Reducing Oil Leakage in Heavy Duty Transformers Made in Small-Scale Manufacturing Industry Through Six Sigma DMAIC: A Case Study for Jaipur

Neeru
Department of Mechanical Engineering, Amity University Rajasthan

Nitesh Singh Rajput
Department of Mechanical Engineering, Amity University Rajasthan

Patil, Arun
Sanjay Ghodawat University

https://doi.org/10.5109/6781070

出版情報：Evergreen. 10 (1), pp.196-211, 2023-03. 九州大学グリーンテクノロジー研究教育センター
バージョン：

Reducing Oil Leakage in Heavy Duty Transformers Made in Small-Scale Manufacturing Industry Through Six Sigma DMAIC: A Case Study for Jaipur

Neeru[1*], Nitesh Singh Rajput[1**], Arun Patil[2***]

[1]Department of Mechanical Engineering, Amity University Rajasthan, India - 303002

[2]Sanjay Ghodawat University, Kolhapur, India 416118

*Author to whom correspondence should be addressed:

E-mail: neerukhola@gmail.com*, nsrajput@jpr.amity.edu**, vc@sanjayghodawatuniversity.ac.in***

(Received December 1, 2022; Revised March 20, 2023; accepted March 20, 2023).

Abstract: The purpose of this study is to address the issue of oil leaks in transformers manufactured by small scale enterprises in Jaipur, India. The DMAIC technique of Six Sigma methodology was used to analyze the problem and develop solutions. The study focused on both newly manufactured and warranty-period transformers, and a number of design tools were used, including SIPOC, DEMATEL, Ishikawa diagram, P-chart, Pareto chart, and cause and effect matrix and diagram. The findings showed that Six Sigma can be an effective tool for small scale industries and their customers in resolving product issues. However, limitations of the study include the potential for inaccurate findings due to improper data gathering, as the available company data for Six Sigma analysis was minimal.

This study highlights the importance of adopting Six Sigma principles in small-scale manufacturing sectors, particularly in the production of oil-filled transformers, where a lack of research has been reported globally. By investigating the challenges faced by customers during and after the purchasing process, the study aims to assist companies entering the manufacturing industry by improving working conditions and reducing replication issues in the production process. The study's contribution is to fill the gap in research on the application of Six Sigma in the small-scale transformer industry and provide valuable insights for companies operating in this sector.

Keywords: Six Sigma, DMAIC methodology, Small Scale Industries, Oil Filled Transformers, Customer Complaints

1. Introduction

Small enterprises face numerous challenges due to limited access to management and business technologies such as Six Sigma. Some of the most significant challenges they face include issues with product defects, customer complaints, poor product quality, ineffective work management, and difficulties with employee management, among others.[1-5]. Implementing the Six Sigma methodology in smaller manufacturing facilities can help address these challenges, particularly in industries such as heavy-duty transformers and oil sealing. Six Sigma is a method that detects errors in the manufacturing or assembly process. One of its most effective tools is the DMAIC approach, which has proven to be beneficial in reducing errors during production and assembly. The Six Sigma methodology provides a comprehensive solution for managing an entire industry.[6,7,8].

The analysis of the instances discussed in the scholarly literature provides a clear overview of the various approaches used for different types of processes. Furthermore, the evaluation sheds light on the tools that may be applied at different stages and for different types of problems. The literature selected for this review specifically focused on manufacturing processes and those similar to the current process used to manufacture heavy-duty transformers to ensure a consistent understanding of the application of DMAIC. The literature suggests that the DMAIC technique is not only relevant to manufacturing activities but also to service operations, which was previously not taken into consideration.

2. Literature Review

According to Muraleedharan et al. (2017)[9], Six Sigma is utilized in both the manufacturing as well as the service sectors. (Ferreira and Lopes, 2010;)[10] The implementation of the DMAIC technique, a key tool in the

Six Sigma methodology, has led to a decrease in defects and improved outcomes in areas such as product development, customer retention analysis, cycle time optimization, productivity improvement, and market share. The "define" step in the DMAIC process involves observing the process and identifying opportunities for quality assurance improvement. This is done using tools such as Pareto charts, process flow diagrams, SIPOC diagrams, and a project charter. In the "measure" step, data on quality attributes and variables is collected and analyzed using instruments such as gauge R&R studies and process capability analyses. This data is visually represented using diagrams such as stem and leaf plots, scatter plots, and histograms. The "analysis" step involves examining the collected data to trace the production of defects back to their causes. This is done using tools such as control charts and failure mode and effects analysis (FMEA). The "improve" step investigates the causes of differences using techniques such as "cause and effect" diagrams, brainstorming, and design of experiments (DOEs). Finally, the "control" step puts the improvements into action and evaluates the current status of the process using quality control tools such as control charts (Montgomery, 2009)[11].

(Junankar and Shende, 2011)[12] studied Six Sigma's adoption to eliminate belt manufacturing faults. Rework orders were the industry's flaws. This project aimed to eliminate leather belt rework, notably fabric rough, and faults. According to the study, rework enhanced productivity and decreased time. During the research, cloth roughness caused most rework requests. The industry produced 167,484 belts with a 5.93% rejection rate, leading to 15,832 remade belts. Belt processing took 140.97 minutes, and sigma was 2.7. According to business standards, reworking 15,832 belts cost 1,209,374. Using a Pareto chart and FMEA, the reworking was caused by insufficient cutter penetration, poor operator attention, insufficient cutting angle, and cutter bluntness over time. After taking precautions and improving processes, DPMO faults dropped to 37,480. Defects contributed 2.7% of belt reworking costs, or 415,203. 3.2 sigma was achieved.

(Desai and Shrivastava, 2008)[13] studied the SAW boom machine process while working on a Six Sigma implementation project at a large-scale enterprise. The purpose of this project was to increase the productivity of the SAW A101 boom machine. The A101 machine had the lowest yield of the four machines, coming in at 42.3% of its potential output. This machine process was utilized at a level of 61.8%, which was equivalent to a sigma level of 1.8. Using a Pareto chart, we were able to determine that the lack of work, which is dependent on job scheduling, was the primary factor contributing to the poor yield. The group deliberated, carried out an FMEA as well as a cause and effect analysis, and designed a method that would reduce the impact of the existing problem. The overall yield of the process increased to 90 percent, which corresponds to a sigma level of 2.78. After an initial investment of 1,420,000, the cost of poor quality has been lowered to a total of 220,000.

Researchers (Kaushik et al., 2012)[14] conducted a study in which they applied the Six Sigma methodology to a small unit that manufactured bicycle chains and had declining productivity levels. They discovered that the chain manufacturing company could increase its profit by controlling the high rejection rate of cycle chain bush. The application of the Six Sigma technique increased the process sigma level to 5.46 from 1.40 by reducing the variance in bush diameter, which resulted in a financial savings of INR 0.288 million per year.

(Sambhe, 2012)[15] successfully implemented Six Sigma at a mid-sized auto auxiliary unit that consisted of between 350 and 400 people. The technique was used on one of the product assemblies with the purpose of reducing the number of defects, which are important to the clients, and the installation of the methodology has resulted in a large financial blow to the bottom line of the company. In addition, (Sambhe and Dalu, 2011)[16] have demonstrated that it is possible to use the Six Sigma framework in the field of medium-sized Indian automotive companies. During the course of the comprehensive market analysis, the prospective qualities of Indian SMEs were taken into consideration. In the context of the Indian automobile sector, a number of different Six Sigma frameworks already in existence were investigated[47,48,49].

(Singh and Kumar, 2014)[17] implemented Six Sigma in a small CO2 laser equipment manufacturer. Due to diameter variance, laser nozzle heads have a significant rejection rate. In this procedure, the measuring system was overloaded. Drill regrinding and work holding mechanisms were the leading sources of faults after a brief assessment of operator, drill regrinding, drill replacement, and job holding mechanisms. Experiments were done to determine ideal settings by varying two parameters. The process' sigma level improved from 2.21 to 5.64 after applying optimum values.

(Panat et al., 2014)[18] used Six Sigma to Intel's R&D production. Manufacturing R&D entails developing a process and scaling it up if successful. Authors focused on R&D waste elimination. Reduce non-value-added activities and system idle time. After comprehending the process map, non-value-added operations were quantified and removed. Time was quantified and FMEAs were generated. Based on risk priority, the procedure was eliminated or modified. System idle time decreased by 60% after deployment.

