J. Appl. Res. Ind. Eng. Vol. 5, No. 1 (2018) 10–26

Journal of Applied Research on Industrial Engineering
www.journal-aprie.com

Reduction of Rework in Bearing End Plate Using Six Sigma Methodology: A Case Study

***Boby John*[1]*, *Abdulrahiman Areshankar*[2]**
[1] *SQC &amp, OR Unit, Indian Statistical Institute, Bangalore, India.*
[2]*Manzusha Machinery Works, Bangalore, India.*

PAPER INFO

Chronicle:
Received: 20 December 2017
Accepted: 27 April 2018

Keywords:
Six Sigma.
DMAIC.
Analysis of Variance.
Simultaneous Optimization of Multiple Characteristics.
Taguchi's Loss Function.
Bearing End Plate.

ABSTRACT

Six Sigma is a structured and systematic approach to performance and quality improvement. Six Sigma is a rigorous methodology consists of five major phases, namely definition, measure, analysis, improvement, and control for problem solving. A lot of case studies have been published and many large organizations have reported financial benefits by the application of Six Sigma methodology. This paper is a case study on reducing the bearing end plate reworks in a machining process through the application of Six Sigma methodology. The study focuses on reducing the rework due to thickness and diameter variation. From the list of identified potential causes, two causes, namely tool type and coolant pH are shortlisted as root causes. The optimum values of tool type and coolant pH, which would simultaneously optimize the diameter and thickness, are identified using the design of experiments and Taguchi's loss function approach. The implementation of optimum settings shows that the capability of the machining process to meet the customer requirements on thickness and diameter has substantially improved and rework has reduced.

1. Introduction

The organizations need to improve the quality and operational performance continuously to survive and grow in the highly competitive business world. Six Sigma has become one of the widely popular methodologies for problem-solving and performance improvement in the industry. Many large organizations like Motorola, General Electric, Honeywell, Texas Instruments, 3M and Caterpillar have reported a lot of success stories and financial savings due to the adoption of Six Sigma methodology [1-5]. The practitioners and researchers of Six Sigma have provided multiple dimensions and interpretations of this methodology. It is a business strategy to improve the effectiveness and efficiency of all the operations [6]. Six Sigma is the relentless and rigorous pursuit of the reduction of variation in core processes to achieve continuous and breakthrough improvement in performance that impacts the bottom line of an organization [7]. Six Sigma is a comprehensive framework to provide solutions to the industrial problems using a set of quantitative tools [8]. It is designed to reduce process variation by defining, measuring, analyzing, improving, and controlling processes [9]. It is a well-established approach to identify and eliminate defects, mistakes, or failures in business processes or systems [10].

* Corresponding author
Email: boby@isibang.ac.in
DOI: 10.22105/jarie.2018.120059.1033

Six Sigma is often defined as a quality improvement program aiming to reduce the number of defects to as low as 3.4 parts per million opportunities [11]. It is a business strategy that focuses on improving customer satisfaction, productivity, and financial performance [12]. A brief literature survey of the important success stories and case studies on the implementation of Six Sigma and lean methodologies are given in the next Session.

2. Literature Survey

A lot of research have been carried out, and successful case studies have been published on the application of Six Sigma methodology. The implementation of Six Sigma at Ms/ Dow Chemicals has resulted in an impressive savings of $1.5 billion since 1999 [13]. The optimization of the task level and servicing cycle level of an aircraft maintenance environment using Six Sigma has resulted in reducing the cycle length by 56 – 68 % and manpower by 26% [14]. The deployment of the solution that is obtained by the application of Six Sigma methodology for reducing the weld defects in a valve component resulted in the reduction in weld defects and substantial financial saving [15]. The application of Six Sigma methodology in research and development has resulted in the reduction of cost and time to development and delivery of new technologies and products [16]. The application of Six Sigma for reduction of defects in rubber gloves resulted in reducing defects per million opportunities from 195,095 to 83,705 and improving the sigma level from 2.4 to 2.9 [17]. The application of Six Sigma in textile industry reduced the changeover times in two lines and metal contamination in a third line [18]. A plastic injection molded-parts manufacturing company has reduced the defects like short molding, contamination, etc. that is led to annual saving of Indian rupees 100,080 [19]. The deployment of the framework that was developed using DMAIC tools and techniques in automotive manufacturing organization resulted in reducing defects and eliminating wastes with enhanced bottom line improvement [20]. Some of the recent applications of Six Sigma and lean methodologies are in improving the grinding process [21], development of a three-dimensional model for measuring the perceived quality for institutes of higher education [22] and in medical laboratory industry [23].

In this paper, the authors discuss a case study on reducing the rework in a machining process using Six Sigma methodology. The reduction in rework will help the organization to save the rework cost and effort. This will reduce the customer dissatisfaction and improve the company’s chances to get more and more orders from the customer. The study also demonstrates the usefulness of simultaneous optimization of multiple response techniques in Six Sigma problem-solving methodology.

3. Case Study

The Six Sigma projects for problem-solving, quality or performance improvement often use the DMAIC framework. The DMAIC denotes the five critical phases or stages in Six Sigma methodology, namely definition, measure, analysis, improvement, and control [24]. The major activities that are executed at different phases of DMAIC approach in the case study are as follows:

3.1. Define Phase

In definition phase, the selection of project team, preparation of project charter, identification of the project scope and project goal, definition of the problem statement, development of business case and preparation of project schedule are carried out [25].

The study is carried out at an ISO 9001 certified micro scale industry in Bangalore, India. The company's core competency is on performing a variety of machining operations on high precision components, castings, forgings and assemblies for the automotive industry. The organization is a recognized subcontractor for many reputed automobile parts manufacturers in India. Recently, the company is experiencing difficulty in getting the desired results from the machining operations. As a result, the components need to be reworked that is resulted in additional operational cost, delayed deliveries, and customer dissatisfaction. The data on reworks during December 2016 to January 2017 is collected and the reasons for the rework are prioritized using a Pareto chart. The Pareto chart is given in Fig. 1.

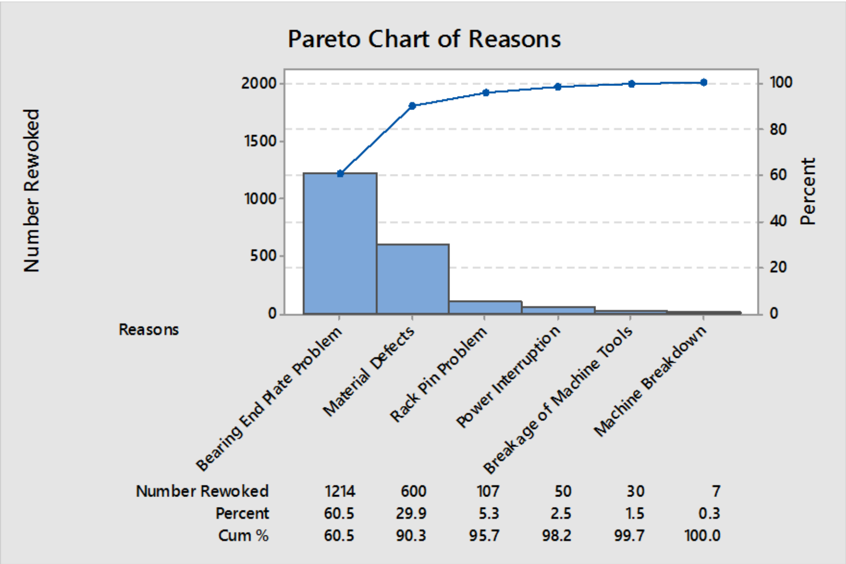

Fig. 1. Pareto chart on reworks.

