of process defects. Control Charts, Histograms, Cause Validation Plan, Experimental Design, Work Study, and Loss Function Evaluation all contributed to understanding the process problems and solutions, making explicit knowledge new tacit knowledge. As each member of the cohesive group of CoP gains more

expertise on the selected project, these knowledge conversion procedures enhance the domain knowledge. Their participation in the improvement exercise was a major factor in this. Thus, these development programs have made knowledge-based resources outside the participants' cognitive domain available. The creation of a knowledge repository for the organization is necessary to accomplish the goal of institutionalizing the knowledge gathered from the projects. This repository will house the improvement project's output for convenient access in the project report and as a production guide against defects. This research makes four notable contributions to the case organization:

1. It engages employees' capabilities towards solving organizational quality-specific problems, thus replication of best practices is not far-fetched.
2. The study exposed the initiated community of practice (CoP) within the organization to the statistical approach to process control.
3. An engineering tolerance that fits a Six Sigma process was designed for the organization.
4. The study improved the Sigma level of the extrusion process through experimental designs regarding the cable diameter quality characteristics.

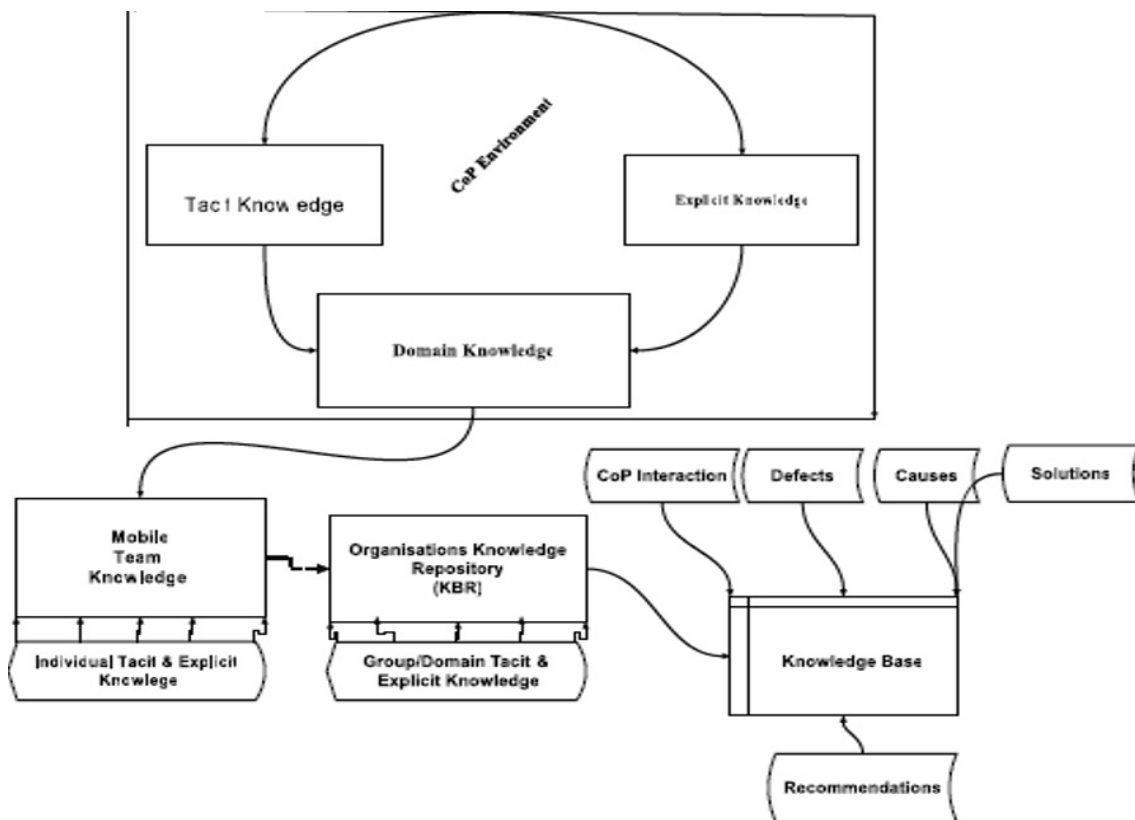


Figure 7. Integrated Knowledge-based Network.