(Kumar et al., 2015)[19] studied Six Sigma in a submersible pump casting factory. Inferences about the process were made to eliminate faults. Housing, motor pulley, and tiny chaff cutter made up the final product. Due to the casting process, the bow holes were discovered to be the major cause of pump rejections. Upper housing, motor pulley, and small chaff cutter had 8.63, 7.63, and 5.18 percent blow hole rejection after four months. The blow hole produced 5.83% of 1,539 rejections. Blowing holes were caused by soil moisture, lack of ventilation, inadequate permeability, etc. High soil wetness and poor permeability were revealed to be the primary reason. According to testing, the soil had 7.26% moisture and 122 cc/min permeability. This was poor-quality dirt, therefore it was replaced. Upper housing loss improved from 67,230 to 26,082 after the renovation. Motor pulley loss decreased from 35,720 to 9,785. Mini chaff cutter faults dropped from 87,864 to 31,080. Sigma increased from 2.04 to 5.83.

(Krotov and Mathrani, 2017)[20)] studied a nutritional product manufacturer. The study focused on ingredient variety, contamination, foreign matter in nutrition formulas, and late delivery rates. 61 out of 196 batches were rejected, and 47% were late. Lack of uniform batches and no waiting time measurement were noted in this line. Errors increased. Blending duration, waiting time, blender load, blender type, raw material used, and cleaning method were the primary drivers of mistakes. According to FMEA, waiting time and blender load were key. To save waiting time, mixing division employees were also responsible for packing, which improved cleanliness. Optimizing blender loads with DOEs. Ingredients were part-hopped. These improvements cut faults and late deliveries from 47 to 23%.

(Costa et al., 2017)[21)] improved tire extrusion. Work-off is extrusion fault. 13% of tread and 24% of sidewall extrusion was work-off. Failure to feed product mixture into the extruder was a major factor. Air blower treadmill was replaced for improvement. Digging deeper. The work-off was cut by 0.9%, saving €165,194 annually.

(Singh and Lal, 2016)[22)] studied a muffler-producing automaker. DMAIC was used to study the process and muffler issues. 8.21% of mufflers were rejected. After utilizing a cause-and-effect diagram and brainstorming, we concluded that faulty MIG and TIG welding caused the rejection. Better welding procedures enhanced weld quality. After improving weld techniques, the rejection rate dropped to 4.8%. The company's sigma level rose to 3.16. The process yield increased from 91.73 to 95.19%, saving the firm 940,800.

Effective maintenance and management of manufacturing equipment is critical to a company's success in various aspects such as economic, environmental and social performance. Improper maintenance activities can lead to a range of problems, including increased costs, downtime, defects, additional inventory, and reduced product quality (Jasiulewicz-Kaczmarek et al., 2021)[50)]. Effective maintenance processes can not only enhance the equipment's performance by reducing the failure rate, but also minimize operating costs by increasing the equipment's lifespan (Zonta et al., 2020)[51)].

From an environmental viewpoint, insufficient maintenance practices can result in hazardous emissions, inefficient energy utilization, ineffective resource utilization, and other environmental impacts (Xia et al., 2018; Franciosi et al., 2020; Vrignat et al., 2022)[52,53,54)]. On the social front, inadequate maintenance can also result in unsafe and unhealthy work conditions, accidents, and incidents that can negatively impact a company's reputation (Lovrencic et al., 2017; Franciosi et al., 2019)[55,53)].

The perception of maintenance has undergone a significant change in the last few decades. Gone are the days when maintenance was viewed as an insignificant aspect of business operations. Today, its impact on various other company processes such as production, logistics, occupational health and safety management, and the environment, has led to the recognition of maintenance as a crucial business function. The maintenance process plays a vital role in supporting companies in their efforts towards sustainable production. It helps organizations in meeting the economic, environmental, and social challenges that come with it. The importance of maintenance in today's business landscape cannot be overstated, and its role in driving a company's success is increasingly being acknowledged by experts and industry leaders alike (Saihi et al., 2022, Hami et al, 2020, Karuppiah etal, 2021)[56,57,58)]

Some general used tools of the six sigma were list out in table 1.

Table 1 Some important research work published on SS implementation in SME

Reference	Industry	Six Sigma Tools
Antosz et al (2022)	Small Manufacturing plant for assembly layout	DMAIC, Six Sigma tools
Vrignat et al (2022)	Review on various industries	Various tools including Six Sigma
Saihi et al (2022)	Review on maintenance importance for cost cutting	Six Sigma based studies selected
Hami et al (2020)	Review on sustainable development in SMEs	Importance of the Six Sigma tools
Kaaruppiah et al (2021)	Barriers identifications in SMEs	Using Six Sigma tools
Krotov and Mathrani (2017)	Food product manufacturing industry	DMAIC, SIPOC DOE, Cause and Effect, Pareto Chart, MAT (Measurement Assessment Tree)
Costa et al. (2017)	Tire manufacturing Industry	DMAIC, SIPOC, Cause and Effect diagram
Srinivasan et al. (2016)	Nozzle manufacturing Industry	TQM, DMAIC, Pareto Chart, DOE, Cause and Effect

Reference	Industry	Six Sigma Tools
		diagram
Singh and Lal (2016)	Automobile muffler Manufacturing Industry	Six Sigma DMAIC
Yadav and Sukhwani (2016)	Automobile Clutch manufacturing Industry	DMAIC, Pareto Chart analysis, DOE, Run Chart
Drab et al. (2015)	Steering assembly unit	DOE, pareto analysis, Regression and ANOVA testing
Indrawati and Ridwansyah (2015)	Iron ore manufacturing unit	Process capability, DMAIC, failure analysis
Kumar et al. (2015)	Casting of the hydraulic pumps	DMAIC and cause and effect analysis
Panat et al. (2014)	SMEs general manufacturing industry	SIPOC, DMAIC, FMEA and time series analysis

The objective of the current work is to use Six Sigma methodology and the DMAIC technique to decrease the amount of oil leaking from heavy-duty oil transformers. This study is focused on small-scale enterprises located in the industrial region of Jaipur. To accomplish this goal, a new stage referred to as "Review" has been added to the DMAIC model, with the purpose of validating the Six Sigma deployment methods. The review stage involves the use of several performance indicators to measure the success of the methodology. The ultimate goal of this process improvement effort is to reduce the number of heavy-duty transformers that are rejected or have problems, which will in turn reduce the costs associated with rebuilding the transformer's body and the money lost due to scrap. The study will provide a concise summary of the implementation of DMAIC in the quality engineering community, a detailed explanation of the situation being considered and the phased implementation of DMAIC, a summary of the findings, and a discussion of the future scope for further enhancements.

In addition, the study will also address any challenges faced during the implementation of DMAIC and suggest potential solutions to overcome them. The results of this study have the potential to positively impact the efficiency and profitability of small-scale enterprises in the industrial region of Jaipur by reducing costs and improving the quality of their products. In conclusion, the use of Six Sigma methodology and DMAIC technique in the current work has the potential to make a significant impact on reducing oil leakage from heavy-duty oil transformers. By applying this methodology and adding a "Review" stage to the DMAIC model, the study aims to improve the efficiency and profitability of small-scale enterprises in the industrial region of Jaipur. The framework developed for the present study was shwon in figure 1.

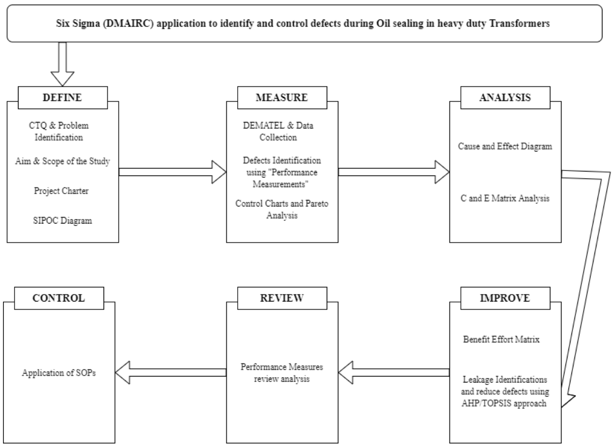

Figure 1 model framework for six Sigma DMAIC method

2 Research Work Approach

The purpose of the current study is for researcher to investigate oil leakage problems that may arise during the manufacturing of oil-supported transformers and then apply the Six Sigma "DAMIC" approach to find solutions to such concerns. The focus of this particular research is on the examination of regional industry, and more specifically, small-scale industry. The capacity of the transformers that were utilized in this research investigation ranged anywhere from 20 kVA all the way up to 5000 kVA on average. The transformer's look is seen in its entirety in figure 2.