Fig. 1 shows that the major reworks are due to bearing end plate problem and material defects. The company receives the raw material, namely castings from the customer. Occasionally the material defects are observed after the machining activity. The company has no control over the material defects as the raw material, namely, the castings are supplied by the customer. Often, the casting defects will be detected only after material removal by machining operations. Since the company does not make the castings, the company only has to report the problem and return the casting with defects to the customer. The reduction of the casting defects is not the responsibility of the organization, so the focus of this project is to reduce the rework due to bearing end plate problem. A picture of bearing end plate is given in Fig. 2.

The major deliverables of the define phase are the formation of project team and preparation of project charter. The project team consists of four members, namely the production head, process supervisor and two workers along with an external Six Sigma consultant. The production head is chosen as the project leader. The project charter is a document, which explains the project in brief. The project charter briefly describes the reasons for taking up the project, the problem that the team is trying to solve through the project, the project goal, project scope, the team working on the project, and the expected benefits by executing the project [26]. The prepared project charter is given in Table 1.

Fig. 2. Bearing end plate.

Table 1. Project charter.

Project title	Reduce the rework in bearing end plate
Business case	The rework of bearing end plates is resulting in additional cost, delay in delivering the components leading customer dissatisfaction
Problem statement	During the period December 2016 to January 2017, out of 2008 components reworked 1214 are bearing end plates, which is equal to 60% of the total reworks.
Project goal	The goal of the project is to reduce the bearing end plate rework to below 20% of the total reworks.
Project team	Production head (project leader), process supervisor, two workers and external six sigma consultant
Project scope	Machining process of bearing end plates
Expected Benefits	Reduction of rework cost, reduction in delayed deliveries leading to enhanced customer satisfaction

3.2. Measure Phase

The major activity in measure phase is the project base lining. This includes identification of measurement factors, which need to improve the project Critical to Quality (CTQ) characteristics, assessment of measurement system if required and quantification of the current status of the CTQ characteristics [27-28]. The further analysis of the rework data of bearing end plates shows that in most cases the rework is required as either diameter or thickness or both not meeting the customer requirements or specifications. The specifications on diameter and thickness are given in Table 2. To validate whether the rework is due to thickness or diameter, not meeting specification, the thickness, and diameter are measured on a batch of 24 jobs after machining. The collected data is given in Table 3.

Table 2. Specification on CTQ characteristics.

Characteristic	Target	Tolerance
Diameter	82.55 mm	$\pm$ 0.15 mm
Thickness	15 mm	$\pm$ 0.1 mm

Table 3. Diameter and Thickness data.

Part Id	Diameter	Thickness	Part Id	Diameter	Thickness
1	82.61	14.94	13	82.27	14.95
2	82.41	15.01	14	82.52	14.87
3	82.12	14.86	15	82.56	14.98
4	82.35	14.85	16	82.48	15.12
5	82.5	14.69	17	82.29	14.91
6	82.01	15	18	82.46	14.88
7	82.34	14.93	19	82.28	14.9
8	82.27	14.9	20	81.97	14.77
9	82.25	14.94	21	82.34	14.64
10	82.1	14.94	22	82.12	15
11	82.36	14.84	23	82.52	14.93
12	82.17	14.85	24	82.37	15.07

The descriptive statistics of the diameter is computed and is given in Fig. 3.

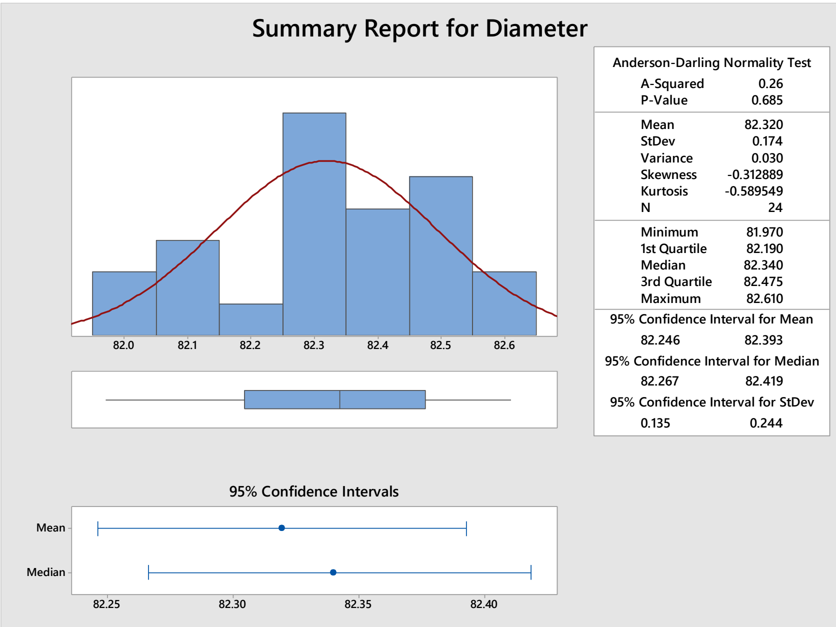

Fig. 3. Descriptive statistics of diameter.

Fig. 3 shows that diameter is normally distributed (Anderson - Darling normality test p-value = 0.685 > 0.05). The 95% confidence interval on mean diameter is 82.246 to 82.393. Therefore, it is very likely that the diameter of individual parts can be outside the specification given in Table 2. The process capability analysis was carried out in diameter is given in Fig. 4.

