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Process performance enhancement in cable manufacturing based on the synergetic integration of LSS-DMAIC approach and knowledge capturing mechanisms

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Abstract: In cable manufacturing, product quality is essential and variation in product is a critical issue, but in most cases results from solutions to cable defects identified during process improvement projects are not sustained. This anomaly is likened to the outsourcing of improvement functions to external professionals most of the time and also due to absence of knowledge-based solution, robust enough to solve most of the real-life quality problems that prevails in a dynamic cable manufacturing environment. Hence there exists a need for an efficient deployment strategy applicable in cable manufacturing that will aid organizations in their improvement studies to solve real life problems as well as to become a knowledgeable organization. The goal of this study is to improve cable manufacturing process performance by utilizing the complementary ideas of Knowledge Management (KM) and Lean Six Sigma-DMAIC (LSS-DMAIC). The conceptualized model also provided an environment for the development of employee capability while preventing excessive financial losses for the cable manufacturing sector through the careful identification of knowledge domains, retention of previously learned information, and the development of strong social capital within the organization. Finally, this study added a type of integration strategy that would help process improvement practitioners in cable manufacturing companies to the body of existing process improvement studies. It focused on the complementary benefits of these two different disciplines, "LSS and KM," which have been rarely discussed in Nigerian process improvement studies.

Key words: LSS, Cable Manufacturing, Insulation thickness defects, Knowledge Management

INTRODUCTION

The intense competition among business organizations globally is becoming more interesting and most organizations are gearing towards manufacturing defect-free products. It has been a commonplace occurrence in industries that out-of-specification variations are usually detected too late, and most often after part production. The cable manufacturing industry is a field with a lot of variations and defects in its processes, product quality is essential and variation in product is also a critical concern. This variation in the process always affects the product's quality, possibly due to special or common causes (Guleria et al., 2020). However, finding the cause of the cable defect is a lengthy process that requires consideration of material, machine, die and process. In cable manufacturing, product quality is essential and variation in product is a critical issue, but in most cases, results from solutions to cable defects identified during process improvement projects are not sustained. This anomaly is likened to the outsourcing of improvement functions to external professionals most of the time and also due to the absence of a knowledge-based solution, robust enough to solve most of the real-life quality problems that prevail in a dynamic cable manufacturing environment. Hence there exists a need for an efficient deployment strategy applicable in cable manufacturing that will aid organizations in their improvement studies to solve real-life problems as well as to become a knowledgeable organization. Since most experienced employees leave with their process knowledge owing to retirement, layoffs, and job rotations without being transferred, worker knowledge is crucial for any improvement research in the cable manufacturing industry, where observational studies are common.

Most cable industries have over the years tried a good number of improvement strategies to help save on the cost of not knowing, but are still faced with some real-life problems in their manufacturing processes due to process knowledge loss, and lack of knowledgeable workers. Hence a solution to the aforementioned challenges becomes imminent and requires a robust methodology that can be used as a model for the transfer of best practices and contains the Silos effect. Furthermore, most cable-making organizations are more engrossed in instituting a quality management system and often pay less attention to the selection of appropriate tools that will guide them to success. Although most cable manufacturing organizations are ISO certified, it is pertinent for these organisations to be conscious of the fact that ISO does not suggest any tools, methods or solutions on how to improve, but mainly on following standardized procedures. Hence, there is the utmost need to always develop improvement strategies that can be utilized as a tool within a quality management system to meet ISO requirements. Many organizations have sought strategies such as Lean manufacturing (Chanarungruengkij, et al. 2017); Lean Six Sigma (Paramech, 2013); QC tools and DMAIC methodologies (Mondal, et al., 2015); design of experiments (Abdulkareem, et al. 2014), to improve process and product quality. It has been observed through an extensive literature review that none of the approaches presently used to solve process-related problems in cable manufacturing processes emphasized ways to tackle the ever challenges of absorptive capacity (not-invented-here syndrome), development and exploration of organizational social capital, best practice replications and co-location creation. It is right to deploy logical and systematic solutions/procedures to determine the origin of these defects in a processing line if defects are to be eliminated. It is well acknowledged that the integration of knowledge, data, and innovation within Lean Six Sigma plays a crucial role in driving organizational excellence (Rajić et al., 2023).

Although attempts to integrate the benefits of KM and LSS have been undertaken in a number of industries, cable manufacturing has not done so, despite the fact that observational studies are common there and workforce knowledge is crucial to any improvement study. In other words, even though the literature on the application of Lean Six Sigma (LSS) has evolved over time, a deeper understanding of the LSS methods utilized in developing-nation enterprises is necessary (Scheller et al., 2021). This research examined how learning and knowledge can be facilitated in an LSS project by effectively implementing both perspectives, KM and LSS-DMAIC to generate a higher level of knowledge such that a sustainable quality advantage would be sustained in cable manufacturing in Nigeria.

Research Problem

In cable manufacturing, product quality is essential and variation in product is a critical issue, but in most cases, results from solutions to cable defects identified during process improvement projects are not sustained. This anomaly is likened to the outsourcing of improvement functions to external professionals most of the time and also due to the absence of a knowledge-based solution, robust enough to solve most of the real-life quality problems that prevail in a dynamic cable manufacturing environment. Hence there exists a need for an efficient deployment strategy applicable in cable manufacturing that will aid organizations in their improvement studies to solve real-life problems as well as to become a knowledgeable organization.

Purpose of the Study

The purpose of this study is to propose a robust methodology that incorporates the KM concepts in LSS-DMAIC's framework to solve some of the aforementioned quality challenges in Nigeria's cable manufacturing industry.

Research Questions

The research questions that this study sought to answer are as follows:

- How can an efficient and sustainable strategy for tackling process and product variability especially in cable manufacturing industries be developed and,
- What are the ways to tackle the ever challenges of absorptive capacity (not-invented-here syndrome), development and exploration of social capital, and best practice replications in internal operations of an organization?

Literature Review

Lean Six Sigma (LSS) Improvement strategies

Lean Six Sigma is a combination of the Six Sigma methodology and lean mindset. Since its start in 2000, various academics have established an integrated strategy, while others have focused on a framework for the successful integration of Lean and Six Sigma. Six Sigma or Lean manufacturing alone cannot improve quality, customer satisfaction rate, or net earnings, nor can it lower the organization's overall production cost; however, the combined approach may solve these problems (Swarnakar et al., 2021). Lean Six Sigma is an integrated approach between lean thinking and the Six Sigma method that helps to improve process efficiency, optimize resources, and increase customer satisfaction while improving profits and cost reduction (Kharub et al., 2021). While the Six Sigma technique helps firms minimize defects and variance by improving processes and resolving inefficiencies, the Lean methodology aims to reduce waste to increase customer value (Thakur et al., 2023). A company can get a competitive edge by successfully integrating both approaches (Salah & Rahim 2018). Together, the programs will overcome the shortcomings of each when applied separately, creating a lean, Six Sigma (LSS) organization.

A careful examination of the two programs reveals some plausible explanations for why they might not be able to reach complete perfection on their own (Arnheiter and Maleyeff, 2005). Lean Six Sigma is the most widely used business strategy for implementing continuous improvement, but many organizations are having trouble making it work. The main reasons for this are a lack of leadership, shifting business priorities, internal resistance, and resource availability (Laureani & Antony, 2017); Shrivastava & Mishra, (2024; Pongboonchai-Empl et al., 2023; Stemann, and Antony 2021; Albliwi et al., 2015), data inaccessibility (Albliwi et al. 2014), lengthy implementation cycles (Sony et al., 2019), poor project selection and prioritization (Snee 2010), and unsustainable outcomes (Aboelmaged 2011). Add to this, LSS implementation failures are linked to implementation tactics and the inability to institute an improvement framework that is built on knowledge management models (Asif, (2019).In Lean Six Sigma, effective knowledge management is essential to ensure that valuable information generated during improvement projects is documented and disseminated (Rajić et al., 2023; U-Dominic & Godwin 2018).

Lean Six Sigma (LSS) Integrations

Physical labour is being replaced by cognitive work, and greater manufacturing automation has changed the way workers engage with the equipment they use to accomplish tasks. This means that solutions for boosting productivity need to consider a workforce where expertise is a differentiator of results, as well as more complex and less tractable procedures. The integration of Lean Six Sigma with cognitive engineering and human factors methodologies might result in a more productive framework for complex production, as explained by Gleeson et al. (2018). According to reports, LSS has been combined with a variety of tactics to address the socio-technical demands that are present in a normal workplace where people, machines, and technology coexist while working toward a common objective. Similarly, LSS has included ergonomics to safeguard the health and safety of employees while increasing production (Vicente et al., 2024; Nunes 2014). With an emphasis on sustainability and the environment, Lean Six Sigma and other methodologies are being integrated (Erdi et al., 2018; Mohan et al., 2021).

In an Indian automotive component manufacturing company, Ruben et al. (2017) integrated environmental considerations into the Lean Six Sigma framework. A methodology developed by Cherrafi et al. (2016) systematically leads businesses through a five-stage and sixteen-step process to successfully integrate and use the Green, Lean, and Six Sigma techniques to enhance their factory-level sustainability performance. Similar to this, Lean Six Sigma has been combined with digital twins (DT), Big Data Analytics, and Green Manufacturing to improve the environmental performance of manufacturing firms (Chiarini & Kumar, 2020; Belhadi et al., 2020; Maheshwari & Devi, 2024; Farruk et al., (2023); Utama & Abirfatin, (2023). Lean Six Sigma DMAIC now incorporates Industry 4.0 technology (Pongboonchai-Empl et al., 2023; Skalli et al., (2021), and ISO 9001 has also been integrated with Lean Six Sigma (Sá et al., 2020). Double-loop learning (DLL) has been integrated with LSS techniques in food processing firms to minimize waste (Kolawole et al., 2021). The DMAIC roles structure of Six Sigma, Lean's social practices (LSP), and structured improvement procedures all have a positive impact on potential absorptive capacity when it comes to knowledge retention and transfer. Muraliraj et al. (2020) explained the necessity of implementing practices that aid in managing knowledge transfer in organizational settings. Capolupo et al. (2023) recognized that including LSSKM can result in project replication and serve as an organizational strategy for managers to learn about their processes through systematic information exchange. Aldairi et al. (2017) created a knowledge-based (KB) approach to Lean Six Sigma (LSS) building maintenance in eco-friendly structures. Al Khamisi et al.,(2019), developed a knowledge-based system (KBS) to support the implementation of Lean Six Sigma (L6s) principles applied to enhance quality management (QM) performance within a healthcare environment

Research Methods

In this work, Knowledge management techniques and Lean tools were incorporated into the typical DMAIC framework to make the methodology more engaging and resourceful for improvement functions. The conceptual approach considered all these DMAIC phases in its implementation and in chronological order. This entails quantitative and qualitative analysis at different phases depending on the nature of the problem to be solved.

The underlying philosophy for the proposed hybrid improvement approach

In the development of the improvement strategy, the matching advantages of these two distinct disciplines Lean Six Sigma and knowledge management were explored. The knowledge management concept that was explored emphasized the social environment through the use of Cop and IT techniques. The Knowledge management ideas in the conceptual development were based on the informal knowledge in tacit order, and the need to move people from a departmental thinking in which they are least inclined to share information up to an ideal where knowledge is shared intuitively.