Figure 2 Heavy duty transformer at company site (Jaipur)

The procedure of producing heavy-duty transformers, which are utilized in a variety of sectors, has been chosen as the case study that will be analyzed here. The research was carried out in a sector of the economy that was responsible for the production of a wide range of transformers, many of which experienced oil leakage issues both during the manufacturing phase and after the product had been sold. Electrical panels, low voltage transformers, and a variety of other electrical goods were just a few of the additional products that were created in the industry that was chosen. The transformer, the operation of which is being investigated, is seen in figure 2. The business sector utilized a pull system, in which production was carried out in response to orders placed by customers. This product was the one that had the most number of rejections, and the cost of reworking it was also rather expensive. As a result, considering this method was one of the options available in order to cut down on the amount of errors utilizing DMAIC.

The primary obstacle that the industry encountered when it came to the production of heavy-duty transformers was trying to keep the quality level the same while simultaneously lowering the rejection rates. The production of transformers requires a number of different procedures, including punching, bending, spot welding, TIG welding, sanding, and polishing. However, the most significant cause for worry was the mounting of the bushings, welded joints, Oil Gauges, body cover, and Pressure Relief Devices (PRD) on the surface of the constructed transformers. In many cases, the rejections are the consequence of variations in the dimensions of the components that are necessary for the assembly of the transformers. These variations led to faulty alignment of the oil seals, which caused oil leakage difficulties, which in turn led to rejections.

In this particular case study, the defining step consisted of observing and comprehending the process, as well as deciding the scope of the project. The data pertaining to the present procedure were gathered at the phase known as "measure." Using the information gathered in the measure phase, the present performance was evaluated during the analyze phase. During the period designated for improvement, a number of potential solutions are conceived with the intention of resolving the issue at hand and then put into action. During the control phase, the solution that was implemented is evaluated, and performance is measured to determine the degree to which there has been an improvement.

3 Phase -I: Define

It is chosen what aspects of the project's scope will be examined in further detail during the define phase. Following these discussions, it was decided that the objective of the project would be to reduce the number of defects at site and customer locations by approximately half within approximately six months of the beginning of the project. This target was established based on the case that was being examined at the time. The degree to which staff members are familiar with and get along with patrons will be evaluated as one of the most significant aspects of the business. The project charter of the present study was present in table 2

Table 2 Project Charter for Defects reduction in Heavy Duty Transformers

Project Title:Defect reduction in Oil Sealing Process during Transformer fabrication		
Project Location:Small Scale Industry which manufacture/Repair Heavy Duty Transformers		
Problem Statement	**In-Scope**	**Out of Scope**
To identify the defects causes during fabrication of Oil fitted transformers and reduce these defects	Defect identification and improvement in working conditions	Not include all manufacturing steps during fabrication of transformers
Aim/Goal of the Study	**Time Line of the Project**	
To identify and reduce oil leakage problem from transformer with in a six month period with approx 50% customer complaints solutions	**D**efine **M**easure **A**nalysis **R**eview and **C**ontrol	Six Month Time Duration
Advantages to Business	**Advantages to Customer**	
Can reduce cost to product, which help to expand market to company and survive in competition	Provide more faith to company by customers, which help to increase growth	
Project Plan	**Project Stake Holders**	
Application of Six Sigma "**DMAIC method**" to control this problem	Managers from different department like production, quality, purchase, sells, marketing etc Research Candidate, Guide Floor Operators	

The process of building a transformer involves putting together a number of distinct parts, including the body of the transformer, its coils and winding, oil chambers, explosion vents, insulating materials, oil sealing, and other important parts like electrical connections, amongst other things. The major focus of this research is on all of the many assembling techniques requiring to control the oil leakage from transformers. Small-scale transformer producers frequently face the challenge of repairing transformers that have oil leakage issues. As a result, an outline of the essential steps involved in oil sealing is presented in this paper. The meticulous process that was utilized to check and test the transformer's seals as it was being constructed is seen in figure 3.

Table 3 SIPOC diagram for the oil leakage in transformer

Supplier (S)	Input (I)	Process (P)	Output (O)	Customer (C)
Steel Sheets Suppliers	Body making	Body Fitting		
Electrical Components Suppliers	Electrical Boards Circuit Assembly	Electrical Fitting	Product Looking	
Oil & Sealing materials Suppliers	Oil Sealing and proper Assembly	Sealing Fitting	Safely Packaging	Deliver to Customers
Tools and other Equipment Suppliers	Welding and tightening of the final product	Final Alignment	Time Control	
Work Force and Operators	Fitting and Testing	Final Testing	Product Quality	

Observations were made of the rejected transformers, and quantitative analyses were performed with regard to the cause of the rejection. Table 3 outlines the primary reasons for rejections of the transformers. These locations are identified by observations of the transformers during making phase as well as after sales of the transformers to the customers.

Table 4 Locations of oil leakages in transformers

Designation	Full terms
LD-I	Bushings
LD-II	Welding Joints
LD-III	Oil Gauges
LD-IV	Body Cover
LD-V	Handle
LD-VI	Pressure Relief Device (PRD)

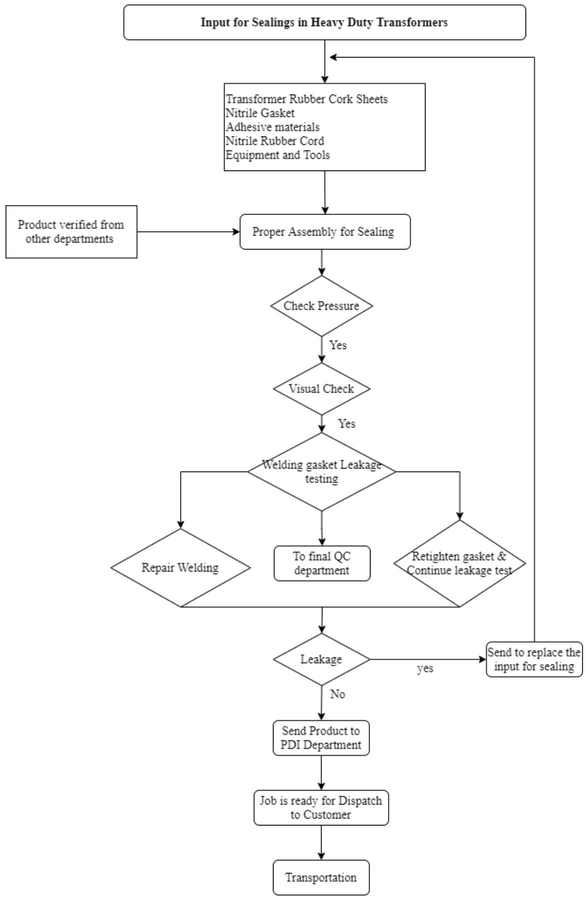

Figure 3 Sealing process used for heavy duty transformer making

As can be seen in Figure 4, a Pareto chart was utilized in order to conduct an analysis of the contribution made by faults. It is clear from looking at Figure 4 that the majority of the problems were from the handle, the body cover, and the welding joints. As a result, it was agreed that the scope of the improvement of this process would be to decrease the flaw that was caused by these three measures. The general work-flow of the production process is depicted in Figure 1, as can be seen.

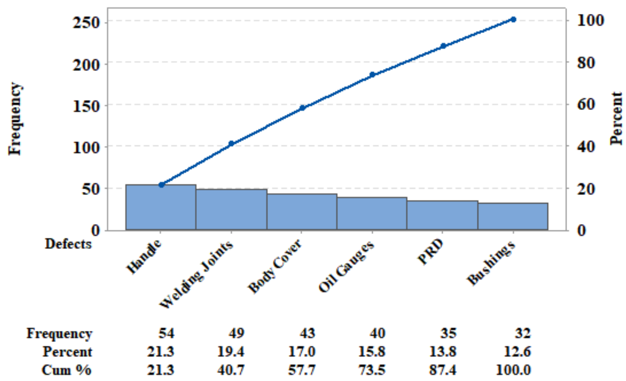

Figure 4 Pareto analysis for oil leakage defects at various locations of Transformers (N=2800, Total Defects=250)

Taking into account all of the aspects of the investigation, a project charter was developed, and it is presented in Table 1. The list of team members, objectives, tools utilized, features of the data, and other relevant information are all included in the charter. In addition, a SIPOC illustrates the entire chain, beginning with the order and ending with the supply. Table 2 displays the SIPOC in its entirety. According to the data presented in the Pareto chart, out of a sample size of 250 transformers that were not accepted, 21.3% of those transformers were not accepted because of oil leaking at the handle (LD-V) position of the transformers. The welding joints (LD-II) at various parts of the oil tanks, as well as the body cover (LD-IV), were identified as the other locations where an oil leakage problem existed.