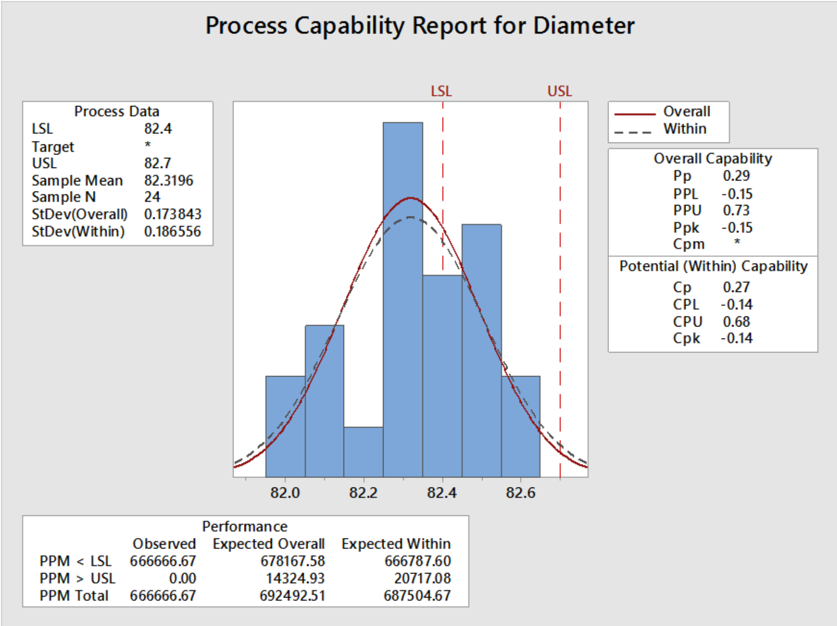

Fig. 4. Process capability analysis of diameter.

Fig. 4 shows that the machining process is not capable of meeting the customer requirements on the diameter. Similarly, the process capability analysis is carried out on thickness. The descriptive statistics of the thickness dimension is given in Fig. 5 and process capability analysis is given in Fig. 6. Fig. 5 shows that the thickness is normally distributed (normality test p-value = 0.224 > 0.05) and Fig. 6 shows that the machining process is not capable of meeting the customer requirements on thickness. Figures 4 and 6 show that the process is not capable of meeting the customer requirements on diameter and thickness of the bearing end plates. Therefore, this study is undertaken to reduce the rework of bearing end plate component by improving the performance of the process to meet the customer requirements on diameter and thickness.

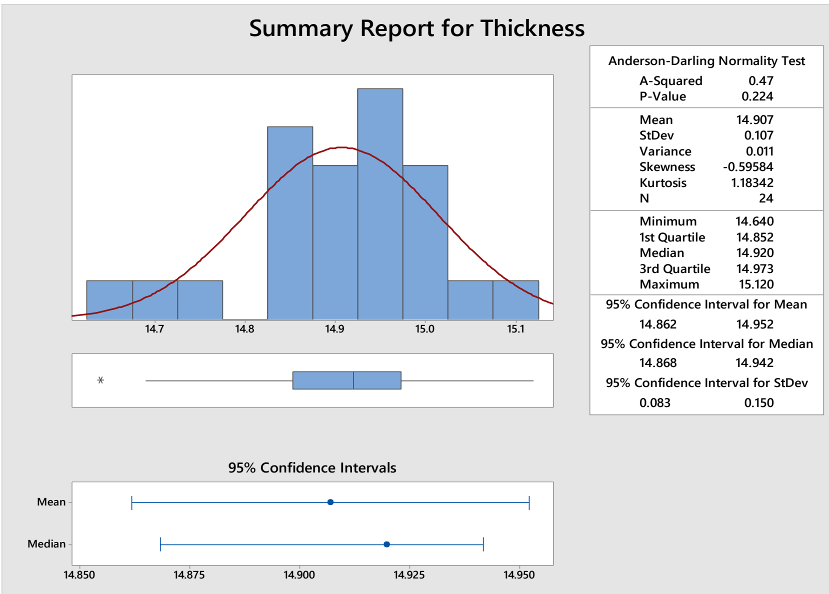

Fig. 5. Descriptive statistics of thickness.

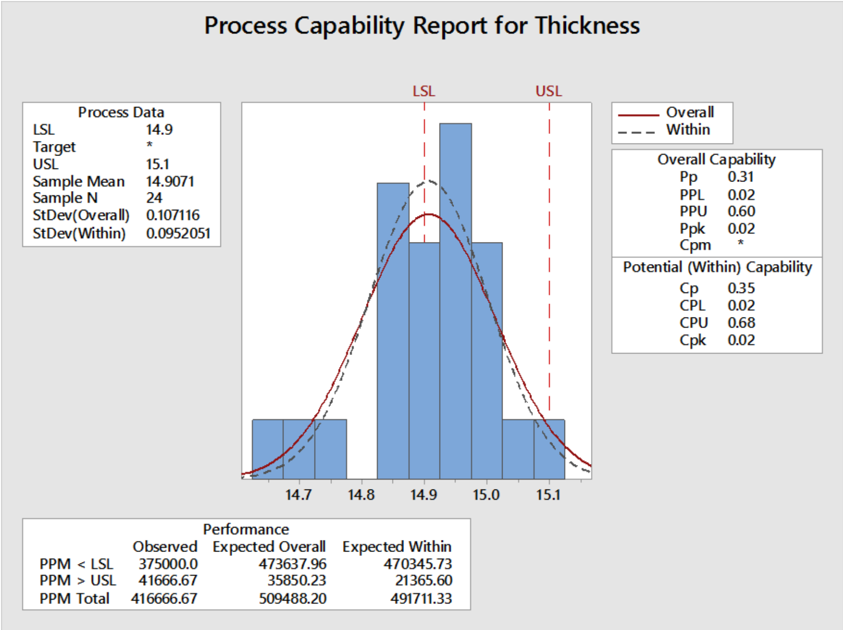

Fig. 6. Process capability analysis of thickness.

3.3. Analyze Phase

In the analysis phase, the potential causes of the problem are identified and the root causes are shortlisted from the potential causes. The deliverable of the analyze phase of the Six Sigma methodology is to list down the root causes of the problem [29-30]. To verify whether the rework of bearing end plates due to diameter and thickness issues is a process control problem or not, the collected data on diameter and thickness is plotted on individual x charts [31-32]. The individual chart for diameter is given in Fig. 7 and that for thickness is given in Fig. 8.

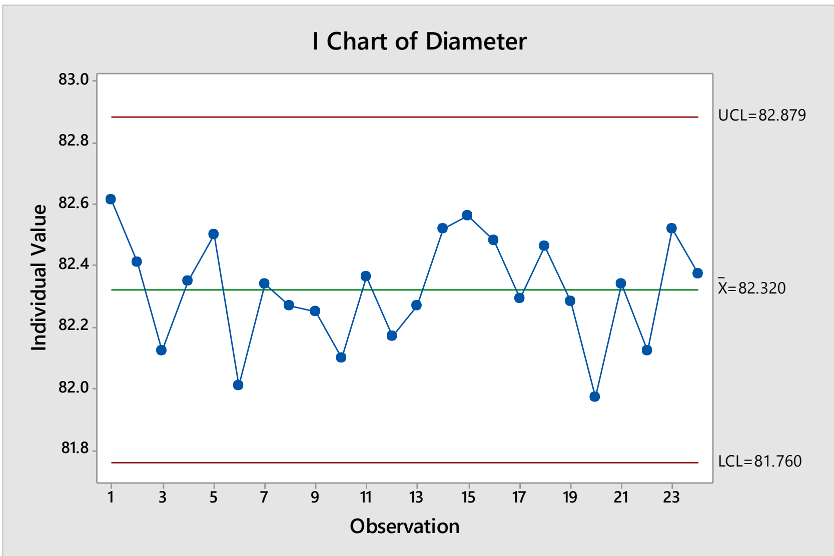

Fig. 7. Individual chart of diameter.