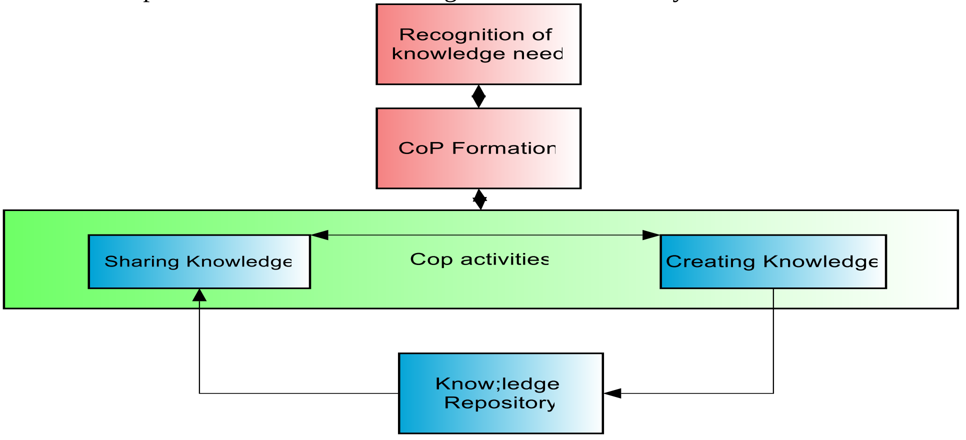

Fig. 1: Knowledge Management Process Model

The knowledge process model as described in Fig. 2 depicts how organizational knowledge are enriched as each member of the unified group of Cop becomes more knowledgeable on chosen projects through the knowledge dynamics processes in a Cop environment. The modeled processes are distinctively in three separate parts, knowledge need identification, knowledge creation/sharing and knowledge coordination. This organizational knowledge creation process is continuous and ideally creates a "knowledge spiral" as it moves from an individual to a group and to the organization which is the eventual goal through active documentations.

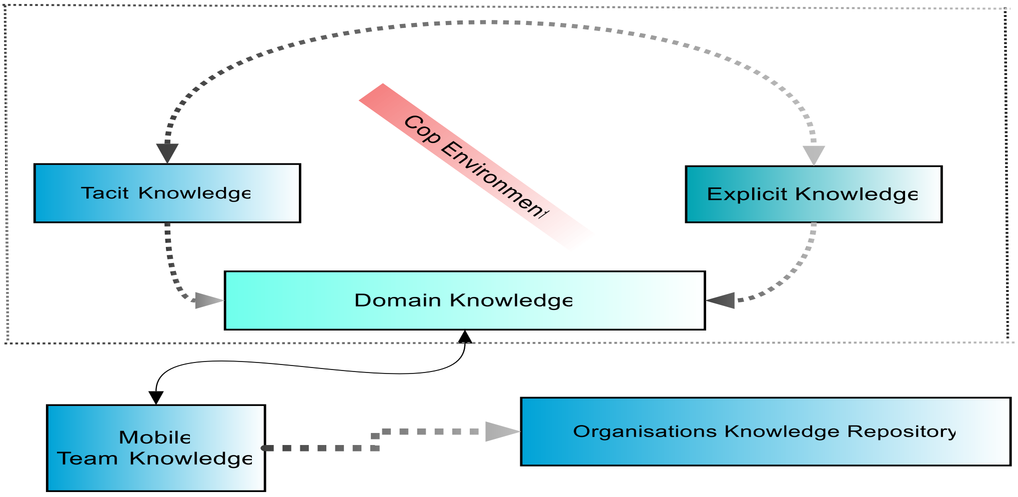

Fig. 2: Knowledge dynamics in CoP environment.

The Cop interaction as described in Fig. 2 would create a knowledge spiral whereby tacit knowledge of the member groups involved in the improvement studies is made explicit. During the improvement studies, knowledge is created and shared and is often located within the cognitive domain of the members involved in the improvement function. Knowledge at this stage is seen as mobile team knowledge which is still transitory and can be lost due to several factors such as retrenchment, retirement etc. The mobile team knowledge is transferred to organizational knowledge through proper documentation and updates on the standard operating procedure (SOP) of the organization. On the other hand, LSS-DMAIC is a rigorous and systematic approach to improvement, capable of providing a platform for knowledge creation across its phases and is an ideal improvement framework for the incorporation of knowledge management techniques. The conceptualized approach was of a typical five-phased DMAIC structure, with some adaptive modifications. In the proposed hybrid structure shown in Fig. 3 Knowledge Management techniques and Lean tools were incorporated into the typical DMAIC framework to make the methodology more engaging and resourceful for improvement functions.

Description of the proposed LSS-DMAIC KM Framework

The proposed LSS-DMAIC framework starts with the "Define Phase" and the research aim at this phase was centred on the identification of real-life problems. The Define phase of the LSS-DMAIC provides the socialization environment, just like a reflection of the Nonaka SEIC model, where sharing experiences with other members aids in the transfer of tacit knowledge. 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. Important tasks and techniques were incorporated like the Project charter and after-action review session. These two tools were incorporated to provide the externalization experience as tacit knowledge were made explicit through documentation (writing down tacit knowledge).

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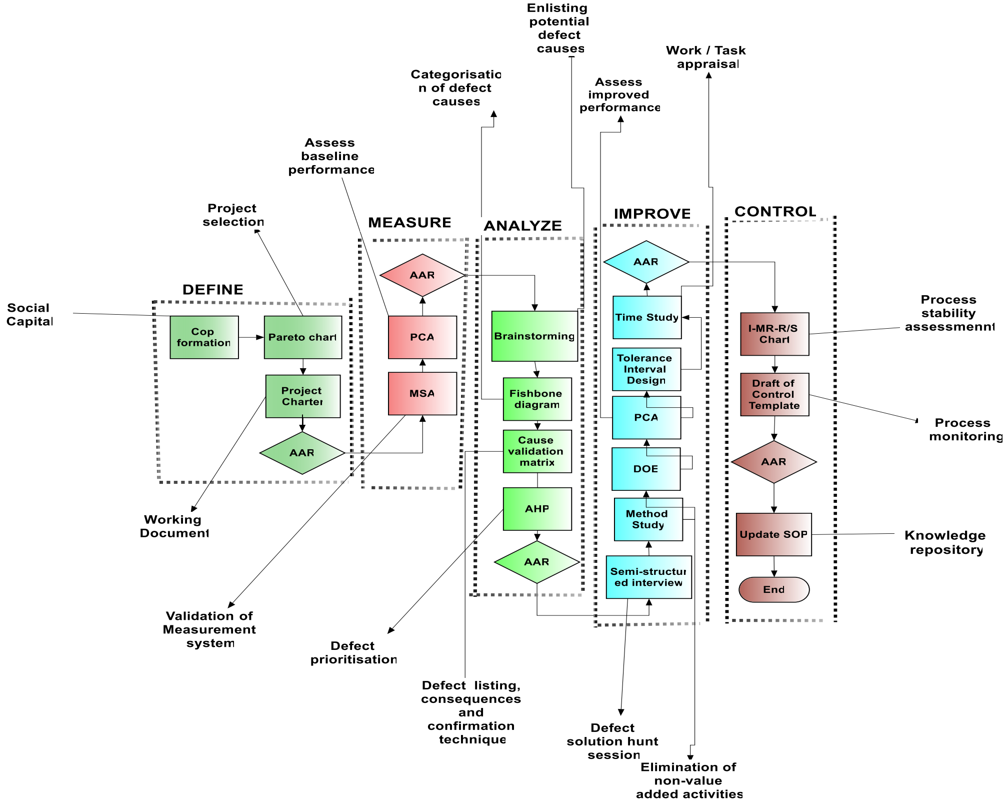

Fig.3. The Proposed LSS-DMAIC conceptualized improvement framework

After the define phase is the Measure phase, aimed at understanding the baseline performance of the system/process through the use of important tools and execution of tasks such as Measurement System Analysis (MSA), Process Capability Analysis (PCA) and eventual action review (AAR). This is followed by the Analyze phase. This phase was aimed at identifying process anomalies (defect causes, process variations etc.). On this phase, through team participation in all the processes of problem identifications, the individual members of the team made explicit their innate tacit potential, and notably at this phase, three knowledge creation modes were initiated; socialization, externalization and internalization were found in this third phase of LSS-DMAIC, and by this, Knowledge now moved from tacit to tacit, tacit to explicit and from explicit to tacit as depicted in fig 1. Some of the important tasks and tools incorporated at this phase included brainstorming, a cause and effect diagram, a cause validation matrix, an Analytic Hierarchical Process (AHP), and then followed by an eventual after-action review (AAR). The fourth phase was the “Improve phase” and was aimed at setting up probable solutions to eliminate the identified problems. Some of the important techniques incorporated in this phase include semi-structured interviews, method study, and experimental design, process capability studies, engineering tolerance design, time study and eventual after-action review (AAR). The last phase is the Control phase. This phase was necessarily to ensure that all the implemented solutions were maintained and controlled consistently. This phase is incorporated for systemizing knowledge created in the process into a knowledge system through the updating of the standard operating procedure (SOP) of the system. At this phase, the documented explicit knowledge of the Cop members was converted to organizational knowledge after the entire phase review. The prototypical of the envisaged knowledge management process is mapped in Fig. 2. The improvement projects would now provide the knowledge-based resources that will benefit the internal operations of the organization, outside the participants' cognitive domain.

Mathematically computations used in the study are represented by the following equations;

$$\sigma 2 total = \sigma 2 product + \sigma 2 measurement \tag{1}$$

$$\sigma 2 measurement = \sigma 2 \mathrm{Re}\, peatability + \sigma 2 \mathrm{Re}\, producibility \tag{2}$$

where; **σ**2total = total variance; **σ**2product = variance due to product; **σ**2measurement = variance due to measurement system; **σ**2Repeatability = variance within operator/device; **σ**2Reproducibility = variance between operators.

$$\sigma 2 \mathrm{Re}\, producibility = \sigma 2 Operator + \sigma 2 Part * Operator \tag{3}$$

$$\% contibution = \frac{\sigma^2 \mathrm{Re}\, peatability + \sigma^2 \mathrm{Re}\, producibility}{\sigma^2 Total} \times 100 \tag{4}$$

$$\% Study \mathrm{var}\, iation = \frac{\sigma measurement}{\sigma total} \times 100 \tag{5}$$

$$\sigma t = \sqrt{\sigma 2m + \sigma 2p} \tag{6}$$

$$\sigma p = \frac{R_p}{d_2^*} \tag{7}$$

$$Two - sidedSpec \% P / T = \frac{6 \sigma measurement}{USL - LSL} \times 100 \tag{8}$$

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

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. Equations (10) – (14) were used for the control charts computations.

$$UCL = D4\overline{R} \tag{10}$$

$$LCL = \overline{\overline{X}} - A2\overline{R} \tag{11}$$

$$UCL = \overline{\overline{X}} + A2\overline{R} \tag{12}$$

where A2,D3, and D4 are factors obtained from tables of constants used in constructing control charts.

$$\hat{\sigma} = \frac{\overline{R}}{d2} \tag{13}$$

where d2 is the factor obtained from tables of constant used in constructing control charts.