4 Phase -II: Measure

In this part of this paper, the first duty to discover problems with customers is to collect data from those customers; after this information is collected, the measurement may begin. The process of collecting data takes a significant amount of time and makes use of a number of different important ways. In this part, the theoretical underpinnings of the DEMETAL method are laid forth, and the technique is then continued in the following section. During the phase referred to as "measure," data were collected from measurements taken at every feasible area where oil leakage may occur. The amount of time throughout which the data were gathered was one month. The researcher utilized a Vernier calliper to measure the length of the test product, a right-angled scale to measure the degree of the bend, a steel tape to measure long distances, and a visual inspection and camera to find out where the oil leakage was occurring. All of these pieces of equipment were used in order to measure the data.

It was found that using process sampling to identify top defects was not feasible at this stage of the project because it was estimated that using this method would increase both the cost and the amount of time needed to complete the implementation of the project (Ansu Gupta et al., 2019)[27)], (Drohomeretski et al. 2014)[28)]. Large sampling data was required in order to come to a conclusion regarding the top defects, so process sampling was ruled out. In addition, the quality inspectors of the company pointed out the fact that the detected flaws are interdependent on one another and have a cause-and-effect sort of relationship amongst themselves while they were working on the define phase during the process of identifying faults. Nevertheless, there was a lack of transparency regarding the specific interdependencies. Keeping this indication as a point of reference, in order to find a solution to this predicament, research was conducted in order to find an additional way that can be utilized in this context to rank the 10 flaws in the product. As was previously mentioned, the DEMATEL approach, which originates from the OR discipline and is described in greater depth in "present paper," was recognized as a way to facilitate decision making and to discover the cause and effect link between the faults (Agarwal et al. 2016)[29)].

Using the DEMATEL technique, the six defects that were highlighted in Table 2 were prioritized on the basis of interdependencies between them using the direct relation matrix obtained from experts (including six internal customers of the process: Quality head, Maintenance manager, Research advisor, Quality control inspector, Financial head, and Shop floor operator). The DEMATEL technique was developed by the Defense Advanced Research Projects Agency (DARPA). On the basis of the extent to which they cause or are impacted, respectively, the flaws were categorized as belonging to either the cause group or the effect group (Zhou et al. 2018) [30]. Table 5 contains a list of defects, together with the category to which each one belongs. Tables 9, 10, 11, and 12 of "Appendix A" contain the replies of the project team as well as the interaction matrices.

Table 5 Classification of Defects Into Cause and Effect Groups

Designation	Full terms	Ri	Ci	Ri + Ci	Ri - Ci	C & E
LD-I	Bushings	2.645	3.001	5.646	-0.356	Effect
LD-II	**Welding Joints**	**3.123**	**2.580**	**5.703**	**0.543**	**Cause**
LD-III	Oil Gauges	2.915	3.673	6.588	-0.759	Effect
LD-IV	**Body Cover**	**3.908**	**2.912**	**6.820**	**0.996**	**Cause**
LD-V	**Handle**	**3.197**	**2.969**	**6.166**	**0.228**	**Cause**
LD-VI	Pressure Relief Device (PRD)	2.673	3.324	5.997	-0.652	Effect

The Digrapgh was shown in figure 4 for present study.

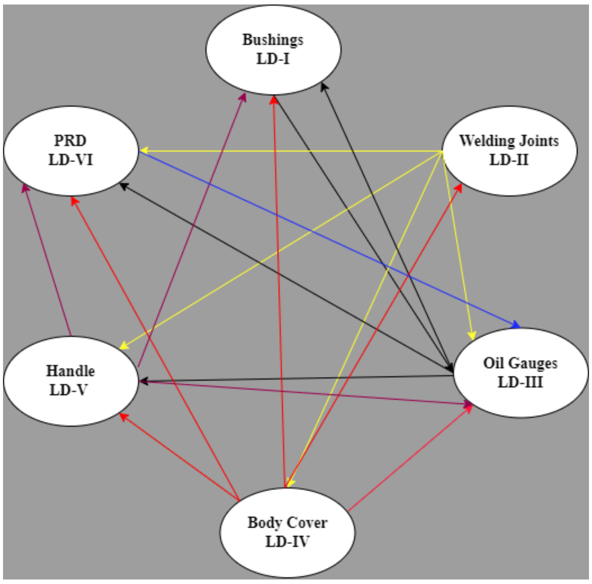

Figure 4 digrapgh for oil leakage DEMETAL process

As was said before, the major objective of the measure phase of the DMAIC approach is to determine the existing level of process performance (in terms of sigma level). At this point, the performance of the transformer manufacturing process is evaluated according to the three locations where oil leakage that have been detected in the cause group. In addition, the information regarding these faults was gathered by watching the output of the manufacturing/assembly process for a period of sixty days while doing one hundred percent product inspection (Montgomery 2007)[31] (Montgomery 2008)[32]. The results from the sample were recorded using the data from the check production (shown in Fig. 5).

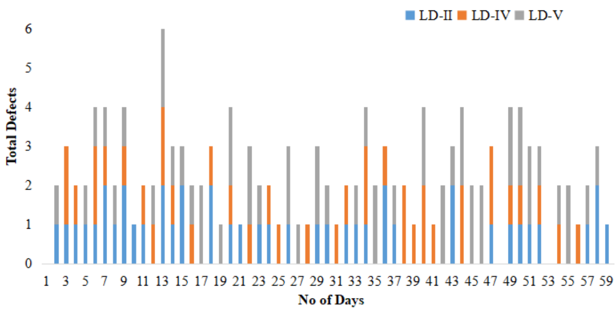

Figure 5 Total defects identified in 60 days sampling process

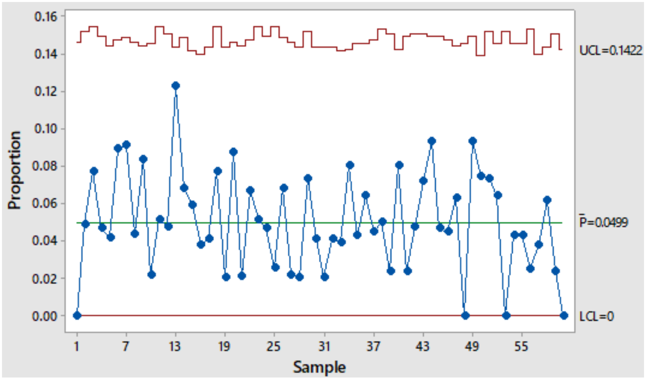

Figure 6 P chart analysis for different sample sizes

The percent deficient, the DPMO, and the sigma level were the performance matrices that were utilized in the process of measuring the performance of the transformer-making procedure. As can be seen in Figure 6, a p-chart for fraction defectives (Gijo et al. 2011)[33] was built for the 60 samples with a process average fraction defective of 0.0499. This was done so that it could be determined whether or not the process was operating in a regulated condition. The base line process performance level was determined to be 3.15 based on this research, which corresponds to 49,853.37 faulty Parts Per Million (PPM) (Jirasukprasert et al. 2014)[34].

The current sigma level of the process was estimated using the DPMO by using the data that was available from the production during the survey period: Number of transformers produced: 2728, number of transformers passed the quality check: 2485, total defects: 136 (LD-II, LD-IV and LD-V)

$$\mathrm{DPMO} = \frac{\mathrm{Defects}}{\mathrm{Total\ Production}} \mathrm{X}10^6$$

$$\mathrm{DPMO} = \frac{136}{2728} \mathrm{X}10^6 = 49{,}853.37$$

Sigma level calculation for the present investigation was following:

$$\text{Sigma level} = 0.8406 + \sqrt{29.37 - 2.221\ln(\mathrm{DPMO})}$$

$$\begin{aligned}\text{Sigma level} &= 0.8406 \\ &\quad + \sqrt{29.37 - 2.221\ln(49{,}853.37)} \\ &= 3.152\end{aligned}$$

5 Phase -III: Analyse Phase

An in-depth analysis of the oil sealing leakage issues with respect to the three key defect locations identified in the measure phase is performed during the analysis phase of the six sigma study. The purpose of this phase is to determine the underlying causes of the problem in detail, which involves identifying the root causes of the problem. During the manufacturing process of the transformers, the handle was the most critical area since it was where the majority of oil leaks occurred.