Figures 7 and 8 show that the process is in control with respect to diameter and thickness. So, it is concluded that the problem is not due to the presence of assignable causes, and the process needs breakthrough improvement. Through brainstorming with design and process engineers in the company, the potential causes for part rework due to diameter and thickness are identified. The identified causes are given in the cause and effect diagram in Fig. 9 [33].

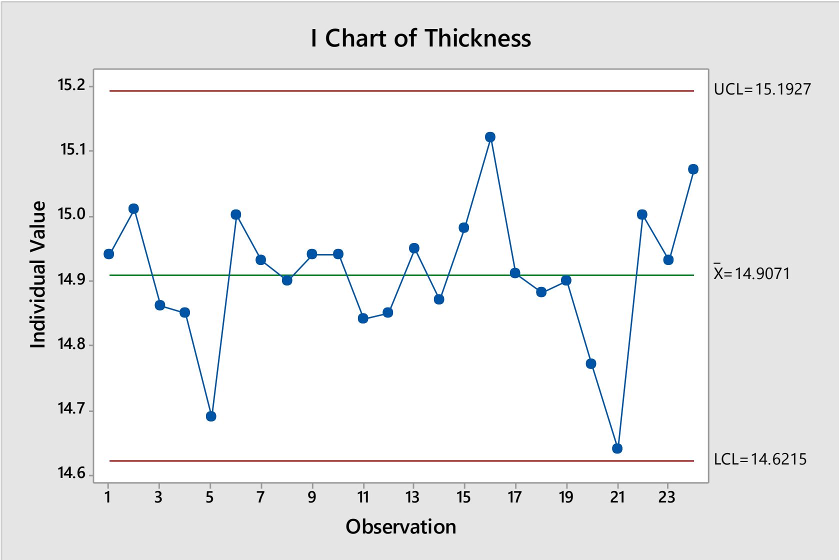

Fig. 8. Individual chart of thickness.

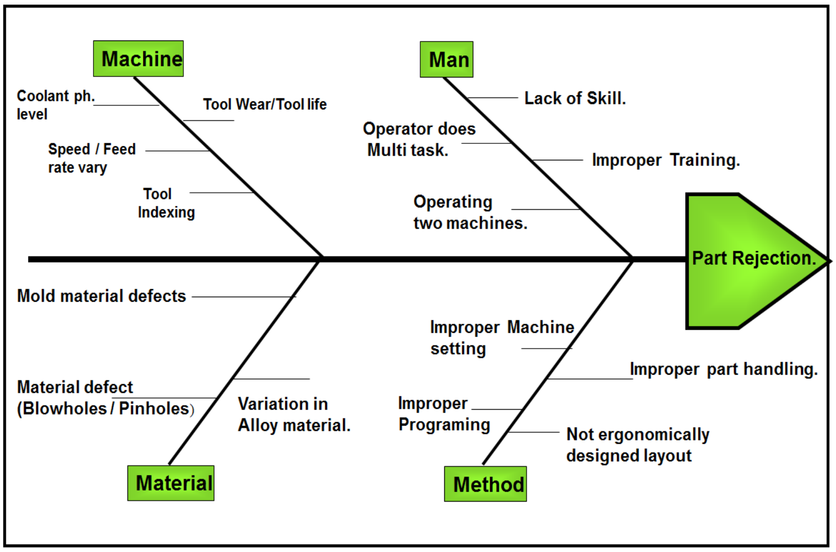

Fig. 9. Cause and effect diagram.

From the potential causes, the root causes are identified using Gemba investigation, a technique to verify whether a potential cause is a root cause or not through the physical observation of the process. Gemba investigation is carried out by the project team that was observing the process for a week at random frequency. During this period, two batches of bearing end plate component have been processed. The Gemba investigation results are given in Table 4. Gemba investigation revealed that the tool problems and improper cooling of the tool and work piece are the root causes.

Table 4. Gemba investigation results.

Potential Cause	Verification Method	Status
Improper machine setting. (Cutting parameters speed, feed, depth of cut)	Machine setting Log check	Not a root cause
Operator multi-tasking.	Visual observation	Not a root cause
Wrong program selection or malfunction of the program.	Visual observation (List of the program for respective part displayed).	Not a root cause
Improper tool & part handling	Visual observation	Not a root cause
Defective material (Blow holes /Pin holes, molding defect)	Incoming inspection Records verified.	Not a root cause
Tool quality problems like wear/life, etc.	Visual observation	Root cause
The temperature of a part/tool is not maintained accurately. (tool & workpiece cooling)	Visual inspection & pH level measurement.	Root cause

3.4. Improve Phase

The improving phase focuses on identification of the best solution to eliminate the root causes or minimize the effect of root causes [34]. The technical experts have suggested the reliable and good quality tool and an increase of the coolant oil frequency to maintain a higher ph (above 8.5) level, which may eliminate the root causes. To verify the suggestion, a small experiment is designed with two factors with two levels [35-36]. The chosen factors and levels for the experiment are given in Table 5.

Table 5. List of chosen factors and levels for the experiment.

Factor Name	Factor Code	Levels	
		-1	1
Tool type	x_1	Existing	New
Coolant ph	x_2	7 - 8	8.5 – 9.5

The response is chosen as the dimensions diameter and thickness. The experiments are conducting as per the layout. The responses, namely diameter and thickness are measured. The experimental layout with the response diameter (y_1) values is given in Table 6.

Table 6. Experimental layout with the response – diameter.

x_1	x_2	Response – Diameter (y_1)		
-1	-1	82.00	82.10	82.22
-1	1	82.2	82.32	82.39
1	-1	82.35	82.40	82.46
1	1	82.42	82.55	82.53

The experimental data is subjected to analysis of variance to identify the significant factors and interaction. The ÀNOVA table for response diameter is given in Table 7.

Table 7. ANOVA table for diameter.

Source	df	SS	MS	F	p-value	F- table value
x_1	1	0.18253	0.18253	24.92	0.001	5.318
x_2	1	0.06453	0.06453	8.81	0.018	5.318
x_1*x_2	1	0.0075	0.0075	1.02	0.341	5.318
Error	8	0.0586	0.00733			
Total	11	0.31317				

The ANOVA table shows that both factors have the significant effect (p-value < 0.05) on the diameter but the interaction effect is not significant (p-value ≥ 0.05) at 5% level [37]. Consequently, the analysis is carried out again by excluding the interaction term. The factor effects and model coefficients table is given in Table 8.

Table 8. Effects and coefficients table.