References

- Aboelmaged, M. (2010). Six Sigma Quality: A structure review and implications for future research. *International Journal of Quality & Reliability Management*, 27(3), 268-317.
- AIAG (2010). *Measurement Systems Analysis*. AIAG reference manual, 4th ed., Michigan.
- Alsagheer, A., and Mohammed, H. (2011). Applying Six Sigma to achieve enterprise sustainability: Preparations and aftermath of Six Sigma projects. *Journal of Business & Economics Research*, 9, (4).
- Andersson, R., Eriksson, H., and Torstensson, H. (2006). Similarities and differences between TQM, Six Sigma, and Lean. *The TQM Magazine*, 18(3), 282-296.
- Antony, J. (2004a). Six Sigma in the UK service organizations: Results from a pilot survey, *Managerial Auditing Journal*, 19(8), 1006-13.
- Antony, J. (2004b). Some Pros and Cons of Six Sigma: An Academic Perspective. *The TQM Magazine* 16(4), 303-306.

- Antony, J. (2022). Design of experiments and its role within Six Sigma. *Design of Experiments for Engineers and Scientists (Third Edition)*, 223–231. <https://doi.org/10.1016/B978-0-443-15173-6.00004-4>
- Baral L.M., Kifor C.V., and Bondrea I (2014). Assessing the Impact of DMAIC-Knowledge Management Methodology on Six Sigma Projects: An Evaluation through Participants' Perception. In: Buchmann R., Kifor C.V., Yu J. (eds) Knowledge Science, Engineering and Management. KSEM 2014. Lecture Notes in Computer Science, vol 8793. Springer, Cham.
- Ben Dabbabi, M., Aboulkacem, S., & Mazigh, C. (2024). Application of the Six Sigma approach in the clinical biochemistry laboratory. *Clinica Chimica Acta*, 558, 118703. <https://doi.org/10.1016/j.cca.2024.118703>
- Bower, K.M. (2002). Process Capability Analysis Using Minitab (1). <https://www.minitab.com>.
- Brkic, V.S., & Tomic, B. (2016). Employees' factors importance in Lean Six Sigma concept, *The TQM Journal*, 28(5), pp.774–785.
- Catherwood, P. (2002). What's the difference between Six Sigma? *Manufacturing Engineer*, 81(8), 186–189.
- Chang, C.-M., & Su, C.-T. (2007). Service process design and redesign by fusing design powers for Six Sigma and Lean. *International Journal of Six Sigma and Competitive Advantage*, 3(2), 171–91.
- Cherrafi, A., Elfezazi, S., Chiarini, A., Mokhlis, A., & Benhida, K. (2016). Integrating lean manufacturing, Six Sigma, and sustainability: A literature review and future research directions for developing a specific model. *Journal of Cleaner Production*, 139, 828–846. <https://doi.org/10.1016/j.jclepro.2016.08.101>
- Cupryk, M., Takahata, D., and Morusca, D. (2007). Crashing the schedule in DCS validation pharmaceutical projects with Lean Six Sigma and project management techniques: case study and discussion. *Journal of Validation Technology*, 13(3), 223–33.
- Dagleish, S. (2005). Probing the Limits: ISO 9001 Proves Ineffective. *Quality Magazine*. Retrieved online from www.qualitymagazine.com.
- Dahlgaard, J., and Dahlgaard-Park, S., (2006). Lean Production, Six Sigma Quality, TQM, and Company Culture. *The TQM Magazine* 18(3), 263–281.
- Daniyan, I., Adeodu, A., Mpofu, K., Maladzhi, R., & Kana-Kana Katumba, M. G. (2022). Application of lean Six Sigma methodology using DMAIC approach to improve the bogie assembly process in the railcar industry. *Heliyon*, 8(3), e09043. <https://doi.org/10.1016/j.heliyon.2022.e09043>
- Dasgupta, T. (2003). Using the six-sigma metric to measure and improve the performance of a supply chain. *Total Quality Management and Business Excellence*, 14(3), 355–366. <https://doi.org/10.1080/1478336032000046652>
- De Koning, H., and De Mast, J. (2006). A Rational Reconstruction of Six Sigma's Breakthrough Cookbook. *International Journal of Quality and Reliability Management*, 23(7), 766–787.
- Ehie, I., and Sheu, C. (2005). Integrating Six Sigma and theory of constraints for continuous improvement: a case study. *Journal of Manufacturing Technology Management*, 16(5), 542–53.
- Evans, J. R., & Lindsay, W. M. (2008). *The Management and Control of Quality*. *The Management and Control of Quality*, 768.
- Gavagan, L., Arnejo, A., Dowling, A., & Maxwell, M. (2024). Applying Lean Six Sigma methodologies to Radiation Safety Training for Ancillary workers at the Regional Hospital in Mullingar. *Physica Medica*, 118, 103241. <https://doi.org/10.1016/j.ejmp.2024.103241>
- Gowen, C., Stock, G.N. & Mcfadden, K.L (2008). Simultaneous implementation of Six Sigma and Knowledge Management in hospitals. *International Journal of Production Research*, Vol. 46, Issue 23.
- Graves, A. (2014). Integrating Business Process Management with Six Sigma. Retrieved online from <http://www.sixsigmadaily.com/integrating-business-process-management-six-sigma>.
- Gremlin, P. (2016). Integrating Value Stream Mapping and DMAIC methodology. A case study: Unpublished master's thesis. Lulea University of Technology. Retrieved online on Nov. 16, 2017, from <http://www.diva-portal.org>.
- Gupta, N. (2013). An application of DMAIC methodology for increasing the Yarn Quality in the Textile Industry. *Journal of Mechanical and Civil Engineering*, 6(1), 50–65.
- Hussain, K., Sun, H., Ahmad, N., & Iqbal, M. (2024). Assessment of risk factors to Green, Lean, Six Sigma adoption in the construction sector: Integrated ISM-MICMAC approach. *Heliyon*, 10(12), e32749. <https://doi.org/10.1016/j.heliyon.2024.e32749>
- Knowles, G., Whicker, L., Femat, J., & Canales, F. (2005). A Conceptual Model for applying Six Sigma Methodology to Supply Chain Improvement. *International Journal of Logistics Research and Application*, 8(1), 51–65.
- Kwak, Y., and Anbari, F. (2004). Benefits, Obstacles, and Future of the Six Sigma Approach. *Technovation*, 26, (5/6), 708–715.
- Martin, J.W. (2006). *Lean Six Sigma for Supply Chain Management*. McGraw-Hill, New York. In De Mast Lobberkoll, 2012.
- Minitab 17 Statistical Software (2013). [Computer Software]. Minitab Inc.
- Moosa, K., and Sajid, A. (2010). Critical Analysis of Six Sigma Implementation. *Total Quality Management*, 21(7), 745–759.
- Murugappan, M., and Keeni, G. (2003). Blending CMM and Six Sigma to meet business goals. *IEEE Software*, 20(2), 42–8.
- N. A. Maidin, S. M. Sapuan, M. T. Mastura, M. Y. M. Zuhri, Materials Selection of Thermoplastic Matrices of Natural Fibre Composites for Cyclist Helmet Using an Integration of DMAIC Approach in Six Sigma Method Together with Grey