In this phase, the Six Sigma methodology is applied to determine the significance of the data and to identify the underlying causes of the difficulties associated with the oil sealing step of the heavy-duty transformer manufacturing process. These difficulties are in relation to the two significant faults that were discovered in the measure phase. The misalignment of the seal and the inability to undertake the proper testing during the early phases of manufacturing are the primary factors that contribute to oil leaking from the transformer body cover and the welded joints. Following an investigation into the numerous factors that can lead to oil leakage, two primary causes have been pinpointed: improper assembly of the oil-sealing product or a problem with the oil-sealing product manufactured by the manufacturer, and improper assembly of the entire product, which can result in a number of issues such as faulty welding, warping of the surface, inefficient working conditions, and other issues.

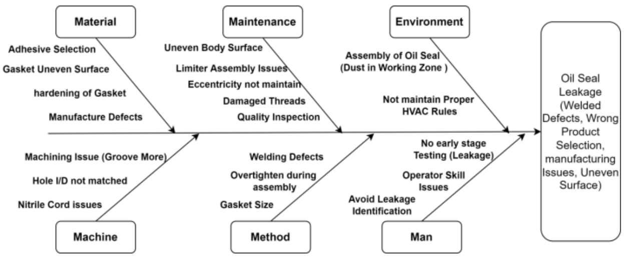

Figure 8 Fish-bone diagram for oil seal leakage in transformer

In modern era, the person in charge of the project's quality ensures that upper management and the members of the team get together for a brainstorming session to discuss the origins and fundamental causes of the faults (Gijo et al. 2011; Prashar 2016a,b)[33,34,35,36]. Another goal of this discussion is to identify the potential solutions that may be used to bridge the gap between the current performance level and the aspirational level that has been established (Gijo and Scaria 2010)[37]. Following the conclusion of the meeting, probable sources of the issue were identified and categorized into six broad categories: material, manpower, maintenance, method, machine, and environment (5 M&1E), which were depicted using a fishbone diagram (Gupta et al. 2016)[38]. In order to arrive at a diagnosis of the root reasons, each of the probable causes that are indicated in the fishbone diagram (Fig. 8) is investigated in great depth utilizing the information that is readily accessible, floor observations, and conversations with operators and engineers.

Several methods, such as the Interrelationship Diagram (ID) (Doggett 2005)[39], the C&E matrix (Lee et al. 2009)[40], and the Cause and Response Tree (CRT) (Sharma et al. 2018)[41], have been discussed in the literature for the purpose of locating these underlying causes. (Rajagopalan et al. 2004)[42] The C&E matrix is utilized in this research to get an understanding of the interrelationships that exist between the probable causes, the undesired faults that they provide, and the primary issue. As was just said, it links the process stages with the KPIVs and then takes those KPIVs and relates them to the KPOVs. On a scale that ranges from one to ten, with one being the least significant and ten representing the most significant, a score has been assigned to each KPOV based on the customers' point of view, and this has been done so that these linkages may be understood. In addition, correlation scores are calculated between each KPIV and KPOV by applying the scale developed by (Sokovic et al.,2005)[43]. The significance ratings of each of the KPIVs may be determined by using these scores in conjunction with other information. The final C and E matrices for the oil sealing leakages issues at selective three locations (LD-II, LD-IV and LD-V) are present in table 6.

Table 6 C and E matrix for Oil Leakage Problem

No	**Rating of Importance to Customer**						**Total**	**% of total**
			6	**6**	**8**	**9**		
	Process Setup	**Process Input**	**Product looking**	**Safely Packaging**	**Time Control**	**Product**		
1	Set up	Collect all parts	1	3	9	3	123	8.64
2	Set up	Prepare for assembly	1	6	3	3	93	6.53
3	Set up	**oil seal components collection**	3	3	9	9	**189**	**13.27**
4	Set up	**assemble final product**	1	3	9	3	123	8.64
5	Apply	initial testing	1	3	6	3	99	6.95
6	Apply	**leakage testing (Initial)**	1	9	5	3	127	8.92
7	Apply	reproducti	3	3	3	1	69	4.85

No	Rating of Importance to Customer						Total	% of total
			6	6	8	9		
	Process Setup	Process Input	Product looking	Safely Packaging	Time Control	Product		
		on manufacturing isses						
8	Apply	**welded defects reproduction**	1	3	9	9	**177**	**12.43**
9	Apply	**war page reproduction**	1	1	9	9	**165**	**11.59**
10	Apply	Mismatch the product size	1	1	1	3	47	3.30
11	Apply	**Oil Leakage testing (Final)**	1	6	3	9	**147**	**10.32**
12	Apply	Final Testing (Full Product)	0	3	1	9	107	7.51
13	Set up	Collect all parts	1	3	9	3	123	8.64
							1466	

The team came to the conclusion that the KPIVs with the highest ratings were the root causes, and they focused on these KPIVs during the enhance phase of the DMAIC process (Sokovic et al. 2005)[43]. Ratings that are higher than the threshold value of about 150 (which was indicated by the person making the choice) are considered to be the root cause, as shown by the numbers that are highlighted in bold in column 8 of Tables 5. The investigation of the C&E matrix led to the discovery of six significant underlying factors that contributed to the oil leaking critical faults. These were as follows:

Oil seal components collection
Assemble final product
Leakage testing (Initial)
Welded defects reproduction
Oil Leakage testing (Final

6 Improve and Review Phase

During this stage of the DMAIC process, the factors that contributed to the fundamental causes were analyzed, and possible remedies were devised. In the analyze phase, five significant root causes were found for the three critical defect areas (LD-II, LD-IV and LD-V) of the oil seal leakage. These reasons are given in the first column of Table 6, as indicated in the previous phase (see figure 6).

The first priority of the improve phase was to identify the corrective actions that could be taken to get rid of the underlying issues and to investigate whether or not it would be possible to put these actions into practice based on the anticipated amount of time, effort, and money needed for implementation. Further, it was realized that multiple corrective actions couldn't be implemented at the same time because of the barriers of limited resources, availability of skills, small scale of operation, internal resistance, lack of ownership especially from temporary employees, lack of knowledge, and poor training methods. It was also realized that multiple changes are likely to bring about process instability if they are implemented simultaneously. Following a meeting with the senior management, it was decided to execute corrective actions sequentially rather than in simultaneously in order to address these difficulties. This decision was supported by evidence from the relevant literature and was made based on the firm's prior experience. In addition, prior to implementing corrective actions for these root causes, they were first prioritized using a benefit-effort matrix. This ranking was done on the basis of the amount of time, effort, and cost that would be required to implement these corrective actions, as well as the impact that these actions would have once they were put into place (Gijo and Sarkar 2013)[44].

The Body Parts, the handle, and the Welded Joints are currently in the phase known as Improve and Review. The process of selecting the appropriate oil seal components, followed by the installation of these components within the body structure, is a crucial and delicate operation that, if not performed correctly, can lead to problems with product quality and, ultimately, the rejection of the product on the assembly floor or even at the customer's location. As a direct consequence of this, the expansion of the firm is impeded. According to table 5, a total of five key root causes have been selected for further investigation in order to improve product quality and all. The following are the five primary reasons that are most important:

Oil seal components collection (Purchase of Oil Seal Components) Assemble final product (Tightening of the product) Welded defects reproduction/War page reproduction Oil Leakage testing (initial and final)

The improvement is carried out once the findings of the benefit-effort analysis have been analyzed and interpreted. In Table 7, Column 2 provides a summary of the remedial measures that were determined to be necessary in order to address the fundamental causes. The trials that follow discuss in further detail the analysis that was conducted to identify remedial actions and the changes that were implemented.

Table 7 Five important Causes with selective Measures

Main Causes	Correction Measures
CI: Oil seal components	**CMI**: Select the new vendor which has product range for best efficiency, leave purchase cost parameter
CII: Tightening of Components	**CMII**: Follow the proper tightening rule and provide proper instrument for tightening the nut and bolt
CIII: Welded Defects	**CMIII**: Hire a person who has associate certification for Welding and has quality inspection knowledge for welded Joints
CIV: War Page (Uneven Surface)	**CMIV**: Proper Instrument purchase for measurement of uneven surface
CV: Testing	**CMV**: Conduct training programs for operators from all floor of assembly unit

According to the findings of the benefit-effort matrix, the corrective actions for C-I and C-V were located in the second quadrant, which is the high impact and low effort group. On the other hand, the corrective actions for C-IV were located in the third quadrant, which is the high impact, high effort group. Lastly, the corrective actions for C-III were located in the fourth quadrant, which had low impact and high effort (as shown Fig. 9). These root causes were discarded from further considerations because they had a low impact and needed a large amount of work to address. Instead, corrective actions for C-I, C-II, C-IV, and C-V were adopted in one improvement trial because they had a high impact. The findings of the benefit effort matrix are shown in Figure 9, which covers all of the fundamental causes.

