PROOF COVER SHEET

Author(s): Jiju Antony

Article title: Case Study in Six Sigma methodology: manufacturing quality improvement and guidance for managers

Article no: TPPC-576404

Enclosures: 1) Query sheet
2) Article proofs

Dear Author,

1. Please check these proofs carefully. It is the responsibility of the corresponding author to check these and approve or amend them. A second proof is not normally provided. Taylor & Francis cannot be held responsible for uncorrected errors, even if introduced during the production process. Once your corrections have been added to the article, it will be considered ready for publication.

For detailed guidance on how to check your proofs, please see http://journalauthors.tandf.co.uk/production/checkingproofs.asp.

2. Please review the table of contributors below and confirm that the first and last names are structured correctly and that the authors are listed in the correct order of contribution. This check is to ensure that your name will appear correctly online and when the article is indexed.

Sequence	Prefix	Given name(s)	Surname	Suffix
1	<prefix>	Antony	Jiju	
2		Gijo	E.V.	
3		Childe	S J	

Queries are marked in the margins of the proofs. Unless advised otherwise, submit all corrections and answers to the queries using the CATS online correction form, and then press the “Submit All Corrections” button.

AUTHOR QUERIES

General query: You have warranted that you have secured the necessary written permission from the appropriate copyright owner for the reproduction of any text, illustration, or other material in your article. (Please see http://journalauthors.tandf.co.uk/preparation/permission.asp.) Please check that any required acknowledgements have been included to reflect this.

AQ1: “Montgomery 2002” is not cited in text. Please cite or delete it.

AQ2: Please provide author’s photographs.

Production Planning & Control
Vol. ??, No. ?, Month?? 2011, 1–17

Taylor & Francis
Taylor & Francis Group

Case study in Six Sigma methodology: manufacturing quality improvement and guidance for managers

Jiju Antony[a]*, E.V. Gijo[b] and S.J. Childe[c]

[a]*Department of DMEM, University of Strathclyde, Glasgow, Scotland G1 1XJ, UK;* [b]*SQC & OR Unit, Indian Statistical Institute, 8th Mile, Mysore Road, Bangalore 560059, India;* [c]*College of Engineering, Mathematics and Physical Sciences, University of Exeter, England EX4 4QJ, UK*

(*Received 11 October 2010; final version received 14 March 2011*)

This article discusses the successful implementation of Six Sigma methodology in a high precision and critical process in the manufacture of automotive products. The Six Sigma define–measure–analyse–improve–control approach resulted in a reduction of tolerance-related problems and improved the first pass yield from 85% to 99.4%. Data were collected on all possible causes and regression analysis, hypothesis testing, Taguchi methods, classification and regression tree, etc. were used to analyse the data and draw conclusions. Implementation of Six Sigma methodology had a significant financial impact on the profitability of the company. An approximate saving of US$70,000 per annum was reported, which is in addition to the customer-facing benefits of improved quality on returns and sales. The project also had the benefit of allowing the company to learn useful messages that will guide future Six Sigma activities.

Keywords: Six Sigma; DMAIC; Taguchi methods; regression analysis; classification and regression tree; process capability evaluation; cause validation plan; matrix plot

1. Introduction

Six Sigma is a systematic methodology aimed at operational excellence through continuous process improvements (Pande *et al*. 2003). Six Sigma has been successfully implemented worldwide for over 20 years, producing significant improvements to the profitability of many large and small organisations (Treichler 2005). Motorola introduced the concept of Six Sigma in the mid-1980s as a powerful business strategy to improve quality. Six Sigma has been claimed to be the best known approach to process improvement (Snee and Hoerl 2003). Six Sigma was initially introduced in manufacturing processes; today, however, marketing, purchasing, billing, invoicing, customer call answering, hospitality, etc. functions are also implementing Six Sigma methodology with the aim of continuously improving the processes and thereby improving customer satisfaction.

The Six Sigma approach is top-down, starting with business strategy and customer voice and leading to implementation, having a significant impact on profit, if successfully deployed (Breyfogle 1999). It takes users away from 'intuition-based decisions' to 'fact-based decisions' (Breyfogle 1999). A number of papers and books have been published addressing the fundamentals of Six Sigma. Topics include: what is Six Sigma? (Harry and Schroeder 1999); why do we need Six Sigma? (Pande *et al*. 2000); what makes Six Sigma different from other quality initiatives? Six Sigma deployment (Keller 2001); critical success factors of Six Sigma implementation (Treichler 2005); hurdles in Six Sigma implementation (Gijo and Rao 2005); Six Sigma project selection (Pande *et al*. 2003); and organisational infrastructure required for implementing Six Sigma (Taghizadegan 2006).