$$Cp = \frac{USL - LSL}{6\sigma} \tag{14}$$

Where LSL and USL are lower and upper specification limits, NT = natural tolerance. In practice, it is often impossible to know parameters, therefore it is suitable to use sample standard deviation ‘s’ to estimate process standard deviation σ. Thus, when the parameters are unknown, i.e. when process standard deviation σ is unknown, by replacing sample standard deviations to estimate process standard deviationσ, the formula used for estimating Cp is given below as:

$$C\hat{p} = \frac{USL - LSL}{6s} \tag{15}$$

$$Cpk = \frac{1}{3\sigma}\min\left[USL - \mu, \mu - LSL\right] = \min\left[Cpu, Cpl\right] \tag{16}$$

$$\hat{C}pk = \frac{1}{3s}\min[USL-\mu, \mu-LSL] = \min[Cpu, Cpl] \quad (17)$$

$$C\hat{p}k = Cp(1-k) \quad (18)$$

Where k = is an index that explains the amount the process mean is off-center (bias factor) and computed as follows:

$$K = \frac{|m-\mu|}{\frac{USL-LSL}{2}} \quad (19)$$

$$Cpk = \frac{ZMIN}{3} \quad (20)$$

$$Cpm = \frac{USL-LSL}{6t} \quad (21)$$

The target value T, is known to be the midpoint of the specification interval

$$T = \frac{1}{2}[LSL+USL] \quad (22)$$

The formula for process variation around desired process target is given below:

$$Ŧ2 = \mathrm{E}[X - T]E[X - \mu]2 + [\mu - T]2 = \boldsymbol{\sigma}2 + [\mu - T]2 \quad (23)$$

Computation of Cpm can also be done the following way:

$$Cpm = \frac{USL-LSL}{\sqrt[6]{\sigma^2+[\mu-T]}} = \frac{Cp}{\sqrt{1+\left[\frac{\mu-T}{\sigma}\right]2}} \quad (24)$$

$$CR = 100 \times \frac{6\hat{\sigma}}{Engineeringtolerance} \quad (25)$$

$$ZU = \frac{Upperspecification - \overline{\overline{X}}}{\hat{\sigma}} \tag{26}$$

$$ZL = \frac{\overline{\overline{X}} - Lowerspecification}{\hat{\sigma}} \tag{27}$$

Equations (28) to (33) were used for the AHP computations to priorities and rank the defects in order of severity. The comparative judgment is captured on a semantic scale (equally important/moderately more important/strongly important and so on) and is converted into a numerical integer value a_{ji}. The relative importance of C_i over C_j is defined as its reciprocal;

$$a_{ij} = \frac{1}{a_{ji}} \tag{28}$$

[A reciprocal pairwise comparison matrix A is then formed using a_{ji}, for all j and i. Note that a_{jj}=1.]

$$A_w = \lambda_{\max} w \tag{29}$$

$$C.I = \frac{\lambda_{\max} - n}{n-1} \tag{30}$$

$$\lambda = \frac{\sum \frac{w}{p}}{n} \tag{31}$$

$$CR = \frac{CI}{RI} < 0.1 \tag{32}$$

$$GP = Scp * Cp \tag{33}$$

For the experimental design (DOE), the relationship between the response variables and the independent variables (factors) can be represented as;

$$Y = f\left(X_1, X_2, X_3, X_4 \ldots X_n\right) \tag{34}$$

where f is a multivariate function, the items represent the factors (independent variables), and the relationship describes a curved surface y = f $\left(x_1, x_2, x_3, x_4 \cdots x_n\right)$ that is known as a response surface.

$$y = \beta 0 + \beta 1 x_1 + \beta 2 x_2 + \varepsilon \tag{35}$$

$$y = \beta 0 + \beta 1 x_1 + \beta 2 x_2 + \beta 12 x 1 x_2 + \beta 11 x 12 + \beta 22 x_{22} + \varepsilon \tag{36}$$

Equation (35) and (36) are first-Order and Second-Order Response Surfaces respectively. Generally, Response Surface Methodology utilizes First-Order and Second-Order models. Equations (37) – (38) were used for the tolerance interval design for the cable.

$$\overline{K} \pm K_s \tag{37}$$

$$s = \sqrt{\frac{\sum\left(x - \overline{x}\right)^2}{N - 1}} \tag{38}$$

where K is a constant, and is determined so that the interval will cover a proportion P of the population with confidence ϒ, s is the sample standard deviation, x = each value in the sample, $\bar{x}$= the mean of the values and N = the sample size. After the tolerance design interval then the time study to determine the standard time of operation at the new extruding parameter setting using equations (39) – (44).

$$S_x = \left[\sum\left[\left(\left(t1 - t\right)2\right)\right] / n\right]0.5 \tag{39}$$

Lower limit = t- 2Sx (40)

Upper limit = t +2Sx (41)

$$n = \left[\left(k * S_x\right) / \left(r * t\right)\right]2 \tag{42}$$

Where; t = Average time for performing the element, Sx = Sample variance for the element; n = number of data points in the data sample; k = number of standard deviations at the confidence level; r = measure of error precision; and ti = individual observed time.

Basic Time (BT) = $\frac{ObservedPerformancerating}{NormalRating}$ (43)

Standard Time (ST) = BT + RTA + CTA (44)

Where RTA = Relaxation Time Allowance; CTA = Contingency Time Allowance (contingency time allowance are allowances due to unanticipated official disturbance to one at work).

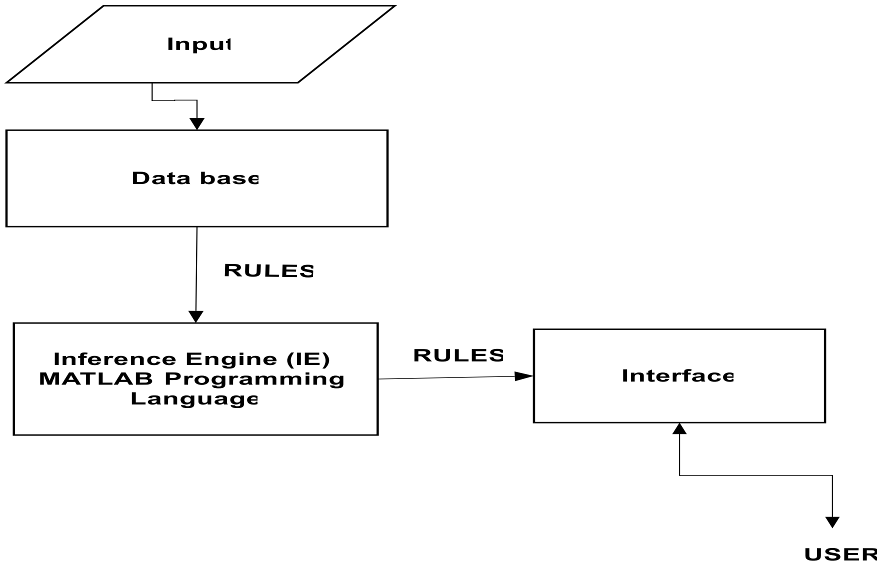

Fig. 4: Flowchart for the Generic Graphical User Interface Support System Development

Results and discussions

Each of the phases in the methodology was analyzed in detail and the outcomes of every one of the phases were highlighted in an ordered manner since each of the phases is characterized with a unique responsibility. At the Define Phase, real-life problems which deal with the variations that occurred during the production of single-core house wiring cables in the extrusion process were clarified. The selection criterion for the eventual projects was based on the rejection percentage of cable products, associated financial cost, and material waste. Historical data were provided by the Manufacturing Department (MD) and Quality Assurance Department (QAD). Seven different types of defects were identified to be related to the product and the defect types that occurred frequently with the highest accrued financial loss are defects due to Insulation thickness failures, followed by Insulation Surface Flaws, Low conductor diameter (LCD), inconsistent cable dimension (ICD). Pareto charts were used to streamline the selected project among the seven most common defects and the most prevalent and most daring quality defects in the case organization are failures due to cable Insulation thickness and Insulation smoothness

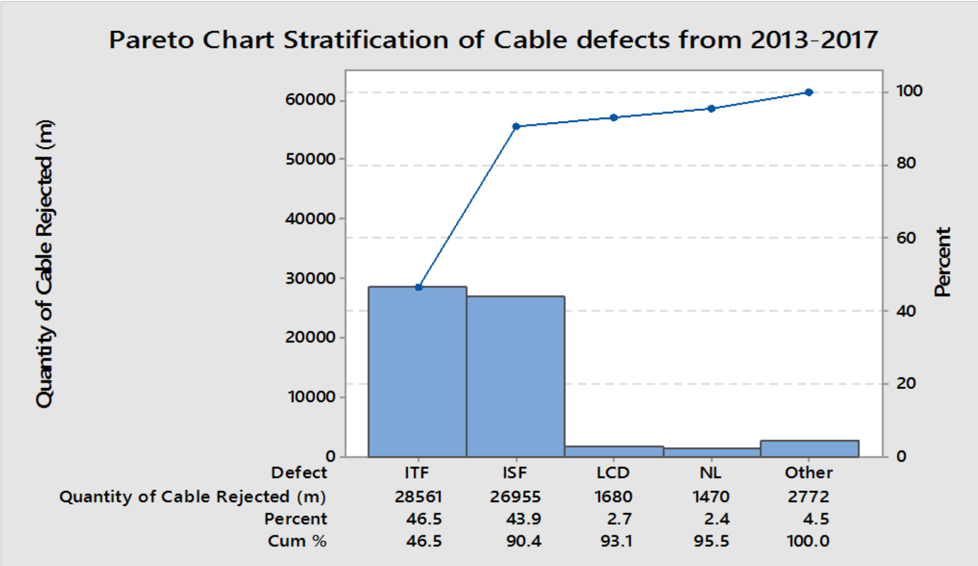

Fig.4: Pareto chart of defects (a)

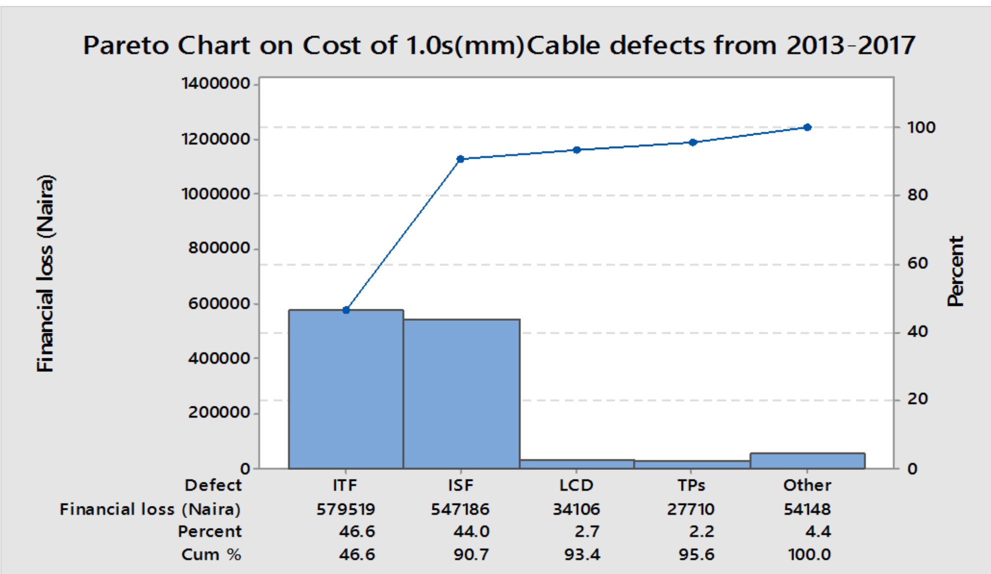

Fig.5: Pareto chart of defects (b)

A project charter was drafted as the working document containing necessary information about the selected project. After the Define phase is the Measure Phase, and at this phase, the baseline performance of the process was established in terms of process capability. But before embarking on the objectives of this phase, the measurement system analysis (MSA) was first conducted to validate that the measurement system to be used in the study are good enough. Using equation (1), (2), (3), (4), (5), (6), (7), (8), (9) for the Gage Reproducibility and repeatability, the analytical results on the four most important gage R & R metrics as shown in appendix 1 depict 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. After the validation of the measurement system, the baseline PCA for the cable insulation thickness was conducted to determine the organization's performance level. Based on the study's findings, only the lower specification limit (LSL) was established in the company (one-sided specification). By using this assessment method, the quality check is limited to making sure that the extruded cables' insulation thickness stays within the authorized 0.53mm range. The process capability studies for the insulation thickness measurement would be impossible to conduct without establishing an upper specification limit (USL). For this reason, the process's USL was determined as follows; For 1.0s (mm) cable; USL = 2.90 LSL = 2.53, and the input conductor diameter = 1.13(mm).