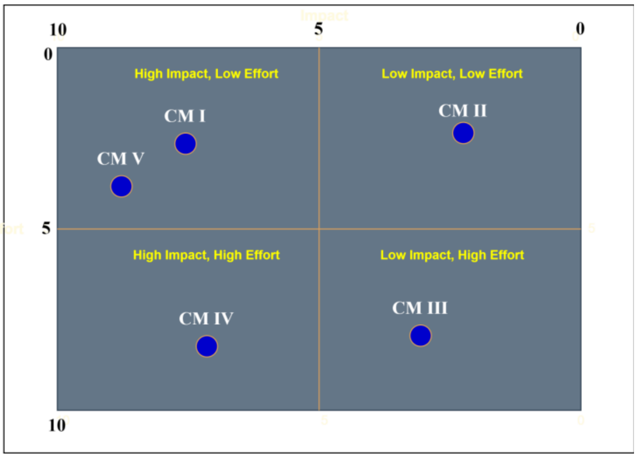

Figure 9 benefit and effort matrix for five causes

So final causes which are required to select for the improvement phase are following:

Oil seal components ***Tightening of Components*** ***War Page (Uneven Surface)*** ***Testing*** ***Training to Employees***

Improvement Trial for Purchase of sealing and testing instruments for control the oil leakage (C-I, C-IV)

During the first improvement trial, the root causes—Oil sealing components (C-I) and instruments required to manage the warpage/welding faults (C-IV)—were identified, and the remedial measures that corresponded to these root causes were put into effect. At that time, all of the necessary components and instruments, including the oil sealing, were purchased from a single supplier, vendor, or business. The first thing that needed to be done was to evaluate the present level of quality of the components that were needed for the construction of the transformers. This included looking at things like price, delivery, quality and safety. After having this conversation with the vendor, the team was able to determine that the existing vendor was unwilling to deliver components of a higher quality due to the financial ramifications for both sides as well as the transnational nature of their relationship with the vendor. After more conversation on the subject, it was finished with the recommendation that a new vendor for the items' acquisition should be chosen as the next step to take.

In order to eliminate the underlying problem that is being considered, six potential suppliers have been identified as being prepared to offer the essential components with the quality that is wanted at the best price possible with on-time delivery. However, the challenge here was to select a supplier in such a way that would allow for the components of the required quality to be procured at the best prices, taking into consideration other important criteria that the supplier should meet in order to ensure that the overall procurement of the products would be profitable.

The highest level of management recommended doing a comparison analysis of the available options in order to identify the most appropriate providers. The team working on the project came up with four criteria that should be used as the foundation for making this pick (Caliskan et al.,2013)[45]. These criteria consisted of the following:

Delivery (D),
Safety (S)
Quality (Q) and
Price (P),

As a result, the suppliers were evaluated with the TOPSIS (technique for order performance by similarity to ideal solution) method, which is frequently discussed in the relevant body of literature for the purpose of supplier selection. Figure 10 provides a description of the framework of TOPSIS, which was utilized in the evaluation of the providers; the "Appendix E" document provides information about the specific phases of the technique.

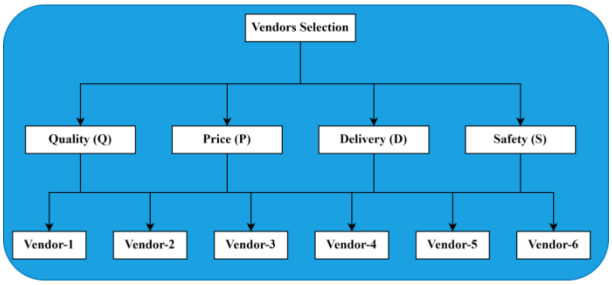

Figure 10 framework design for TPOSIS method

The replies of the people working on the project were recorded after the preparation of a questionnaire for the purpose of calculating the weights of relevance of the criteria. Table 7 displays the main parameters and ranks that were achieved through the use of the TOPSIS approach. According to the results presented in table 8, the first ranked vendor was number one, and the second ranked vendor was number five. These two suppliers are able to meet all of the company's procurement requirements at prices that are both competitive and affordable, without sacrificing product quality.

Table 8 TOPSIS results

Vendor	D	S	Q	P	Si+	Si-	CI	Rank
1	36.0	56.3	60.2	43.0	0.0030	0.0315	0.9130	**1**
2	65.7	46.6	57.3	38.1	0.0323	0.0019	0.0560	**6**
3	53.0	55.4	45.6	61.0	0.0200	0.0170	0.4595	**4**
4	56.6	33.1	61.6	30.7	0.0246	0.0130	0.3459	**5**
5	40.9	45.7	62.7	33.9	0.0088	0.0272	0.7563	**2**
6	40.9	62.6	56.7	42.8	0.0089	0.0259	0.7437	**3**

Following the implementation of corrective steps for RC1, which included switching suppliers, the process was carefully monitored for a period of sixty days. After conducting 100% sampling, the process output was sampled for a period of sixty days, and the pieces that were sampled were examined for each of the four categories of defects that were taken into account. It was found that the process sigma level had increased from the baseline sigma level of 3.15 to 3.85 during the course of the observation period.

Improvement Trial for Training of Employees (C-V) and Development Rule for Tightening (C-II)

On the shop floor, it was found that the majority of the workers were contract employees or those with only a moderate level of training. Following conversations with team members and shop floor operators, problems linked to an inadequate instructions manual and a lack of staff training were found (Gijo and Sarkar 2013)[44]. The terminology utilized was too complex for the floor operators to grasp, and they were not effectively taught to follow these standards. This was seen despite the fact that the measurement requirements and instructions were written accurately in the manuals. Because of this, the operators were unable to follow the process guidelines as closely as they should have. The group working on the project came to the conclusion that each stage of the production process should have a graphical representation included in the guides. The manuals should also highlight the safety measures and standard operating procedures (SOPs) that the operators should adhere to. According to (Henderson and Evans 2000)[46], "training is a cornerstone and that improved human input is critical in the productivity equation." As a result, unique training routines should be designed and carried out for employees in order to provide them with the necessary training in both technical and organizational skills. As was suggested, the members of the project team collaborated with a documentation specialist to draft the initial set of standard operating procedures (SOPs), and the workshop also featured graphical representations of some of the most significant SOPs. In addition, brief trainings on standard operating procedures (SOPs) were provided to the shop floor operators. These trainings focused on organizational skills, with a particular emphasis on the significance of including all relevant stakeholders in ongoing quality improvements.

7 Phase -V: Control

After each iteration of the improvement cycle has been completed, the DMAIC model moves on to the control phase with the intention of bringing the process to a stable operating state. This stage of the model plays an extremely essential part in maintaining the changes that were accomplished by putting the corrective measures into effect. As a result of the efforts put into improvement, the short-term sigma level of the improved process was discovered to be 3.85, which is much higher than the baseline sigma level of 3.15.

At the end of the project, a suggestion was made stating that sampling and monitoring of the process ought to be carried out on a consistent basis in order to ensure ongoing monitoring of the process's performance. The group suggested keeping consistent records of data at all levels in order to support ongoing quality management operations, data-driven decision making, and the speedy repair of faults if there is a signal for process changes.

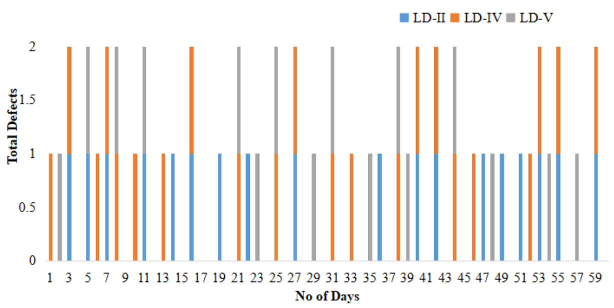

Figure 11 Defects control after Six Sigma implementation

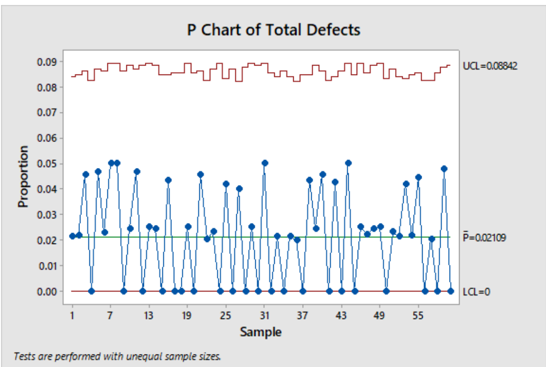

Figure 12 p-chart analysis of control phase for control of oil leakage issue

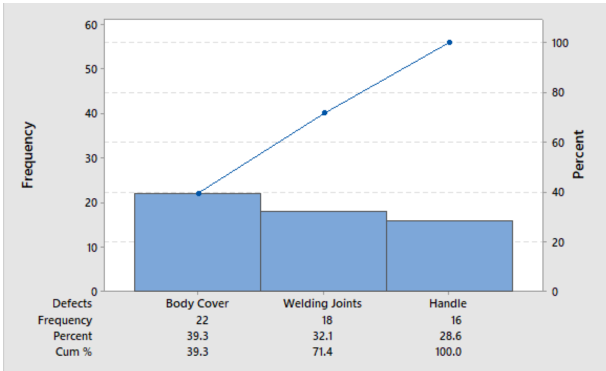

Figure 13 Pareto chart analysis for control phase

8 Implications of Six Sigma Study

A new hybrid DMAIC framework has been suggested to implement SS in SMEs firms. It blends MCDM methods with the necessary requirements. Our research looks into the current status of six sigma implementation in small scale firms in developing nations and the challenges they face. A real-world case study is employed to assess the effectiveness of the proposed framework. The results of the study lead to several conclusions based on the findings.