Term	Effect	Coefficient	SE	t	p-value	VIF
Constant		82.3283	0.0247	3327.82	0.00	
x_1	0.2467	0.1233	0.0247	4.99	0.001	1
x_2	0.1467	0.0733	0.0247	2.96	0.016	1

From Table 8, the model for estimating diameter (y_1) is identified as

$$y_1 = 82.3283 + 0.1233x_1 + 0.0733x_2. \quad (1)$$

The residual plots are given in Fig. 10.

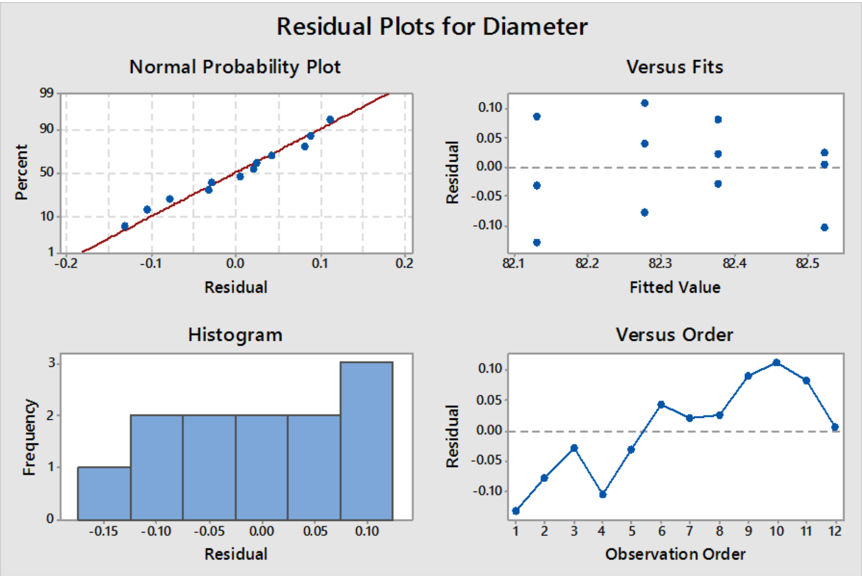

Fig. 10. Residual plots of diameter.

The residual plots show that the residuals are normally distributed and there is no trend or pattern in residuals versus fitted value plot. Hence, it is concluded that model is reasonably adequate and the important assumptions on the model are satisfied. Similarly, the collected experimental data from response thickness (y_2) is also analyzed. The experimental layout with thickness values is given in Table 9.

Table 9. Experimental layout with the response – thickness (y_2).

x_1	x_2	Response – Thickness (y_2)		
-1	-1	14.65	14.7	14.77
-1	1	14.8	14.94	14.80
1	-1	14.86	14.8	14.93
1	1	14.98	15.0	14.94

The analysis of variance is carried out on the experimental data to identify the significant factors and interaction. The ANOVA table is given in Table 10.

Table 10. ANOVA table for thickness.

Source	DF	SS	MS	F	p-value	F table value
x_1	1	0.06021	0.06021	15.71	0.004	5.318
x_2	1	0.04688	0.04688	12.23	0.008	5.318
x_1*x_2	1	0.00068	0.00068	0.18	0.686	5.318
Error	8	0.03067	0.00383			
Total	11	0.13843				

The ANOVA table shows that both the factors are significant at 5%, and the interaction is insignificant. So, the analysis is carried out by dropping the insignificant interaction term. The effect and model coefficients table is given in Table 11.

Table 11. Effect and coefficient table.

Term	Effect	Coefficient	SE	t	p-value	VIF
Constant		14.8475	0.017	871.57	0.00	
x_1	0.1417	0.0708	0.017	4.16	0.002	1
x_2	0.125	0.0625	0.017	3.67	0.005	1

From Table 11, the model to estimate the thickness (y_2) value is identified as

$$y_2 = 14.8475 + 0.0708x_1 + 0.0625x_2. \quad (2)$$

The residual plots of the model are given in Fig. 11. The residual plots show that the residuals are more or less normally distributed and there is no trend or pattern in residual versus fitted value plot. Therefore, it is concluded that the model is reasonably adequate and the important assumptions are satisfied.

The optimum values of x_1 and x_2, which would simultaneously bring the responses diameter and thickness to the respective target values are identified using a simultaneous optimization of multiple characteristics methodology [38]. In this study, Taguchi's loss function approach is used for simultaneous optimization of characteristics. The general form of Taguchi's quality loss function [39] is

$$l(y) = k(y - T)^2, \quad (3)$$

where y is the response variable or characteristic under study; T is the target and k is a constant known as quality loss coefficient. For simultaneous optimization of multiple characteristics with the two-sided specification, k is generally chosen as [40]

$$k = \left(\frac{2}{USL-LSL}\right)^2, \quad (4)$$

where *USL* and *LSL* are upper and lower specification limits on the characteristic y. The Eq. (3) shows that the loss $l(y)$ will be zero when the characteristic y is on target t and the loss $l(y)$ increases as the y deviates from the target. The Eq. (4) ensures that $l(y)$ will be equal to 1 when the characteristic y is on the specification limit and is greater than 1 when the characteristic y is out of specification limit. In other words, the $l(y)$ increases from 0 to 1 as characteristic y moves away from the target to either upper or lower specification limit. The $l(y)$ will be greater than 1 whenever the y is beyond the specification limits. Finally, the overall expected loss is computed as the average of the loss function values of the individual output characteristics. The optimum combination of the factors, which would simultaneously optimize the multiple characteristics is the combination with the minimum overall expected loss.

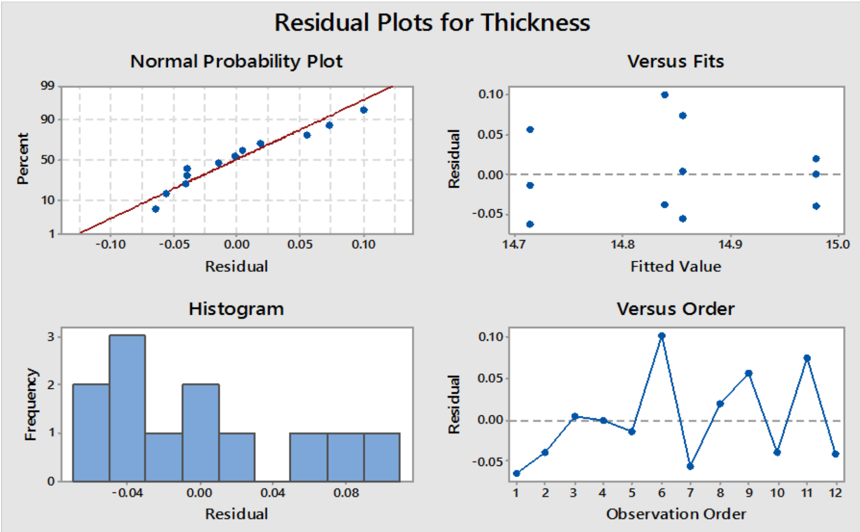

Fig. 11. Residual plots of thickness.