Derivations:

$$\text{USL} = \frac{USL - Inputconductor}{2} = \frac{2.90-1.13}{2} = 0.885 \quad (45)$$

Construction of $\bar{X}$ and R-chart to assess the statistical stability of the insulation thickness measurements

Control limits for $\bar{X}$–chart:

$\text{UCL} = \bar{\bar{X}} + \text{A2}\bar{R} = 0.8210 + 0.729(0.2141) = 0.8210 + 0.1561 = 0.9771$

$\text{LCL} = \bar{\bar{X}} - \text{A2}\,\bar{R} = 0.8210 - 0.729(0.2141) = 0.8210 - 0.1561 = 0.6649$

Control limits for R-chart:

$\text{UCL} = \text{D4}\bar{R} = 2.282(0.2141) = 0.4886$

$\text{LCL} = \text{D3}\bar{R} = 0.00(0.2141) = 0.000$

From the standard table of control chart constants (appendix 2 (a)) n = 4, A2 = 0.729, d2 = 2.059, D3 = 0, D4 = 2.282

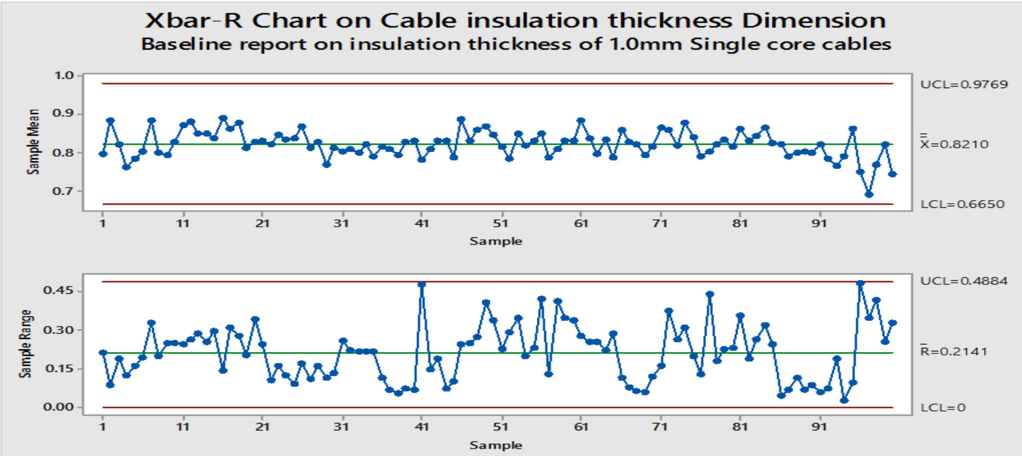

Fig.6: X-Bar-R chart of the Cable Insulation thickness data

From the X-R chart, of figure 6, the center line on the $\bar{X}$ chart is at 0.8210, implying that the process falls within the specification limits, implying a stable process. The center line on the R chart is 0.2141, and is also quite large considering the maximum allowable variation of ± 0.18. This implies that there is excess variability in the process. The result of the normal probability plot shows that Mean: 0.8210, standard deviation: 0.09988, Anderson Darling test statistic value: 0.590 and P-value: 0.123 is greater than the significance level (α = 0.05), and this implies that the data is distributed normally.

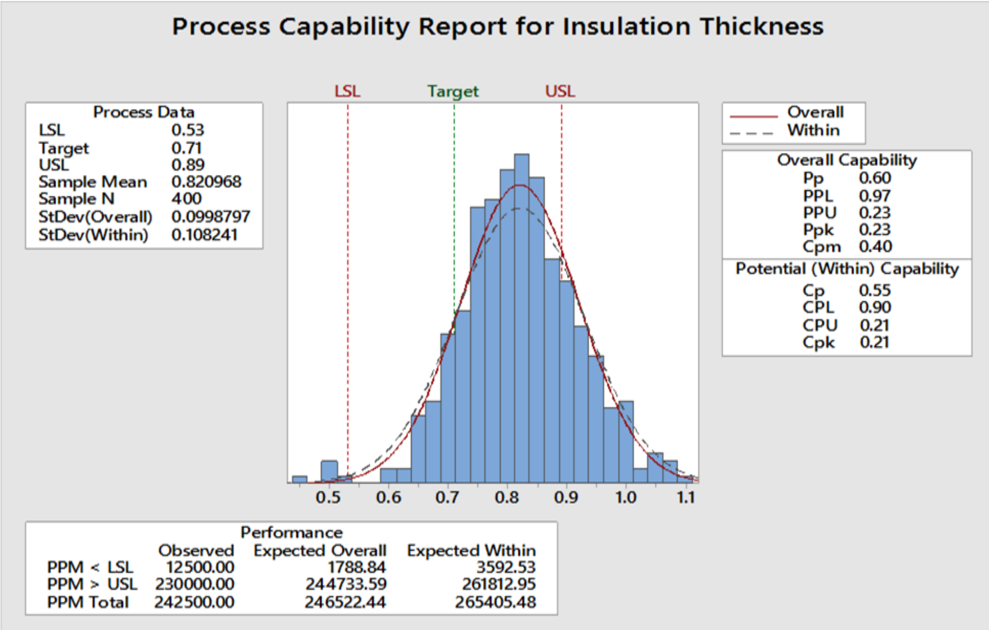

Fig. 7: Graphical illustration of the cable insulation thickness baseline data

According to the images in Fig. 7, the distribution's two tails are outside the specified bounds. As a result, some cables have a diameter that is smaller than the lower criteria of 0.53 and others that is larger than the higher specification of 0.89.The result of the capability study on the baseline process shows that the CP = 0.577 since the minimum acceptable value for this index is 1, the 0.577 result indicates that this process cannot meet the requirements most of the time. The CR is 173.3%, and with this value, it means that the “natural tolerance” of the process uses 173.3% of the engineering requirement, which is, of course, unacceptable. The Cpk is 0.21, and this value is smaller than that of Cp by 0.37, which is an indication that much can still be gained through centering the process. The calculated ZU for the process is 0.66, and checking from appendix 3, we have ZU = 1-0.7454 which is 25.46%. By this estimation, approximately 25.46% of the production will exceed the upper specification. The calculated ZL for the process is 2.79, we have ZL = 1-0.9974 which is 0.26%. By this estimation, approximately 0.26% of the extruded cable will have insulation thickness that is less than the lower specification. Total reject rate now becomes 25.72% (i.e 25.46% + 0.26%) and projected yield = 74.28%, checking from the abridged Six Sigma conversion table (appendix 4), the Sigma level is at 2.1. In the following phase (the analysis phase), the first job was to map the process using the Supplier-Input-Process-Output-Customer (SIPOC) diagram to help troubleshoot and formulate the hypothesis that would be explored further in this phase. A brainstorming session was then held among the chosen community of practitioners (CoP) to elicit and unlock the group's implicit process knowledge to address the poor extrusion performances. A cause-and-effect diagram that appropriately depicted the categorization of these defects into 5Ms (Measurement, material, machine, man & method) is presented as shown in figure 8.

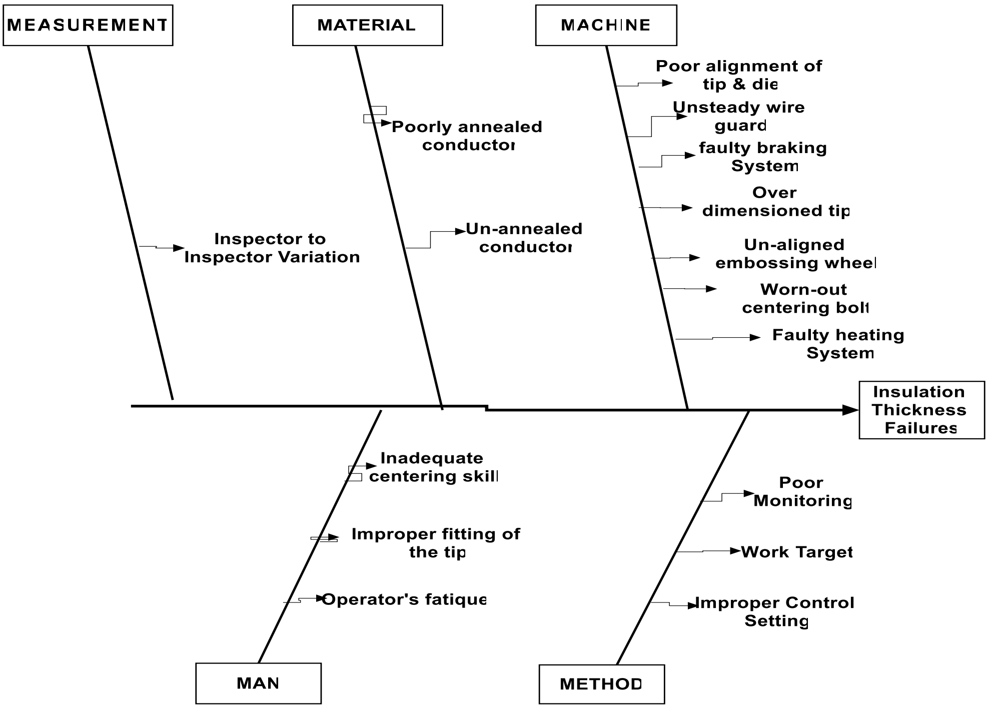

Fig. 8: Cause and Effect diagram on the Cable Insulation Thickness Failures

Based on the CoP's involvement, a cause validation strategy was developed that specified the types of information to be collected and the potential types of analysis for each of these potential causes. Possible reasons based on the cause validation strategy (see appendix 5) such as unaligned embossing wheel, worn-out centering bolts, faulty heating system, poor monitoring system, unsteady wire guide, poorly annealed copper conductor, faulty tensioning system, operator’s fatigue, an unsteady wire guide. AHP was used to rank the importance of various defect sources, beginning with failures related to insulating thickness. To get the final priorities or the major priority vector, the insulation thickness criteria were compared pairwise, and the comparison matrix was normalized using the approximation technique. The Cop and a few other seasoned employees from the case organization's manufacturing division helped with this AHP step, which compares each of the two sub-causes pairwise. It was determined how much of a contribution one cause made to the development of faults linked to insulation thickness failures, and all of the consistency tests were deemed satisfactory.