Six Sigma can facilitate in solving complex cross-functional problems where the root causes of a problem (in this case, it is yield problem) are unknown and help to reduce undesirable variations in processes (Breyfogle 1999). The team members decided to adopt Six Sigma over other methods like Kaizen, Quality Circles, Small Group activities, 5S, etc. due to the following reasons. Six Sigma creates a sense of urgency by emphasising rapid project completion within 6 months and uses define–measure–analyse–improve–control (DMAIC) methodology for problem solving which successfully integrates a set of tools and techniques in a disciplined fashion (Kumar *et al*. 2006).

This article discusses a case study performed in an automotive supplier company in India with the aim of improving the first pass yield of a match grinding

*Corresponding author. Email: jiju.antony@strath.ac.uk

ISSN 0953–7287 print/ISSN 1366–5871 online

DOI: 10.1080/09537287.2011.576404
http://www.informaworld.com

process, using Six Sigma methodology. The application of the Six Sigma problem-solving methodology, DMAIC, improved the first pass yield of the process and thereby improved productivity and on time delivery to customer. Regression analysis (Montgomery and Peck 1982, Draper and Smith 2003), hypothesis testing (Dudewicz and Mishra 1988), design of experiments (Montgomery 1991), classification and regression trees (CARTs; Breiman *et al*. 1984), Taguchi methods (Taguchi 1988, Phadke 1989, Gijo 2005), etc. were applied to analyse the data and to identify solutions at different stages.

The structure of this article is defined as follows. Section 2 provides a brief description regarding the case study research methodology. Section 3 gives an introduction to the case study and the solution to the problem in different stages of the Six Sigma approach. Section 4 explains the key lessons learned from the project and Section 5 illustrates the managerial implications in the organisation due to this project followed by Section 6, the concluding remarks and significance of the project.

2. Case study research methodology

This section explains the methodology adopted for this case study. The researcher worked with the company to provide support for the project in Six Sigma techniques, whilst recording data about the exercise from which to develop a case study. A literature review was undertaken with an objective of identifying the past history of various improvement initiatives carried out to address process-related problems.

A case study entails the detailed and intensive analysis of a single case – a single organisation, a single location or a single event (Bryman and Bell 2006). Yin (2003) describes a case study as an empirical inquiry that investigates a contemporary phenomenon within its real-life context. According to Lee (1999), the unit of analysis in a case study is the phenomenon under study and deciding this unit appropriately is central to a research study. In this article, a case study is designed to study the underlying process problem so that solutions can be implemented for process improvement. The extent to which generality can be claimed from a single case study is limited, but by documenting case experiences in the light of existing literature, each case adds to the sum of knowledge available for future practitioners and researchers.

Based on the available data on the process, the team studied the baseline status of the process and drafted a project charter, which explains the details of the problem. The collected data were analysed using descriptive and inferential statistics. Measurement system analysis, regression analysis, design of experiments with Taguchi methods, CARTs, etc. were used for analysing data and inferences were made. Graphical analyses like histogram, dot plot, control chart, etc. were also utilised for summarising the data and making meaningful conclusions. Minitab and JMP statistical software were used to analyse the data collected at different stages in the case study. Management observations and progress were monitored to allow the process to be evaluated.

3. Case study

The company in question is a large manufacturing company in India, manufacturing fuel injection pumps for diesel engines. These pumps were used in a variety of vehicles starting from small cars to locomotives. These are high-precision items and the company is equipped with high accuracy machines and a highly competent workforce of around 1200 people. The problem that arose was the assembly of monobock elements for the fuel injection pumps. Each element consists of a barrel in which a plunger operates. The element pressurises fuel to around 1300 bar for injection into the engine. The clearance between the outer diameter of the plunger and the inner diameter of the barrel is critical. If the clearance is more than specified, there can be fuel leakages and if the clearance is less than the specified value, the fuel injection pump may jam during operation and the diesel engine will stop working. Hence the clearance is a 'critical to quality' characteristic (CTQ). A grinding operation known as 'finish match grinding' is used to grind a minute amount of material from each plunger to match its barrel before assembly. Before the project, the first pass yield of the process was as low as 85%. Second, there were on average 34 customer complaints per month from the field regarding fuel leakages and pump jamming in fuel injection pumps supplied by the company. Once this field complaint occurs, the vehicle cannot be used until the pump is replaced, requiring a tow to a garage. This was leading to total customer dissatisfaction and a negative impact on business.

This problem was addressed by the application of Six Sigma methodology. The basic approach of Six Sigma deals with the functional form of $Y = f(X)$, where Y is the dependent variable or output of the process and X, a set of independent variables or possible causes that affect the output. In this case, Y is the clearance rejection in the match grinding process for monoblock elements. Solving this problem was of highest priority to the management of the company as it was clear that an effective solution to this problem would have a significant impact in reducing costly rework and repair and improving customer satisfaction.