- Relational Analysis Approach, *Journal of Renewable Materials*, Volume 11, Issue 5, 2023, Pages 2381–2397, <https://doi.org/10.32604/jrm.2023.026549>.
- Oliveira, D., Teixeira, L., & Alvelos, H. (2023). Integration of Process Modeling and Six Sigma for defect reduction: A case study in a wind blade factory. *Procedia Computer Science*, 232, 3151-3160. <https://doi.org/10.1016/j.procs.2024.02.131>
- Parast, M. M. (2011). The effect of Six Sigma projects on innovation and firm performance. *International Journal of Project Management*, 29(1), 45–55. <https://doi.org/10.1016/j.ijproman.2010.01.006>
- Pepper, M.M.J., & Spedding, T.A. (2008). The evolution of Lean Six Sigma. *International Journal of Quality and Reliability Management*, 27(2), 138–155.
- Pyzdek, T. (2003). *The Six Sigma Handbook: A Complete Guide for Green Belts, Black Belts, and Managers at all levels*, McGraw-Hill
- Revere, L., & Black, K. (2003). Integrating Six Sigma with Total Quality Management: A case example for measuring medication errors. *Journal of Healthcare Management*, 48(6), 377–391.
- Snee R. (1999). Why should statisticians pay attention to Six Sigma? *Quality Progress*, 100–3.
- ThanhDat, N., Claudiu, K V., Zobia R., & Lobont, L. (2016). Knowledge portal for the Six Sigma DMAIC process. *Organization and Management of Industrial Processes*, IOP Conference Series: Materials Science and Engineering, 145.
- Uluskan, M., Godfrey, A., & Joines, J.A (2017). Integrating Six Sigma to traditional quality management theory: an empirical study on organizational performance. *Total Quality Management & Business Excellence*, 28(13-14).
- Vicente, I., Godina, R., & Teresa Gabriel, A. (2024). Applications and future perspectives of integrating Lean Six Sigma and Ergonomics. *Safety Science*, 172, 106418. <https://doi.org/10.1016/j.ssci.2024.106418>.