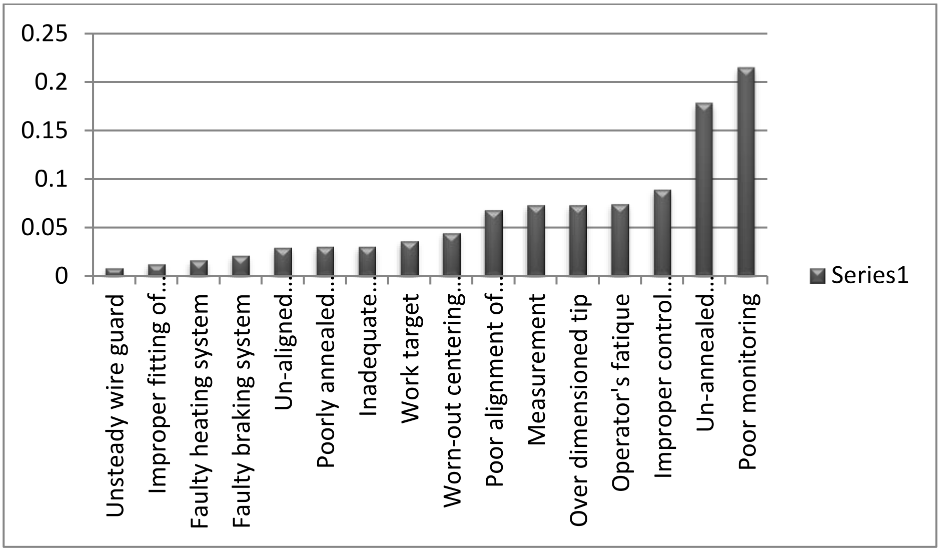

Fig. 9: Ranking of the sub criteria/ sub causes for improving Insulation thickness in cable

According to the charting in Figure 9, the factor that had the least impact on the creation of insulation thickness defect cables was the unsteady wire guard. This was followed by the use of un-annealed conductor to incorrect control settings, and so on. Sub-causes and sub-criteria that affect the creation of cables with failing insulation thickness were identified using the 80-20 rule. inadequate monitoring, un-annealed conductor, incorrect control setting, operator fatigue, over-dimensioned tip, measurement, inadequate tip-die alignment, and worn-out centering are the eight sub-causes that accounted for 80% of the problems, according to the rule.

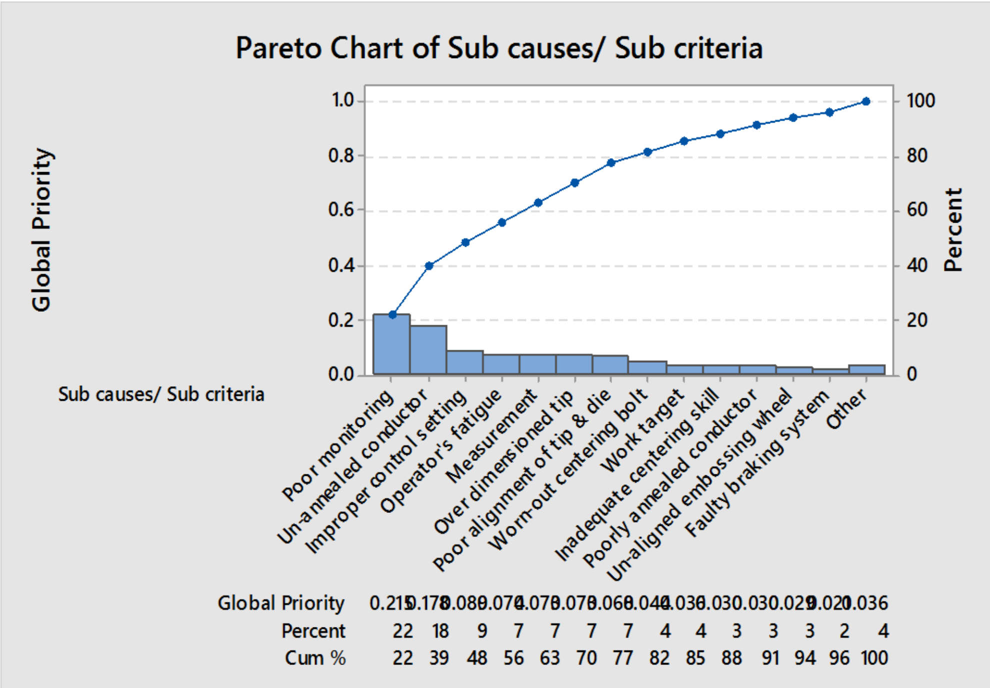

Fig. 10: Pareto Chart of sub causes of Insulation Thickness Failures

Based on members' prior experiences with extrusion processes, remedies to the identified fault causes were proposed during the Improve phase through a qualitative assessment using an open-ended questionnaire. These ideas were highlighted (see to Appendix 6). Since the majority of faults are brought on by excessive workloads that result in weariness, one way to address this issue is to estimate work through a work study. The "Start-up operation," which is the most crucial aspect of extrusion operations because of its production significance and the fact that it demands greater care and attention to execute, was chosen as the extrusion bottleneck activity for the method study. The chosen "Start-up" job was divided into fourteen (14) components for a more thorough analysis. In order to reduce time and enhance the quality of the final product, it was noted that some tasks needed to be removed from the operation. In addition to the productive hours lost in obtaining the input material for a regular operation, the current process revealed that the majority of idle times were caused by the time wasted transporting the input copper conductor from the wire drawing section to the extrusion line. This results in operator fatigue and other quality issues in the production line. Moreover, unnecessary time is lost when checking the input wire's diameter. Certain issues, such as inadequate centering, were also resolved under the research solutions. The new centering technology was applied, and cables were extruded and put through process capability tests to confirm its effectiveness. Variations in the cable's dimensions have been associated with a correlation between capstan and extruder speed, according to common knowledge of the extrusion process derived from the CoP interaction. A further experiment was created to find out if the presumed association was statistically significant. The extrusion machine's speed settings were appropriately selected during the experimental design process to achieve uniformity in the extruded cables' dimensions. Using the new parameter setting, a confirmation test was performed, and the cables that were extruded this time had a nominal cable dimension of 2.715mm in the near range.

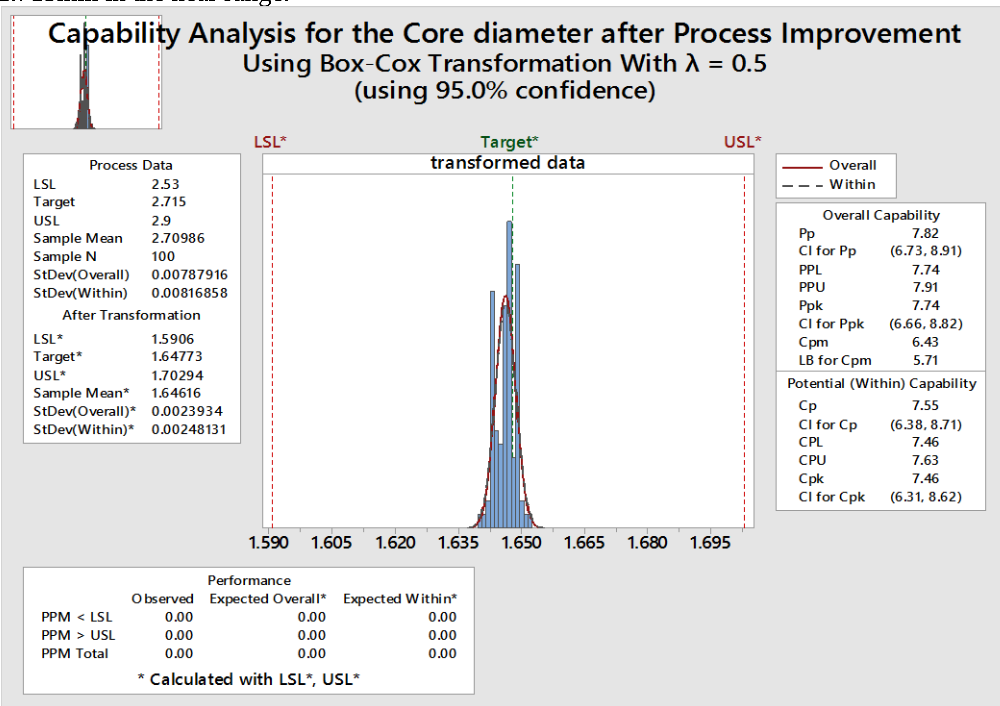

Fig 11: Capability analysis for the Cable diameter measurements after the process improvement

A capability study was conducted on the new sample to ascertain the level of improvement achieved after the experimental design, and the results are as follows; Cp = 7.55, CR = 13.25%, ZU = 22.88, ZL = 22.39, CPK = 7.46, CPM = 6.4. From Fig. 11 and some of the calculations that followed shows that the index values are all on the high side, an indication that the existing engineering tolerance is far apart from each other with a large standard deviation. To correct this anomaly, the next task was to derive an appropriate tolerance interval that can depict the Six Sigma Process. During the tolerance design process, 20 samples were randomly selected from a stable process population, and their standard deviation was found using equations (37) and (38).

$$S = \sqrt{\frac{0.0014706}{19}} = 0.0087977$$

Tolerance intervals now becomes; 2.7114 ± K(0.0087977). finding K value for two sided limits in appendix 7, for n = 20, P = 0.99 and Ƴ = 0.95, K= 3.615. 2.7114±3.615(0.0087977) = 2.7114±0.032. In this new design, the LSL for the insulation thickness = 2.67 and 2.74 as the upper specification limit. Further PCA was conducted on the core cable diameter samples gotten after the process improvement, and the results are as follows;

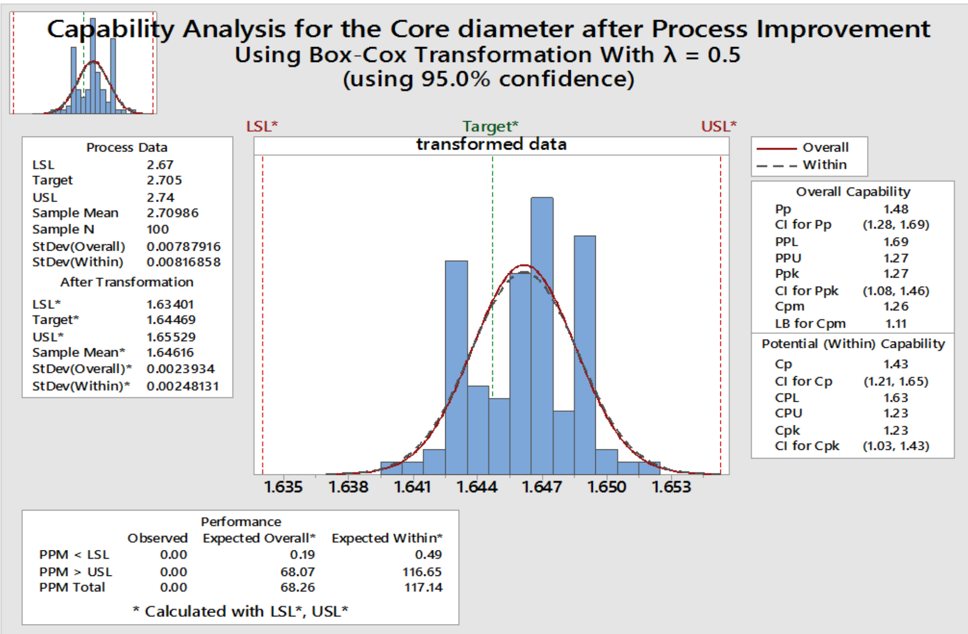

Fig. 12.: Capability analysis for the Cable diameter after the process improvement using the new tolerance design.