In developing countries such as India, SMEs hold a crucial position. But, due to globalization, SMEs in these economies face competition from market leaders, thereby emphasizing the need to enhance product, process, and service quality. This paper presents a proposed SS implementation framework, validated through a single case study, suitable for SMEs management to implement quality improvement initiatives while overcoming organizational challenges.

This research highlights the benefits of incorporating methods from other fields, such as OR (Operations Research), in SS practice. These methods address limitations of SS, such as a lack of theoretical framework and strategic disconnect, as noted by Antony (2004)[47]. OR strategies, tools, and methods have the potential to remove these barriers in SS implementation. The use of DEMATEL in the measurement phase serves as an example of incorporating OR in six sigma. This presents opportunities for academic researchers and practitioners to consider integrating OR and other modern methodologies in the SS implementation framework for improved outcomes.

The study suggests the use of benefit-effort analysis to identify cost-effective remedies for eliminating root causes of variations, based on their impact and cost. This approach allows evaluating the effectiveness of the remedies before implementation and ranking the improvements in order of priority. The improvement efforts can be carried out through a series of trials, each measuring the performance improvement from the previous trial, resulting in consistent advancements. This strategy is particularly useful in overcoming internal resistance to simultaneous changes in work practices and procedural improvements.

9 Conclusion

The present study proposes a hybrid DMIAC Six Sigma framework that merges MCDM methodologies for SMEs enterprises in developing economies specially for India. The framework expands the knowledge of small manufacturing enterprises in emerging nations and offers a tool for various applications. To overcome the limitations of limited resources and data availability during six sigma implementation, the study explores the utilization of MCDM methods, such as the DEMATEL technique, to prioritize defects in the measure phase of the DMAIC model. The proposed benefit-effort analysis in the enhance phase provides a suitable solution for SMEs enterprises to evaluate the impact and effort of corrective actions and make informed decisions for process improvement. The framework was evaluated through a case study in an SMEs manufacturing business in India, which aimed to optimize the control of the oil leakages in transformers. The results showed that DMAIC, along with the integration of Ishikawa diagram, C&E matrix, and benefit-effort analysis, improved the short-term sigma from 3.15 to 3.85. This study provides a foundation for novel methodologies in the suggested six sigma framework.

References

1) Al-Mishari, S. T., & Suliman, S. (2008). Integrating Six-Sigma with other reliability improvement methods in equipment reliability and maintenance applications. Journal of Quality in Maintenance Engineering, 14(1), 59–70. https://doi.org/10.1108/13552510810861941
2) Anand, R. B., Shukla, S. K., Ghorpade, A., Tiwari, M. K., & Shankar, R. (2007). Six sigma-based approach to optimize deep drawing operation variables. International Journal of Production Research, 45(10), 2365–2385. https://doi.org/10.1080/00207540600702308
3) Andersson, R., Eriksson, H., & Torstensson, H. (2006). Similarities and differences between TQM, six sigma and lean. TQM Magazine, 18(3), 282–296. https://doi.org/10.1108/09544780610660004
4) Antony, J., Kumar, M., & Tiwari, M. K. (2005). An application of Six Sigma methodology to reduce the engine-overheating problem in an automotive company. Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture, 219(8), 633–646. https://doi.org/10.1243/095440505X32418
5) Antony, J., Kumar, M., & Madu, C. N. (2005). Six sigma in small- and medium-sized UK manufacturing enterprises: Some empirical observations. International Journal of Quality and Reliability Management, 22(8), 860–874. https://doi.org/10.1108/02656710510617265
6) Arnheiter, E. D., & Maleyeff, J. (2005). The integration of lean management and Six Sigma. The TQM Magazine, 17(1), 5–18. https://doi.org/10.1108/09544780510573020
7) Barbosa, B., Pereira, M. T., Silva, F. J. G., & Campilho, R. D. S. G. (2017). Solving Quality Problems in Tyre Production Preparation Process: A Practical Approach. Procedia Manufacturing, 11(June), 1239–1246. https://doi.org/10.1016/j.promfg.2017.07.250
8) Barbosa, G. F., de Carvalho, J., & Pereira de Souza, C. H. (2014). Deployment of a laser projection solution for stripes plotting based on Six Sigma DMAIC methodology applied to aircraft painting shop. Production and Manufacturing Research, 2(1), 697–711. https://doi.org/10.1080/21693277.2014.943432
9) Muraleedharan, P., Balamurugan, S. and Prakash, R. (2017), “Six Sigma DMAIC in manufacturing industry: a literature review”, International Journal of Innovative Research in Science, Engineering and Technology, Vol. 6 No. 9, pp. 18288-18293.
10) Ferreira, J.E. and Lopes, I.S. (2010), “Improvement of scrap request process with Six Sigma methodology”, Proceedings of the World Congress on Engineering 2010, Vol. III, London, 30 June-2 July.
11) Montgomery, D.C. (2009), Introduction to Statistical Control, 6th ed., Wiley, Hoboken, NJ, pp. 45-59.
12) Junankar, A.A. and Shende, P.N. (2011), “Minimization of rework in belt industry using DMAIC”, International Journal of Applied Research in Mechanical Engineering, Vol. 1 No. 1, pp. 53-59.
13) Desai, T.N. and Shrivastava, R.L. (2008), “Six Sigma – a new direction to quality and productivity management”, Proceedings of the World Congress on Engineering and Computer Science, San Francisco, CA, 22-24 October.
14) Kaushik Prabhakar, Khanduja Dinesh, Mittal Kapil, Jaglan Pawan, (2012) "A case study: Application of Six Sigma methodology in a small and medium-sized manufacturing enterprise", The TQM Journal, Vol. 24 Iss: 1, pp.4 – 16.
15) Sambhe Rajeshkumar U. (2012), “Six Sigma practice for quality improvement – A case study of Indian auto ancillary unit”, IOSR Journal of Mechanical and Civil Engineering (IOSR-JMCE) Volume 4, Issue 4 (Nov-Dec. 2012), pp. 26-42
16) Sambhe, R.U. and Dalu, R.S. (2011) ‘Six Sigma implementation in Indian medium scale automotive enterprises – a review and agenda for future research’ Int. J. Six Sigma and Competitive Advantage, Vol. 6,