To identify the optimum combination of x_1 and x_2 which would simultaneously bring the response variables diameter (y_1) and thickness (y_2) to their respective targets, the expected values of output characteristics y_1 and y_2 are estimated using equations (1) and (2) for all the four possible combinations of factor levels. Then, the predicted responses are transformed to respective loss function using Eq. (3) and the overall expected loss is computed. The details of loss function computation are given in Table 12.

Table 12. Loss function computation.

		Estimated		Loss Function		Overall Expected Loss
x_1	x_2	y_1	y_2	$l(y_1)$	$l(y_2)$	$L(y)$
-1	-1	82.13	14.71	7.78	8.17	7.97
-1	1	82.28	14.84	3.28	2.59	2.93
1	-1	82.38	14.86	1.31	2.08	1.69
1	1	82.53	14.98	0.03	0.04	0.03

The Table 12 shows that when both x_1 and x_2 are at 1, the overall expected loss is minimum. The optimum combination factors, which would simultaneously bring both responses, namely diameter (y_1) and thickness (y_2) to respective targets are identified using Taguchi's loss function approach are given in Table 13.

Table 13. Optimum combination for responses diameter and thickness.

Factor name	Factor code	Optimum level	Optimum level value
Tool type	x_1	1	New
Coolant pH	x_2	1	8.5 - 9.5

3.5. Control Phase

In the control phase, the process performance is evaluated after the implementation of the solution, and compared with that at the start of the project. The achieved improvements are verified. The steps are taken to ensure that the improvements will be sustained in the process [41-42]. After the implementation of the optimum combination, the data on diameter and thickness are measured. The collected data is subjected to normality test. The normality test results of diameter and thickness are given in Table 14.

Table 14. Normality test results.

Characteristic	Anderson – Darling statistic	p-value
Diameter	0.366	0.39
Thickness	0.325	0.491

Table 14 shows that both diameter and thickness are normally distributed (the p-value > 0.05). Since the characteristics are normally distributed, the performance of the process with respect to diameter and thickness are compared using the individual charts. The individual chart of diameter is given in Fig. 12 and that of thickness is given in Fig. 13. Fig. 12 shows that the mean diameter (central line) has come close to the target value of 82.55 mm and variation around the target has been reduced. The Fig. 13 shows that the mean (central line) has come close to the target value of 15 mm and variation around the target has also been reduced for thickness characteristic. The comparison of process capability before and after improvement for diameter is given in Fig. 14 and that of thickness is given in Fig. 15.

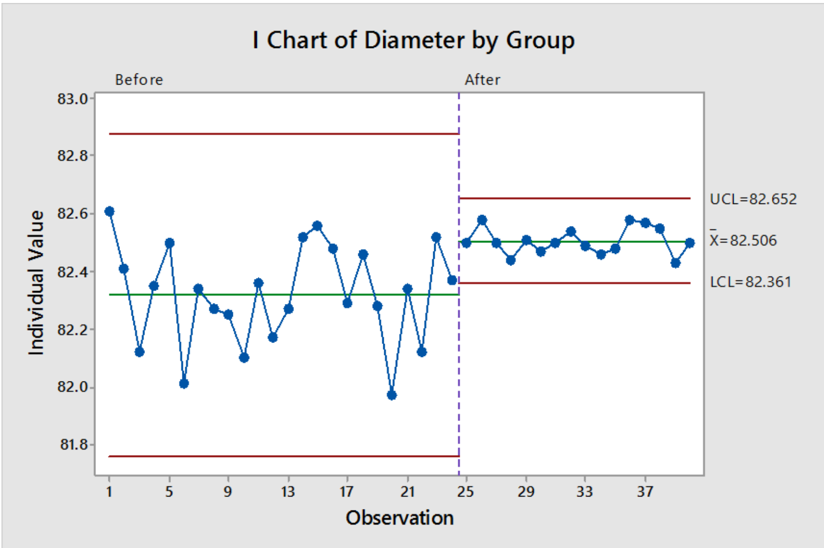

Fig. 12. Comparison of diameter before and after process improvement of diameter.

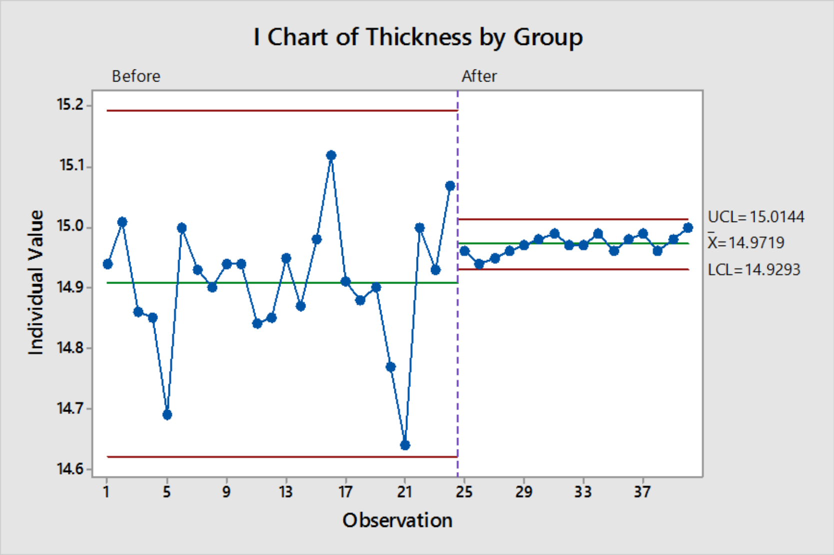

Fig. 13. Comparison of diameter before and after process improvement of thickness.

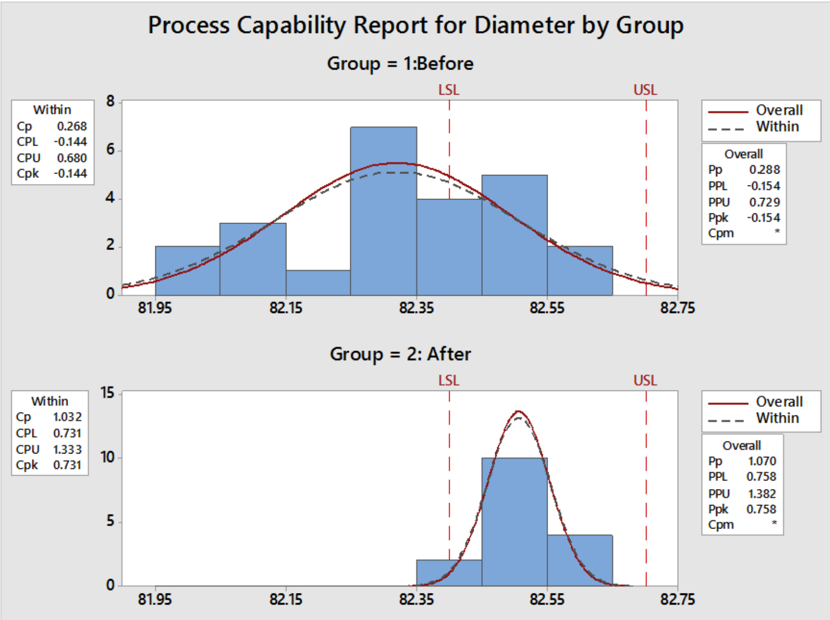

Fig. 14. Comparison of process capability before and after improvement for diameter.