CP = 1.43 since the minimum acceptable value for this index is 1, the 1.43 result indicates that this process can meet the requirements. CR = 69.96%. With this value, it means that the "natural tolerance" of the process uses 69.96% of the engineering requirement, which is, about 14.71% reduction from initial value of 84.67%. Cpk = 1.23, the value of Cpk is smaller than that of Cp by 0.2, thus an indication that much can still be gained through centering the process. The calculated Z_U for the process is 3.68, and checking from appendix 3, we have ZU = 1-0.9999 which is 0.01%. By this estimation, approximately 0.01% of the production will exceed the upper specification, the calculated Z_L for the process is 4.89, and since Z_L value of at least +3, so 4.98 is acceptable. Total reject rate is 0.01%, thus the estimated yield is 99.99%. Next is to conduct PCA, for the cable insulation thickness but this requires derivation of upper specification limit (USL) using the newly

designed engineering limit of 2.74 (USL) and 2.67 (LSL) for the core diameter specification to derive specification for insulation thickness, thus;
Derivations using equation (45):

USL $= \frac{USL - \text{Input conductor}}{2} = \frac{2.74 - 1.13}{2}$ = 0.805. USL value of 0.805 and LSL value of 0.53 was used to conduct the PCA, and the results are as follows:

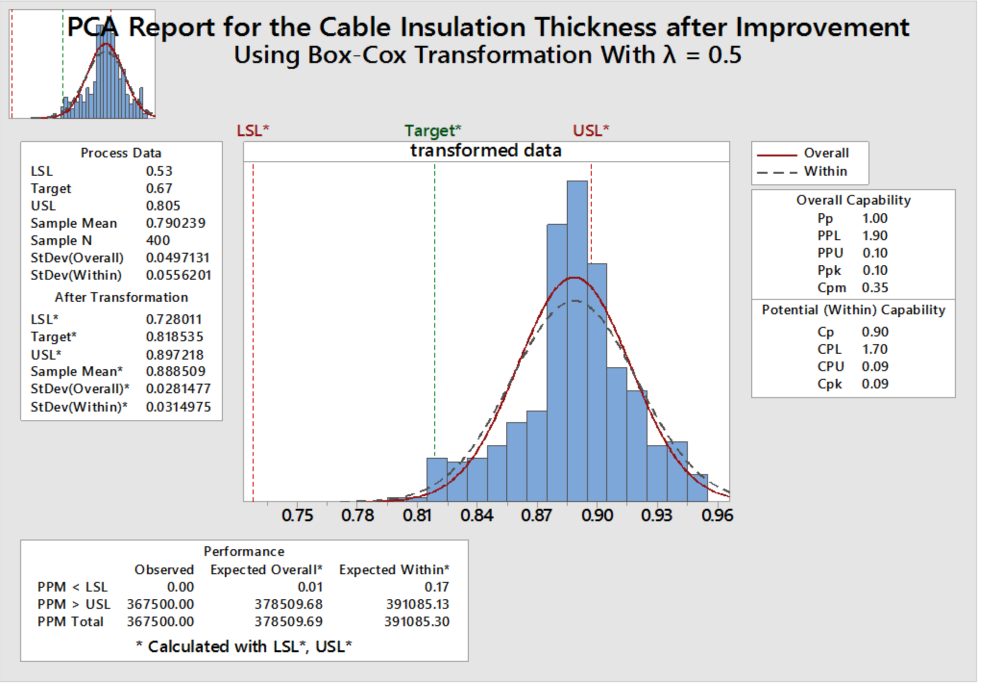

Fig. 13: Process capability report on cable Insulation thickness after the process improvement using the newly-designed engineering tolerance

CP = 0.9 since the minimum acceptable value for this index is 1, the 0.9 result indicates that this process will not meet the requirements most times. The CR = 110%. The number itself means that the “natural tolerance” of the process uses 110% of the engineering requirement, which is not acceptable, and indication that the process mean are still not clustered around the target mean. Cpk = 0.09, the value of Cpk is smaller than that of Cp, an indication that much can be gained through centering the process. The calculated ZU for the process is 0.28; Zu = 1-0.6103, which is 38.97%,by this estimation, approximately 38.97% of the production will exceed the upper specification limit, projected yield = 61.03, the calculated ZL = 5.17 checking from the 6-sigma conversion table in appendix 4 the Sigma level is at 1.7. Dividing the start-up activity into work components and time to establish the typical operating time was another crucial task during this phase. The value obtained would be inferred to determine the anticipated productivity rate for this operation because standard time is a common denominator for assessing productivity. The organization can utilize this observed estimation to predict their production throughput and structure their performance, which would lower the high rate of creating defective cables as a result of unrealistic work targets. During the control phase, the enhanced process was tracked using a control chart. The necessary measures, the target for each measure, the method, the frequency, and the person responsible for checking the measures, as well as the steps that will be taken in the event of an out-of-control event, are all listed in the comprehensive control plan that was drafted (see appendix 8).

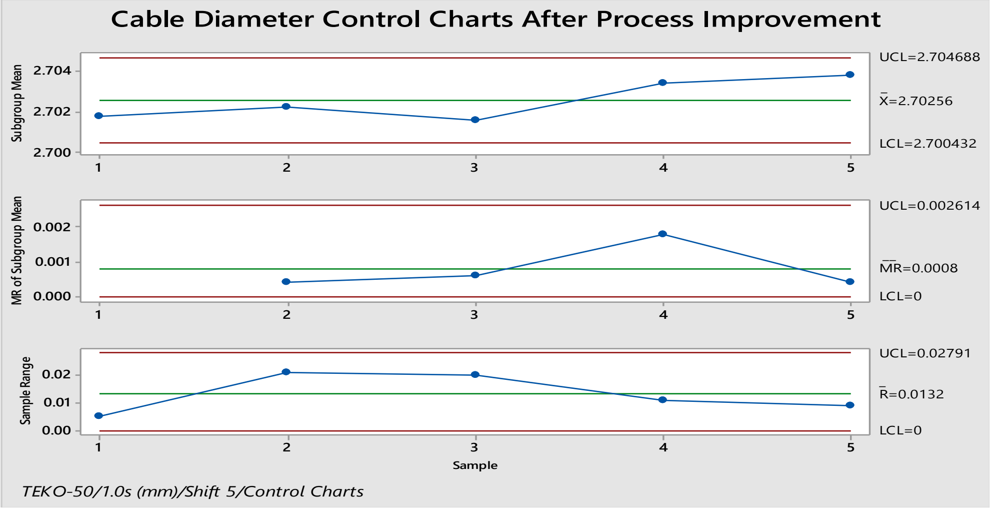

Fig. 14: I-MR-R/S chart for cable diameter for to validate process stability

Further on this phase, process variation reasons were divided into two categories: common and specific factors (see to appendix 9). An I-MR-R/S (Between/Within) chart, which consists of an individual chart, a moving range chart, and an R/S chart, was used as part of the monitoring regimen for the improved process to evaluate the within-sample component of variation, the between-sample component of variation, and the stability of the process location. Using the digital callipers, the process engineers measure five pieces at random from the extruding cable at 30-minute intervals during this process monitoring time. During the three days of the assessment, nine consecutive operational shifts were evaluated. Some of the I-MR-R/S charts for various manufacturing shifts were left out, nevertheless, because of space restrictions. Based on MATLAB toolbox, a higher-level programming language with an interactive development environment, a graphical user interface was created to relieve manufacturers of the burden of numerous and complex mathematical calculations.

The software simulation was advanced using multiple regression equations to create a generic model for predicting uniform cable dimensions in any typical cable manufacturing organization. The simulation program made use of first and second-order models as shown in equation (4.1) & (4.2).

$$C_D = \beta_0 + \beta_{1C} + \beta_2 x_E + \varepsilon \qquad 4.1$$

$$C_D = \beta_0 + \beta_1 x_C + \beta_2 x_E + \beta_{12CE} + \beta_{11} x_C^2 + \beta_{22} x_E^2 + \varepsilon \qquad 4.2$$

where C_D = cable dimension, E = extruder speed, C = Capstan speed, $\beta_0 \ldots \beta n$ = constants, e = statistical error.

Study Implications

This research explored the innate potentials within these two powerful disciplines, knowledge management (KM) and the Lean Six Sigma approach, to monitor the changing distribution of process capabilities in a cable manufacturing organization. The study outcomes suggest that KM integration with the LSS technique aids in establishing the underlying culture of learning to maintain stability in the newly improved process. In this study, the power of generality trade-off was explored by augmenting the LSS methodology with domain-specific adaptations which include the introduction of additional Knowledge Management techniques in the existing method to make it more powerful for application. Although the study findings are specific to the cable manufacturing industry in the Nigerian context, it does have certain implications for other manufacturing companies that intend to reduce variation in their process and become more knowledgeable of their process. The outcome of this study will proffer efficient technical means of eliminating defects and losses in production systems, through careful diagnosis and a systematic problem-assessment approach. The conceptualized model was developed with knowledge-capturing mechanisms to provide an employee capability development atmosphere through cautious identification, and retention of knowledge domains thus building strong social capital within the organization. In a more general dimension, the study would immensely contribute to narrowing the gap between LSS and KM studies in Africa and other regions. Lastly, this study has introduced to the existing body of process improvement studies, a form of integration tactics that would benefit process improvement practitioners in manufacturing companies, on the matching advantages of these two distinct disciplines LSS and KM" that have been scarcely reported in the process improvement studies conducted in Nigeria

Conclusion

The purpose of this study was achieved and answers to sought-out research questions were provided on developing a robust strategy for tackling process variability as well as the ways to develop social capital, best practice replications in internal operations of an organization. In this study, the improvements in project performance and application impacts of the new

methodology have been investigated by comparing the initial and final capability of the process of the executed projects, comparing the initial and final Sigma level of the executed projects, and comparing the initial and final economic impact assessment of the executed project. The root causes of variation in cable manufacturing were identified, mainly as designs, parameter settings, materials, operation techniques, and measurement system errors. A tremendous improvement was achieved at the end of the projects in terms of the increased Sigma level (for both the cable diameter and Insulation thickness), development of standard time of operation, elimination of non-value added activities and the development of extrusion model of the form:
CD preheated PVC= 1.81243+ -0.00126332*A + 0.00156569*B, was developed for predicting the cable dimension. Appropriate engineering specification was designed and tightened for the process from (T±0.185) to (T±0.032) such that a Six Sigma process can easily be captured.