3.1. *The define phase*

The define phase of the Six Sigma methodology aims to define the scope and goals of the improvement project in terms of customer requirements and identify the underlying process that needs improvement. A team of seven persons was formed with the Production Manager as team leader. The other members of the team were the Maintenance Manager, a Production Planning Engineer, a Production Supervisor, a Quality Control Inspector and two operators from the process. These operators were more than 10 years experienced in the process and were knowledgeable about the performance of the product. Also, since they were working directly on the process, they understood the pulse of the process better than anyone else in the organisation. Hence the Champion decided to induct two operators in the team. The team leader is responsible for ensuring the completion of the project within the stipulated time with expected results by involving the team members (Hoerl 2001). Each of the team members is responsible for collection of data and implementing necessary changes in their respective area. The team also had a Champion – the Business Head and a Master Black Belt mentoring the project. The Champion's role was selection and approval of the project and monitoring the execution of the project. The Master Black Belt conducts training for the team and provides guidance for the project for its successful completion. The first step in the project was to develop a project charter with all necessary details of the project including team composition and schedule for the project (Annexure 1). This has helped the team members understand the project objective, duration, resources, roles and responsibilities of team members, project scope and boundaries, expected results from the project, etc. This creates a common vision and sense of ownership for the project, so that the entire team is focused on the objectives of the project.

During the define phase of the project, the team along with the Champion had detailed discussions regarding the problem. The team discussed the pain undergone by the organisation due to this problem. The project team has defined the goal statement of the project as improving the first pass yield of the match grinding process from the current level of 85–95%, which should result in an immense reduction in the internal and external failure cost components of the cost of poor quality (Tsou and Chen 2005). Thus, the aims of the whole project were based upon the requirements of the customer regarding better reliability and the needs of the company in regards of reducing the quality losses.

A basic flow chart of the finish match grinding process was prepared and a supplier–input–process–output–customer (SIPOC) mapping was carried out to have a clear understanding about the process. The process mapping along with SIPOC (Annexure 2) provides a picture of the steps needed to create the output of the process.

Table 1. Results of Gauge R&R study (Minitab output).

Source	Standard deviation	Study variation (%)
Total Gauge R&R	5.29×10^{-4}	19.53
Repeatability	4.40×10^{-4}	16.25
Reproducibility	2.93×10^{-4}	10.82
Part-to-part	2.66×10^{-3}	98.08
Total variation	2.71×10^{-3}	100.00

3.2. *The measure phase*

This phase is concerned with selection of appropriate product characteristics, mapping the respective process, studying the accuracy of the measurement system, making necessary measurements, recording the data, and establishing a baseline of the process capability or sigma rating for the process (Breyfogle 1999).

In this project, the characteristic considered for further study was the clearance between the barrel and plunger. The specification limits for the clearance value are from 0.0030 to 0.0045 mm. Since the tolerance is only 15 μm, it was necessary to validate the measurement system by conducting a *gauge repeatability and reproducibility* (GR&R) study (Kumar *et al*. 2006). For this study, two operators working with this process were identified along with 10 components. After collecting the data, analysis was performed with the help of Minitab statistical software. The Minitab output of GR&R study is presented in Table 1. The total GR&R value was found to be 19.53%. The measurement system may be acceptable when the measurement system variability is between 10% and 30%; at above 30% variability, a measurement system is not considered acceptable (Antony *et al*. 1999). Since the GR&R value in this case was within the acceptable limit of 30%, it was concluded that the measurement system was acceptable for further data collection.

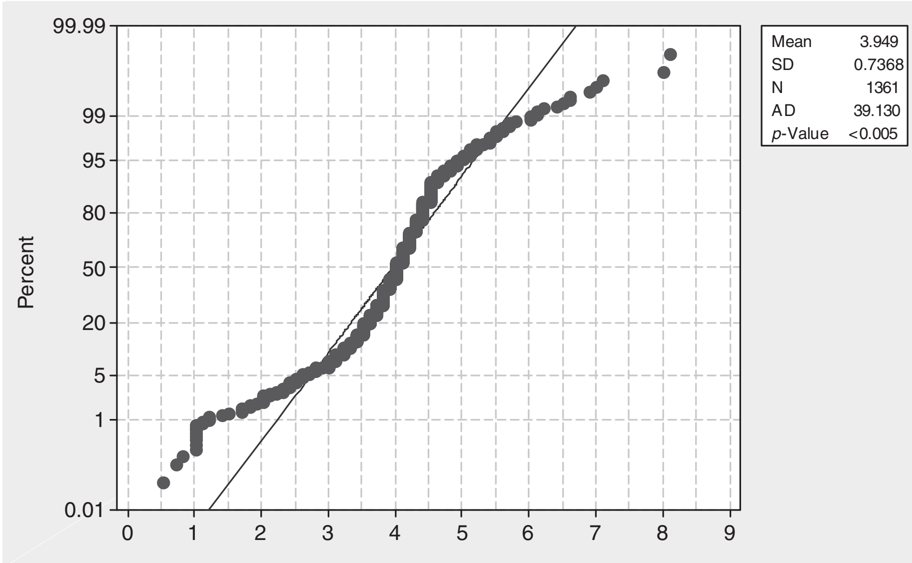

Figure 1. Normal probability plot for clearance.