No. 3, pp.224–242.
17) Singh, R. and Kumar, S. (2014), “Production improvement through the application of Six Sigma in small scale industry: a case study”, International Journal of Current Engineering and Technology, Vol. 4 No. 4, pp. 2926-2932.
18) Panat, R., Dimitrova, V., Selvamuniandy, T.S., Ishiko, K.S. and Sun, D. (2014), “The application of Lean Six Sigma to the configuration control in Intel’s manufacturing R&D environment”, International Journal of Lean Six Sigma, Vol. 5 No. 4, pp. 444-459.
19) Kumar, V., Kumar, P. and Kamboj, R. (2015), “Application of DMAIC for process industry: a case study”, International Journal of Scientific & Engineering Research, Vol. 6 No. 5, pp. 110-119.
20) Krotov, M. and Mathrani, S. (2017), “A Six Sigma approach towards improving quality management in manufacturing of nutritional products”, IEEE Proceedings of International Conference on Industrial Engineering, Management Science and Application, Seoul, 13-15 June.
21) Costa, T., Silva, F.J.G. and Ferreira, L.P. (2017), “Improve the extrusion process in tire production using Six Sigma methodology”, Manufacturing Engineering Society International Conference 2017, MESIC, Vol. 13, Pontevedra, 28-30 June, pp. 1104-1111.
22) Singh, H. and Lal, H. (2016), “Application of DMAIC technique in a manufacturing industry for improving process performance – a case study”, International Journal on Emerging Technologies, Vol. 7 No. 2, pp. 36-38.
23) Srinivasan, K., Muthu, S., Devadasan, S.R. and Sugumaran, C. (2016), “Enhancement of sigma level in the manufacturing of furnace nozzle through DMAIC approach of Six Sigma: a case study”, Production Planning & Control, Vol. 27 No. 10, pp. 810-822.
24) Yadav, A. and Sukhwani, V.K. (2016), “Quality improvement by using Six Sigma DMAIC in an industry”, International Journal of Current Engineering and Technology, Special Issue-6, pp. 41-46.
25) Drab, K., Kwiatkowski, M. and Wasalaski, P. (2015), “How Six Sigma brought saving and improved manufacturing process by 98.9%”, IEEE Proceedings of 37th Electrical Overstress/Electrostatic Discharge Symposium (EOS/ESD), Reno, 27 September-2 October.
26) Indrawati, S. and Ridwansyah, M. (2015), “Manufacturing continuous improvement using Lean Six Sigma: an iron ores industry case application”, Elsevier Procedia Manufacturing, Vol. 4, Special issue for Industrial Engineering and Service Science, pp. 528-534.
27) Gupta, Anshu; Sharma, Pallavi; Jain, Akansha; Xue, Hongbo; Malik, S. C.; Jha, P. C. (2019). An integrated DEMATEL Six Sigma hybrid framework for manufacturing process improvement. Annals of Operations Research, (), –. doi:10.1007/s10479-019-03341-9
28) Drohomeretski, E., Gouvea da Costa, S. E., Pinheiro de Lima, E., & Garbuio, P. A. D. R. (2014). Lean, Six Sigma and Lean Six Sigma: An analysis based on operations strategy.International Journal of Production Research, 52(3), 804–824.
29) Agarwal, V., Govindan, K., Darbari, J. D., & Jha, P. C. (2016). An optimization model for sustainable solutions towards implementation of reverse logistics under collaborative framework. International Journal of System Assurance Engineering and Management, 7(4), 480–487.
30) Zhou, X., Hu, Y., Deng, Y., Chan, F. T., & Ishizaka, A. (2018). A DEMATEL-based completion method for incomplete pairwise comparison matrix in AHP. Annals of Operations Research, 27, 1045–1066.
31) Montgomery, D. C. (2007). Introduction to statistical quality control. New York: Wiley.
32) Montgomery, D. C., & Woodall, W. H. (2008). An overview of six sigma. International Statistical Review, 76(3), 329–346.
33) Gijo, E. V., Scaria, J., & Antony, J. (2011). Application of Six Sigma methodology to reduce defects of a grinding process. Quality and Reliability Engineering International, 27(8), 1221–1234.
34) Jirasukprasert, P., Arturo Garza-Reyes, J., Kumar, V., & Lim, K. M. (2014). A Six Sigma and DMAIC application for the reduction of defects in a rubber gloves manufacturing process. International Journal of Lean Six Sigma, 5(1), 2–21.
35) Prashar, A. (2016a). A conceptual hybrid framework for industrial process improvement: Integrating Taguchi methods, Shainin System and Six Sigma. Production Planning and Control, 27(16), 1389–1404.
36) Prashar, A. (2016b). Six Sigma adoption in public utilities: A case study. Total Quality Management and Business Excellence, 27(5–6), 479–506.
37) Gijo, E. V., & Scaria, J. (2010). Reducing rejection and rework by application of Six Sigma methodology in the manufacturing process. International Journal of Six Sigma and Competitive Advantage, 6(1–2), 77–90.
38) Gupta, A., Sharma, P., Malik, S. C., Agarwal, N., & Jha, P. C. (2016). Productivity improvement in the chassis preparation stage of the amplifier production process: A DMAIC Six Sigma methodology. International Journal of Reliability, Quality and Safety Engineering, 23(06), 1640012.
39) Doggett, A. M. (2005). Root cause analysis: A framework for tool selection. Quality Management Journal, 12(4), 34–45.
40) Lee, K. L., Wei, C. C., & Lee, H. H. (2009). Reducing exposed copper on annular rings in a PCB factory through implementation of a Six Sigma project. Total Quality Management, 20(8), 863–876.
41) Sharma, P., Malik, S. C., Gupta, A., & Jha, P. C.

(2018). A DMAIC Six Sigma approach to quality improvement in the anodising stage of the amplifier production process.International Journal of Quality and Reliability Management, 35(9), 1868–1880.

42) Rajagopalan, R., Francis, M., & Suárez, W. (2004). Managers at work: Developing novel catalysts with Six Sigma. Research-Technology Management, 47(1), 13–16.
43) Sokovic, M., Pavletic, D., & Fakin, S. (2005). Application of Six Sigma methodology for process design. Journal of Materials Processing Technology, 162, 777–783.
44) Gijo, E. V., & Sarkar, A. (2013). Application of Six Sigma to improve the quality of the road for wind turbine installation. The TQM Journal, 25(3), 244–258.
45) Çalışkan, H., Kurşuncu, B., Kurbanoğlu, C., & Güven, Ş. Y. (2013). Material selection for the tool holder working under hard milling conditions using different multi criteria decision making methods. Materials & Design, 45, 473-479.
46) Henderson, K. M., & Evans, J. R. (2000). Successful implementation of Six Sigma: benchmarking general electric company. Benchmarking: An International Journal, 7(4), 260–282.
47) Bhasin, Niti, Rabi Narayan Kar, and Neha Arora. "Green disclosure practices in India: A study of select companies." Evergreen Journal (2015): 5-13.
48) Masaki, Yusei. "Characteristics of industrial wastewater discharged from industrialized provinces and specific industrial sectors in china based on the official statistical reports." Evergreen Journal (2016): 59-67.
49) Kimura, Rikio. "'Social or Business' or 'Social and Business': Problematique of the Hybrid Structure of Community-based cotourism in Cambodia." Evergreen Journal (2017): 38-49.
50) Jasiulewicz–Kaczmarek, M., Antosz, K., Żywica, P., Mazurkiewicz, D., Sun, B. and Ren, Y. (2021). Framework of machine criticality assessment with criteria interactions. Eksploatacja i Niezawodnosc – Maintenance and Reliability 23(2), 207–220.
51) Zonta, T., da Costa, C.A., da Rosa Righi, R., de Lima,M.J., da Trindade, E.S. and Li, G.P., 2020. Predictive maintenance in the Industry 4.0: A systematic literature review. Comput. Ind. Eng. 150, 106889.
52) Xia, T., Xi, L., Du, S., Xiao, L. and Pan, E. (2018). Energyoriented maintenance decision-making for sustainable manufacturing based on energy saving window. Journal of Manufacturing Science and Engineering, 140(5): 051001
53) Franciosi, C., Voisin, A., Miranda, S. and Iung, B. (2020). Integration of I4. 0 technologies with maintenance processes: what are the effects on sustainable manufacturing?. IFAC-PapersOnLine, 53(3), 1-6.
54) Vrignat, P., Kratz, F. and Avila, M. (2022). Sustainable manufacturing, maintenance policies, prognostics and health management: A literature review. Reliability Engineering & System Safety, 218, 108140.
55) Lovrencic, V., Brezavscek, A., Pantos, M. and Gomiscek, B. 2017, Contribution of live working to the quality, safety, effectiveness and efficiency of the maintenance processes, Tehnicki Vjesnik 24(5), 1619-1626;
56) Saihi, A., Ben-Daya, M. and As' ad, R. A. (2022). Maintenance and sustainability: a systematic review of modeling-based literature. Journal of Quality in Maintenance Engineering.
57) Hami, N., Shafie, S. M., Omar, S., Ibrahim, Y. M., Sabah, A. S. and Mohd, R. M. (2020). A review of sustainable maintenance in the manufacturing companies. International Journal of Supply Chain Management, 9(3), 935-944;
58) Karuppiah, K., Sankaranarayanan, B. and Ali, S. M. (2021). On sustainable predictive maintenance: Exploration of key barriers using an integrated approach. Sustainable Production and Consumption, 27, 1537-1553;
59) Antosz, K., Jasiulewicz-Kaczmarek, M., Waszkowski, R., & Machado, J. (2022). Application of Lean Six Sigma for sustainable maintenance: case study. IFAC-PapersOnLine, 55(19), 181-186.