The completion of the study resulted in peak improvement in the capability performance, for the cable diameter, using the newly-designed engineering tolerance, Cp increased from 0.22 to 1.43, Cpk increased from 0.3 to 1.23, CR decreased from 447.43% to 69.96%, ZU improved from -0.88 to 3.68, and ZL now moved from 2.22 to 4.89. Defect per million opportunities (DPMO) reduced from 810,000 to 10, thus improving the Sigma level from the value of 0.6 to 5.2. On the insulation thickness using the newly-derived engineering tolerance, Cp, value increased from 0.45 to 0.90, Cpk increased from -0.035 to 0.09, ZU increased from -0.11 to 0.28, and ZL from 2.79 to 5.17. CR was reduced from 223% to 110%, and the total rejection rate was reduced from 54.64% to 38.97%. A significant reduction in defect per million opportunities (DPMO) from 570,000 to 420,000 was achieved, thus improving the Sigma level from 1.3 to 1.7. In summary, this improvement in the sigma level shows that process variances have been greatly decreased, which dramatically lowers the likelihood of producing more faulty goods. Additionally, the project produced a generic knowledge-based management tool that will facilitate the replication of new cable manufacturing projects without the need for an outside consultant. The findings of this investigation have led to the consideration of a suitable recommendation.

Recommendations

It is advised that the suggested improvement methodology be used more widely in companies and service sector organizations that want to improve process performance and remember the knowledge they have acquired from improvement studies. Future research is advised to incorporate IoT devices into the LSS-DMAIC-KM framework due to the large number of observational studies that have been used to describe process improvement studies. It is possible to eliminate human error due to fatigue and other human factors by integrating smart technologies into real-time process monitoring and improvement solutions.

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Appendix 1

Gage R&R Study - ANOVA Method

Gage R&R for Core diameter

Two-Way ANOVA Table With Interaction

Source	DF	SS	MS	F	P
Parts	4	0.220455	0.0551136	6618.05	0.000
Operators	2	0.000022	0.0000110	1.32	0.319
Parts * Operators	8	0.000067	0.0000083	19.72	0.000
Repeatability	30	0.000013	0.0000004		

Total 44 0.220556

α to remove interaction term = 0.05

Gage R&R

Source	VarComp	%Contribution (of VarComp)
Total Gage R&R	0.0000032	0.05
Repeatability	0.0000004	0.01
Reproducibility	0.0000028	0.05
Operators	0.0000002	0.00
Operators*Parts	0.0000026	0.04
Part-To-Part	0.0061228	99.95
Total Variation	0.0061260	100.00

Process tolerance = 0.37

Source	StdDev (SD)	Study Var (6 × SD)	%Study Var (%SV)	%Tolerance (SV/Toler)
Total Gage R&R	0.0017992	0.010795	2.30	2.92

APPENDIX 2

Table of Control Chart Constants

X-bar Chart Constants | for sigma estimate | R Chart Constants | S Chart Constants

Sample Size = m	A_2	A_3	d_2	D_3	D_4	B_3	B_4
2	1.880	2.659	1.128	0	3.267	0	3.267
3	1.023	1.954	1.693	0	2.574	0	2.568

4	0.729	1.628	2.059	0	2.282	0	2.266
5	0.577	1.427	2.326	0	2.114	0	2.089
6	0.483	1.287	2.534	0	2.004	0.030	1.970
7	0.419	1.182	2.704	0.076	1.924	0.118	1.882
8	0.373	1.099	2.847	0.136	1.864	0.185	1.815
9	0.337	1.032	2.970	0.184	1.816	0.239	1.761
10	0.308	0.975	3.078	0.223	1.777	0.284	1.716
11	0.285	0.927	3.173	0.256	1.744	0.321	1.679
12	0.266	0.886	3.258	0.283	1.717	0.354	1.646
13	0.249	0.850	3.336	0.307	1.693	0.382	1.618
14	0.235	0.817	3.407	0.328	1.672	0.406	1.594
15	0.223	0.789	3.472	0.347	1.653	0.428	1.572
16	0.212	0.763	3.532	0.363	1.637	0.448	1.552
17	0.203	0.739	3.588	0.378	1.622	0.466	1.534
18	0.194	0.718	3.640	0.391	1.608	0.482	1.518
19	0.187	0.698	3.689	0.403	1.597	0.497	1.503
20	0.180	0.680	3.735	0.415	1.585	0.510	1.490
21	0.173	0.663	3.778	0.425	1.575	0.523	1.477
22	0.167	0.647	3.819	0.434	1.566	0.534	1.466
23	0.162	0.633	3.858	0.443	1.557	0.545	1.455
24	0.157	0.619	3.895	0.451	1.548	0.555	1.445
25	0.153	0.606	3.931	0.459	1.541	0.565	1.435

APPENDIX 3
Areas under the Standard Normal Curve

STANDARD NORMAL DISTRIBUTION: Table Values Represent AREA to the LEFT of the Z score.

Z	.00	.01	.02	.03	.04	.05	.06	.07	.08	.09
-3.9	.00005	.00005	.00004	.00004	.00004	.00004	.00004	.00004	.00003	.00003
-3.8	.00007	.00007	.00007	.00006	.00006	.00006	.00006	.00005	.00005	.00005
-3.7	.00011	.00010	.00010	.00010	.00009	.00009	.00008	.00008	.00008	.00008
-3.6	.00016	.00015	.00015	.00014	.00014	.00013	.00013	.00012	.00012	.00011
-3.5	.00023	.00022	.00022	.00021	.00020	.00019	.00019	.00018	.00017	.00017
-3.4	.00034	.00032	.00031	.00030	.00029	.00028	.00027	.00026	.00025	.00024
-3.3	.00048	.00047	.00045	.00043	.00042	.00040	.00039	.00038	.00036	.00035

-3.2	.00069	.00066	.00064	.00062	.00060	.00058	.00056	.00054	.00052	.00050
-3.1	.00097	.00094	.00090	.00087	.00084	.00082	.00079	.00076	.00074	.00071
-3.0	.00135	.00131	.00126	.00122	.00118	.00114	.00111	.00107	.00104	.00100
-2.9	.00187	.00181	.00175	.00169	.00164	.00159	.00154	.00149	.00144	.00139
-2.8	.00256	.00248	.00240	.00233	.00226	.00219	.00212	.00205	.00199	.00193
-2.7	.00347	.00336	.00326	.00317	.00307	.00298	.00289	.00280	.00272	.00264
-2.6	.00466	.00453	.00440	.00427	.00415	.00402	.00391	.00379	.00368	.00357
-2.5	.00621	.00604	.00587	.00570	.00554	.00539	.00523	.00508	.00494	.00480
-2.4	.00820	.00798	.00776	.00755	.00734	.00714	.00695	.00676	.00657	.00639
-2.3	.01072	.01044	.01017	.00990	.00964	.00939	.00914	.00889	.00866	.00842
-2.2	.01390	.01355	.01321	.01287	.01255	.01222	.01191	.01160	.01130	.01101
-2.1	.01786	.01743	.01700	.01659	.01618	.01578	.01539	.01500	.01463	.01426
-2.0	.02275	.02222	.02169	.02118	.02068	.02018	.01970	.01923	.01876	.01831
-1.9	.02872	.02807	.02743	.02680	.02619	.02559	.02500	.02442	.02385	.02330
-1.8	.03593	.03515	.03438	.03362	.03288	.03216	.03144	.03074	.03005	.02938
-1.7	.04457	.04363	.04272	.04182	.04093	.04006	.03920	.03836	.03754	.03673
-1.6	.05480	.05370	.05262	.05155	.05050	.04947	.04846	.04746	.04648	.04551
-1.5	.06681	.06552	.06426	.06301	.06178	.06057	.05938	.05821	.05705	.05592
-1.4	.08076	.07927	.07780	.07636	.07493	.07353	.07215	.07078	.06944	.06811
-1.3	.09680	.09510	.09342	.09176	.09012	.08851	.08691	.08534	.08379	.08226
-1.2	.11507	.11314	.11123	.10935	.10749	.10565	.10383	.10204	.10027	.09853
-1.1	.13567	.13350	.13136	.12924	.12714	.12507	.12302	.12100	.11900	.11702
-1.0	.15866	.15625	.15386	.15151	.14917	.14686	.14457	.14231	.14007	.13786
-0.9	.18406	.18141	.17879	.17619	.17361	.17106	.16853	.16602	.16354	.16109
-0.8	.21186	.20897	.20611	.20327	.20045	.19766	.19489	.19215	.18943	.18673
-0.7	.24196	.23885	.23576	.23270	.22965	.22663	.22363	.22065	.21770	.21476
-0.6	.27425	.27093	.26763	.26435	.26109	.25785	.25463	.25143	.24825	.24510
-0.5	.30854	.30503	.30153	.29806	.29460	.29116	.28774	.28434	.28096	.27760
-0.4	.34458	.34090	.33724	.33360	.32997	.32636	.32276	.31918	.31561	.31207
-0.3	.38209	.37828	.37448	.37070	.36693	.36317	.35942	.35569	.35197	.34827
-0.2	.42074	.41683	.41294	.40905	.40517	.40129	.39743	.39358	.38974	.38591
-0.1	.46017	.45620	.45224	.44828	.44433	.44038	.43644	.43251	.42858	.42465
-0.0	.50000	.49601	.49202	.48803	.48405	.48006	.47608	.47210	.46812	.46414

APPENDIX 4

Abridged "6-sigma" Conversion Table Note: Yield refers to percent of output that is good

Yield	Sigma	Defects per 1,000,000	Defects per 100,000	Defects per 10,000	Defects per 1,000	Defects per 100
99.99966%	6.0	3.4	0.34	0.034	0.0034	0.00034
99.9995%	5.9	5	0.5	0.05	0.005	0.0005
99.9992%	5.8	8	0.8	0.08	0.008	0.0008
99.9990%	5.7	10	1	0.1	0.01	0.001
99.9980%	5.6	20	2	0.2	0.02	0.002
99.9970%	5.5	30	3	0.3	0.03	0.003
99.9960%	5.4	40	4	0.4	0.04	0.004
99.9930%	5.3	70	7	0.7	0.07	0.007
99.9900%	5.2	100	10	1.0	0.1	0.01
99.9850%	5.1	150	15	1.5	0.15	0.015
99.9770%	5.0	230	23	2.3	0.23	0.023
99.9670%	4.9	330	33	3.3	0.33	0.033
99.9520%	4.8	480	48	4.8	0.48	0.048
99.9320%	4.7	680	68	6.8	0.68	0.068
99.9040%	4.6	960	96	9.6	0.96	0.096
99.8650%	4.5	1,350	135	13.5	1.35	0.135
99.8140%	4.4	1,860	186	18.6	1.86	0.186
99.7450%	4.3	2,550	255	25.5	2.55	0.255
99.6540%	4.2	3,460	346	34.6	3.46	0.346
99.5340%	4.1	4,660	466	46.6	4.66	0.466
99.3790%	4.0	6,210	621	62.1	6.21	0.621
99.1810%	3.9	8,190	819	81.9	8.19	0.819
98.930%	3.8	10,700	1,070	107	10.7	1.07
98.610%	3.7	13,900	1,390	139	13.9	1.39
98.220%	3.6	17,800	1,780	178	17.8	1.78
97.730%	3.5	22,700	2,270	227	22.7	2.27
97.130%	3.4	28,700	2,870	287	28.7	2.87
96.410%	3.3	35,900	3,590	359	35.9	3.59
95.540%	3.2	44,600	4,460	446	44.6	4.46
94.520%	3.1	54,800	5,480	548	54.8	5.48
93.320%	3.0	66,800	6,680	668	66.8	6.68
91.920%	2.9	80,800	8,080	808	80.8	8.08
90.320%	2.8	96,800	9,680	968	96.8	9.68
88.50%	2.7	115,000	11,500	1,150	115	11.5
86.50%	2.6	135,000	13,500	1,350	135	13.5
84.20%	2.5	158,000	15,800	1,580	158	15.8
81.60%	2.4	184,000	18,400	1,840	184	18.4
78.80%	2.3	212,000	21,200	2,120	212	21.2
75.80%	2.2	242,000	24,200	2,420	242	24.2
72.60%	2.1	274,000	27,400	2,740	274	27.4
69.20%	2.0	308,000	30,800	3,080	308	30.8
65.60%	1.9	344,000	34,400	3,440	344	34.4
61.80%	1.8	382,000	38,200	3,820	382	38.2
58.00%	1.7	420,000	42,000	4,200	420	42
54.00%	1.6	460,000	46,000	4,600	460	46
50%	1.5	500,000	50,000	5,000	500	50
46%	1.4	540,000	54,000	5,400	540	54
43%	1.3	570,000	57,000	5,700	570	57
39%	1.2	610,000	61,000	6,100	610	61
35%	1.1	650,000	65,000	6,500	650	65
31%	1.0	690,000	69,000	6,900	690	69
28%	0.9	720,000	72,000	7,200	720	72
25%	0.8	750,000	75,000	7,500	750	75
22%	0.7	780,000	78,000	7,800	780	78
19%	0.6	810,000	81,000	8,100	810	81
16%	0.5	840,000	84,000	8,400	840	84
14%	0.4	860,000	86,000	8,600	860	86
12%	0.3	880,000	88,000	8,800	880	88
10%	0.2	900,000	90,000	9,000	900	90
8%	0.1	920,000	92,000	9,200	920	92