Figures 14 and 15 once again confirmed that there is a significant improvement in the process performance with respect to diameter and thickness after the implementation of the solution. Consequently, the company has decided to discard the existing or old type tool and decided to use only the new type tool. Similarly, the standard operating procedure is modified with the information on coolant oil frequency, so that coolant pH can be always maintained at 8.5 to 9.5. After the implementation of the solution, the rework data for the period July – August 2017 is collected. The Pareto chart on rework is given in Fig. 16. The comparison of the Pareto charts has given in Fig. 1 and 15 show that the contribution of bearing end plate rework to the total reworks has reduced from 60% to 13 %. Thus, it is concluded that the project team has successfully achieved the project goal of reducing the bearing end plate rework from 60 % to below 20 % of the total reworks using the Six Sigma methodology.

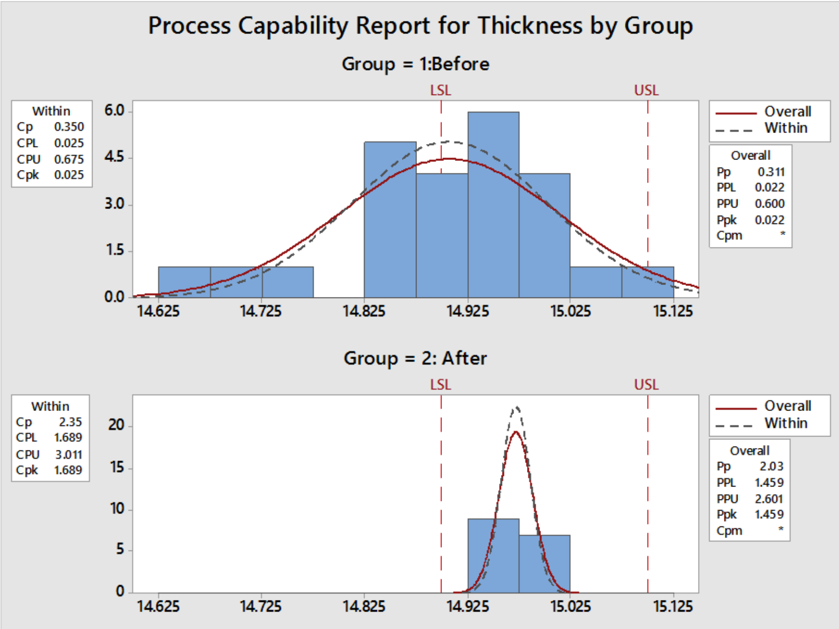

Fig. 15. Comparison of process capability before and after improvement for thickness.

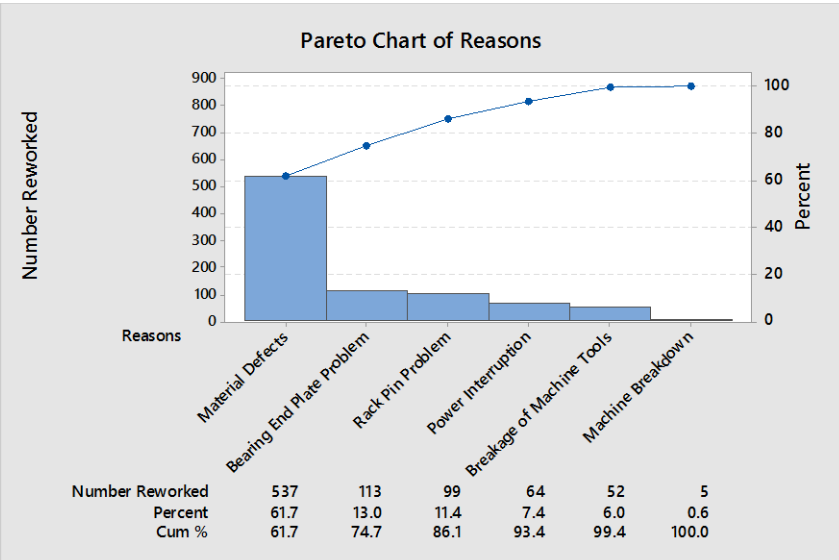

Fig. 16. Pareto chart of reworks after solution implementation.

4. Conclusion

Six Sigma is a rigorous and systematic methodology for problem-solving and performance improvement. This paper was a case study on reducing the bearing end plate reworks in a machining process through the application of Six Sigma methodology. The preliminary investigation revealed that the major reasons for rework are over and undersize diameter, thickness variation, and material damage. Since the raw material, namely casting is supplied by the customer, the company has no control over material damage or casting defects. Hence, the study focused on reducing the rework due to thickness and diameter variation. Through brainstorming, the various potential causes of diameter and thickness variation were identified. The causes were verified through Gemba investigation and two causes were shortlisted as root causes, namely tool type and coolant pH value. To find out the solution, an experiment was carried with tool type and coolant pH value as factors. The optimum combination of factors, which would simultaneously optimize the responses, namely diameter and thickness were identified using

Taguchi’s loss function approach. The analysis showed that the new tool type and the coolant pH value of 8.5 to 9.5 simultaneously brought diameter and thickness close to the respective targets. The results were verified by implementing the optimum setting of factors. The implementation of optimum settings showed that the capability of the machining process to meet the customer requirements on thickness and diameter has substantially improved. The study provided the opportunity to solve an industrial problem, namely reworks in the machining process using the Six Sigma methodology for the employees of a micro-industry. The project also gave hands-on experience on using the statistical package Minitab. The study helped the process manager (head) in setting the process parameters, namely tool type and coolant pH optimally so that the variation around the targets of the both output characteristics were minimized simultaneously. The manager can employ the same approach to identify the optimum process setting for machining other components as well as optimizing other processes.

Acknowledgment

The authors are grateful to the editor and the reviewers for their valuable suggestions, which improved the quality of the paper many folds.

References

[1] Antony, J. (2006). Six sigma for service processes. *Business process management journal*, *12*(2), 234-248.