Appendix 5

Table 4.13: *Cause Validation Matrix for Insulation Thickness Failures*

S/N	Causes	Error Description / Quality Consequences	Confirmation Plan
1	Un-aligned embossing wheel	➢ When the embosser presses hard on the cable, it affects the cable diameter.	GEMBA
2	Worn-out centering bolts	➢ When a bolt or two bolts are worn-out, the molten PVC now exerts uneven pressure to the die cup, thereby pushing it to one end, thus leading to off-centeredness.	Online cut test
3	Poorly annealed copper conductor	➢ Due to sinusoidal movement of poorly annealed copper conductor, off centering becomes imminent, and this lead to insulation thickness failures.	GEMBA / touch
4	Faulty heating system	➢ When the heating system is not heating well, (i.e. either any of the heater bands are not heating well or not heating at all) there is always PVC leakage at the crosshead, and this leakages leads to a drop in the dimension of the cable. This drop in dimension of the able insulation invariably affects the thickness of the insulation.	GEMBA / water spray

5	Over dimensioned tip	➢ When the tip is over dimensioned, there is always a flow back, whereby the molten PVC often moves back into the tip in backward direction. This backward movement of molten PVC through the tip opening pushes the wire to one direction thereby, leading to uneven insulation thickness.	GEMBA / Caliper
6	Inspector to inspector variation	➢ This is the variation that occurs when the same part is measured by different operators.	Gage R & R
7	Faulty Measuring tools	➢ Poorly handled calipers and micrometer screw gauge.	Measurement validation
8	Inadequate skill and operators recklessness	➢ When an operator lacks the proper knowledge of centering. ➢ Poor tightening of the tip to the core tube, resulting to flow back of the molten PVC. ➢ Wrong use of tip and die.	GEMBA, and Process yield
9	Faulty tensioning / braking system	➢ When the braking system fails to regulate the movement of the input reel, the input conductor wire dangles as it move through the core tube. it leads to poor centering and subsequent poor insulation thickness	GEMBA / Touch

10	Operator's fatigue	➢ When an operator becomes uneasy with common tasks and finds it difficult to concentrate. As a result of this uneasiness, the operator often, take longer time to start up extrusion operation.	GEMBA/ survey
11	Improper Speed setting	➢ When the speed of the capstan is higher than the speed of the extruder, the insulation thickness is greatly affected. On the other hand. ➢ When the speed of the extruder is also higher than the speed of the Capstan there is also a witnessed increase in the cable dimension.	DOE
12	Poor Monitoring System	➢ When the process is not properly monitored. For example; when process errors are always detected late, when the insulation thickness checks are not done as it should, when the operators use non-preheated PVC instead of preheated PVC for production, when water trough cotton guides slips-off and the extruded wire is in contact with the trough surface, use of bunched PVC pellets without separating it by bits, when there is volume reduction in the water level in the trough needed to cool off extruding cable and lots more.	GEMBA
13	Unsteady wire guard	➢ When the two opposing metals guide that direct the movement of the wire to the core tube is not steady.	GEMBA

14	Poor fitting of the tip to the core tube	➢ If the tip is not properly fitted to the core tube, Molten PVC from the tip base now penetrate the tube, pushing the conductor to off center position	Opening of the crosshead

Appendix 6

S/N	Causes for Cable Insulation thickness failures.	Solutions for reducing the rate of cable failure due to poor concentricity of cables.
1	Un-aligned embossing wheel	➢ Careful check by the operator on the position of the embossing wheel to the cable, and confirmed by the process engineer on the line immediately after secondary centering has taken place. The process engineer should from time to time check the movement of the embosser in relation to the extruding cable, and also feel the extruding cables to check the quality of the embossment.
2	Worn-out centering bolts	➢ Improvement on centering techniques and use of high temperature yielding bolts and nut, basically medium carbon steel composition of 8.8MPa and above.
3	Faulty measuring tools	➢ Digital calipers should not be placed on vibrating machines. Secondly, before measurement, operators must first measure a reference dimension with the caliper before taking any online measurements.
4	Faulty heating system	➢ The condition of the heating system should

		be checked properly by both the operator and the process engineer and validated at the start of every production shift. The functionality of the heater bands should always be checked at least every 20 minutes using water sprays. Always use candle stick heater bands at the crosshead section for easy replacement and correction.
5	Inadequate skill	➢ Training on “centering” techniques and Standard Operating Procedures (SOP).
6	Faulty heating system	➢ The condition of the heating system should be checked properly by both the operator and the process engineer and validated at the start of every production shift. The functionality of the heater bands should always be checked at least every 20 minutes using water sprays. Always use candle stick heater bands at the crosshead section for easy replacement and correction.
7	Poorly annealed copper conductor	➢ If it will be used at all, then extremely care must be taken by assigning the job to the most experienced operator. Secondly, the extrusion parameter settings must be varied in such a way to increase the cable dimension, thus eliminating the possibility of producing off-centered cables.
8	Over dimensioned tip	➢ Not to be used at all.
9	Poor monitoring system	➢ Improve monitoring system 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].
9	Faulty tensioning system	➢ Total overhaul on the braking system.
10	Operator’s fatigue	➢ Work appraisal
11	Improper speed setting	➢ Optimal setting of the extrusion parameters
12	Poor tip fitting	➢ The fitted tip should be sighted by the process engineer before in use

APPENDIX: 7

FactorsforToleranceIntervals

Values of k forTwo-Sided Intervals									
Confidence	0.90			0.95			0.99		
Percent Coverage	0.90	0.95	0.99	0.90	0.95	0.99	0.90	0.95	0.99
2	15.978	18.800	24.1	32.019	37.674	48.4	160.19	188.49	242.30
3	5.847	6.919	8.97	8.380	9.916	12.8	18.930	22.401	29.05
4	4.166	4.943	6.44	5.369	6.370	8.29	9.398	11.150	14.52
5	3.949	4.152	5.42	4.275	5.079	6.63	6.612	7.855	10.26
6	3.131	3.723	4.87	3.712	4.414	5.77	5.337	6.345	8.30
7	2.902	3.452	4.52	3.369	4.007	5.24	4.613	5.488	7.18
8	2.743	3.264	4.27	3.136	3.732	4.89	4.147	4.936	6.46
9	2.626	3.125	4.09	2.967	3.532	4.63	3.822	4.550	5.96
10	2.535	3.018	3.95	2.839	3.379	4.43	3.582	4.265	5.59
11	2.463	2.933	3.84	2.737	3.259	4.27	3.397	4.045	5.30
12	2.404	2.863	3.75	2.655	3.162	4.15	3.250	3.870	5.07
13	2.355	2.805	3.68	2.587	3.081	4.04	3.130	3.727	4.89
14	2.314	2.756	3.61	2.529	3.012	3.95	3.029	3.608	4.73
15	2.278	2.713	3.56	2.480	2.954	3.87	2.945	3.507	4.60
16	2.246	2.676	3.51	2.437	2.903	3.81	2.872	3.421	4.49
17	2.219	2.643	3.47	2.400	2.858	3.75	2.808	3.345	4.39
18	2.194	2.614	3.43	2.366	2.819	3.70	2.753	3.279	4.30
19	2.172	2.588	3.39	2.337	2.784	3.65	2.703	3.221	4.23
20	2.152	2.564	3.36	2.310	2.752	3.61	2.659	3.168	4.16
21	2.135	2.543	3.34	2.286	2.723	3.57	2.620	3.121	4.10
22	2.118	2.524	3.31	2.264	2.697	3.54	2.584	3.078	4.04
23	2.103	2.506	3.29	2.244	2.673	3.51	2.551	3.040	3.99
24	2.089	2.489	3.27	2.225	2.651	3.48	2.522	3.004	3.94
25	2.077	2.474	3.25	2.208	2.631	3.45	2.494	2.972	3.90
30	2.025	2.413	3.17	2.140	2.529	3.35	2.385	2.841	3.73
40	1.959	2.334	3.06	2.052	2.445	3.21	2.247	2.677	3.51
50	1.916	2.284	3.00	1.996	2.379	3.12	2.162	2.576	3.38
60	1.887	2.248	2.95	1.958	2.333	3.06	2.103	2.506	3.29
70	1.865	2.222	2.92	1.929	2.299	3.02	2.060	2.454	3.22
80	1.848	2.202	2.89	1.907	2.272	2.98	2.026	2.414	3.17
90	1.834	2.185	2.87	1.889	2.251	2.95	1.999	2.382	3.13
10	1.822	2.172	2.85	1.874	2.233	2.93	1.977	2.355	3.09

Appendix 8

		Specifications				Performance Index							
Operation	CTQ Characteristics	USL	LSL	Target	Unit of Measurement	Cpk	CR	Data Description	Measurement Method	Sample size	Frequency of Measurement	Who Measures	Corrective Actions
Cable Extrusion	Cable Concentricity	0.89	0.53	0.71	mm	≥1.33	≤ 75%	Variable	Profile enlarger	10 parts/reel	End of every shift	Process Engineers	Ref. updated SOP
	Cable Dimension	2.74	2.67	2.705	mm	≥ 1.33	≤ 75%	Variable	Profile enlarger	10 parts/reel	End of every shift	Process Engineers	Ref. updated SOP
	Cable Smoothness	N/A	N/A	100%	m	N/A	N/A	Attribute	Visual Inspection / Touching	All the extrusion length	Each extruded length	Shift Operator/ Process Engineers	Ref. updated SOP

Appendix 9

Categorization of Special and Common Causes 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	