[2] *GE Annual Report*. (2002). Retrieved from https://www.ge.com/ar2002/index_noflash.jsp

[3] Honeywell. (2002). *Honeywell Annual Report*. Retrieved from http://investor.honeywell.com/file/4121346/Index?KeyFile=1500081332

[4] 3M science to applied to life. (2003). *3M Annual Report.* Retrieved from http://investors.3m.com/financials/sec-filings/2003/default.aspx

[5] Arndt, M., & Brady, D. (2004). 3M's Rising Star; Jim McNerney is racking up quite a record at 3M. Now, can he rev up its innovation machine?. *Business week*, (3878), 62-62.

[6] Antony, J., & Banuelas, R. (2002). Key ingredients for the effective implementation of Six Sigma program. *Measuring business excellence*, *6*(4), 20-27.

[7] Antony, J. (2004). Six Sigma in the UK service organisations: results from a pilot survey. *Managerial auditing journal*, *19*(8), 1006-1013.

[8] Brun, A. (2011). Critical success factors of Six Sigma implementations in Italian companies. *International journal of production economics*, *131*(1), 158-164.

[9] Ashok Sarkar, S., Ranjan Mukhopadhyay, A., & Ghosh, S. K. (2013). Improvement of claim processing cycle time through Lean Six Sigma methodology. *International journal of lean six sigma*, *4*(2), 171-183.

[10] 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 & reliability management*, *22*(8), 860-874.

[11] Chakrabarty, A., & Chuan Tan, K. (2007). The current state of six sigma application in services. *Managing service quality: An international journal*, *17*(2), 194-208.

[12] Kwak, Y. H., & Anbari, F. T. (2006). Benefits, obstacles, and future of six sigma approach. *Technovation*, *26*(5-6), 708-715.

[13] Motwani, J., Kumar, A., & Antony, J. (2004). A business process change framework for examining the implementation of Six Sigma: a case study of Dow Chemicals. *The TQM magazine*, *16*(4), 273-283.

[14] Karunakaran, S. (2016). Innovative application of LSS in aircraft maintenance environment. *International journal of lean six sigma*, *7*(1), 85-108.

[15] Bharathi, K. S., Vinodh, S., Devarapu, S., & Siddhamshetty, G. (2017). Application of Lean approach for reducing weld defects in a valve component: a case study. *International journal of lean six sigma*, *8*(2), 181-209.

[16] Panat*, R., Dimitrova, V., Selvy Selvamuniandy, T., Ishiko, K., & 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*, *5*(4), 444-459.

[17] Jirasukprasert, P., Arturo Garza-Reyes, J., Kumar, V., & K. Lim, 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.

[18] Adikorley, R. D., Rothenberg, L., & Guillory, A. (2017). Lean Six Sigma applications in the textile industry: a case study. *International journal of lean six sigma*, *8*(2), 210-224.
[19] Desai, D., & Prajapati, B. N. (2017). Competitive advantage through Six Sigma at plastic injection molded parts manufacturing unit: A case study. *International journal of lean six sigma*, *8*(4), 411-435.
[20] Swarnakar, V., & Vinodh, S. (2016). Deploying Lean Six Sigma framework in an automotive component manufacturing organization. *International journal of lean six sigma*, *7*(3), 267-293.
[21] Noori, B., & Latifi, M. (2018). Development of Six Sigma methodology to improve grinding processes: a change management approach. *International journal of lean six sigma*, *9*(1), 50-63.
[22] Biju, S., & Nair, N. S. (2017). Measuring academic quality: a three-dimensional approach for internal audit using DMAIC. *International journal of six sigma and competitive advantage*, *10*(3-4), 236-257.
[23] Isack, H. D., Mutingi, M., Kandjeke, H., Vashishth, A., & Chakraborty, A. (2018). Exploring the adoption of Lean principles in medical laboratory industry: Empirical evidences from Namibia. *International journal of lean six sigma*, *9*(1), 133-155.
[24] Dale, B. G., Van der Wiele, T., & Van Iwaarden, J. (2007). *Managing quality*. John Wiley & Sons.
[25] 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.
[26] Pande, P. S., Neuman, R. P., & Cavanagh, R. R. (2000). *The six sigma way: How GE, Motorola, and other top companies are honing their performance*. McGraw-Hill (New York).
[27] Stamatis, D.H. (2004). *Six Sigma fundamentals: A complete guide to the system, methods and tools*. Productivity Press, New York, NY.
[28] Omachonu, V. K., & Ross, J. E. (2004). *Principles of total quality*. CRC Press.
[29] Adams, C., Gupta, P., & Wilson, C. (2007). *Six sigma deployment*. Routledge.
[30] Garza-Reyes, J.A., Oraifige, I., Soriano-Meier, H., Harmanto, D.,& Rocha-Lona, L. (2010). An empirical application of Six Sigma and DMAIC methodology for business process improvement. *Proceedings of the 20th international conference on flexible automation and intelligent manufacturing (FAIM)*, 92-100. San Francisco, CA.
[31] Montgomery, D.C. (2009).*Statistical Quality Control: A Modern Introduction*. Wiley India.
[32] John, B., Kadadevaramath, R., & Edinbarough, I. (2016). Application of multistage process control methodology for software quality management. *Journal of project management*, *1*(2), 55-66.
[33] Kapuria, T. K., Rahman, M., & Haldar, S. (2017). Root Cause Analysis and Productivity Improvement of An Apparel Industry In Bangladesh Through Kaizen Implementation. *Journal of applied research on industrial engineering*, *4*(4), 227-239.
[34] Breyfogle III, F. W., Cupello, J. M., & Meadows, B. (2000). *Managing six sigma: A practical guide to understanding, assessing, and implementing the strategy that yields bottom-line success*. John Wiley & Sons.
[35] John, B. (2015). A dual response surface optimization methodology for achieving uniform coating thickness in powder coating process. *International journal of industrial engineering computations*, *6*(4), 469-480.
[36] Jafari, H., & Hajikhani, A. (2016). Multi Objective Decision Making for Impregnability of Needle Mat Using Design of Experiment Technique and Respond Surface Methodology. *Journal of applied research on industrial engineering*, *3*(1), 30-38.
[37] Gupta, A. K., & Kabe, D. G. (2013). *Design and Analysis of Experiments*. World Scientific Publishing Company.
[38] John, B., Kadadevaramath, R. S., & EDINBAROU6H, I. A. (2017). Designing Software Development Processes to Optimize Multiple Output Performance Characteristics. *Software quality professional*, *19*(4).
[39] Fowleks, W.Y., & Creveling, C. M. (1998). *Engineering methods for robust product design: using Taguchi methods in technology and product development*. Addison-Wesley Longman, USA.
[40] John, B. (2012). Simultaneous optimization of multiple performance characteristics of carbonitrided pellets: a case study. *The international journal of advanced manufacturing technology*, *61*(5-8), 585-594.
[41] Breyfogle, F. W. (1999). Implementing six sigma: Smarter solutions using statistical methods. John Wiley, New York.
[42] Benbow, D.W., &Kubiak, T.M. (2005). *The certified Six Sigma black belt handbook*. ASQ Quality Press, Milwaukee.