Then, a data collection plan was prepared with details of the characteristic for which data was to be collected including sample size and frequency of data collection with details of stratification factors. As per the data collection plan, data were collected on a sample basis for a period of 2 weeks on clearance value. There were a total of 1361 observations and these data were tested for normality using the Anderson–Darling normality test with the help of Minitab statistical software. From the Minitab software output (Figure 1), the *p*-value was found to be less than 0.05, which leads to the conclusion that the data are from a population that is not normal. Further, the data were tested for all known distributions, but failed to identify any specific distribution for this data. The Box–Cox transformation was also tried for the data but was unsuccessful in transforming the data to normality. Since the sample size considered here was very large, any slight deviation from Normality could get detected during the test. Also, these data were collected only to understand the baseline performance of the process, the deviation from Normality does not affect further analysis in this study. Hence, from the observed performance of the process capability analysis from Minitab output (Figure 2), the parts per million (ppm) total was identified as 157,972. These provided the baseline data for the study.

3.3. *The analyse phase*

The objective of the analyse phase is to identify the root cause(s) that creates the problem for the process. The first step in finding out the root cause is to identify potential causes (Gijo and Scaria 2010). Hence, in the analyse phase, a brainstorming session was conducted with all the team members and associated personnel to identify the potential causes for variation in clearance between plunger and barrel. The output of the brainstorming was presented as a cause and effect diagram (Figure 3). Next, the causes listed in the cause and effect diagram need to be validated as root causes. To validate the causes, the type of data that could be collected on each cause was identified. Based on the availability of data on the causes, the team along with the Master Black Belt had a detailed discussion regarding the type of analysis possible to validate each one of these causes. It was found that some of these causes can only be validated by *GEMBA* and different type of statistical analysis can be performed on data collected for the remaining causes. After this discussion, the team produced a validation plan (Table 2) for validating all potential causes in the cause and effect diagram. This cause validation plan gives the details of analysis planned on each of the 16 causes. Those causes where *GEMBA* is identified as the method of validation, the process was observed with respect to those causes and a decision was taken whether it is a root cause or not. For the other causes, data were collected and the following statistical analysis was performed and inferences were made.

As per the cause validation plan, the causes related to input characteristics need to be validated. For this purpose, 59 components in a batch were selected and data were collected on barrel and plunger

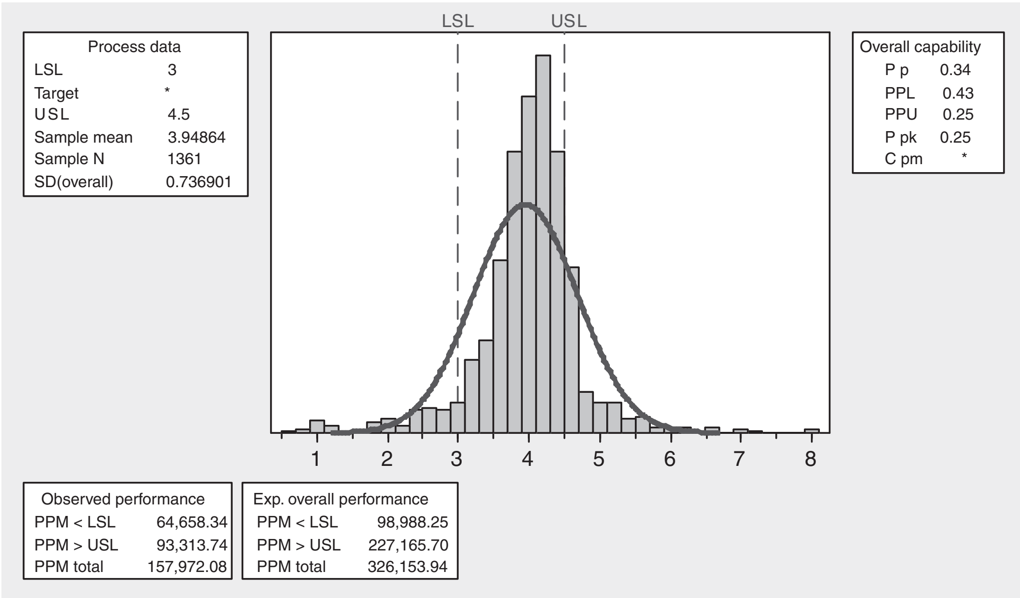

Figure 2. Process capability of clearance.

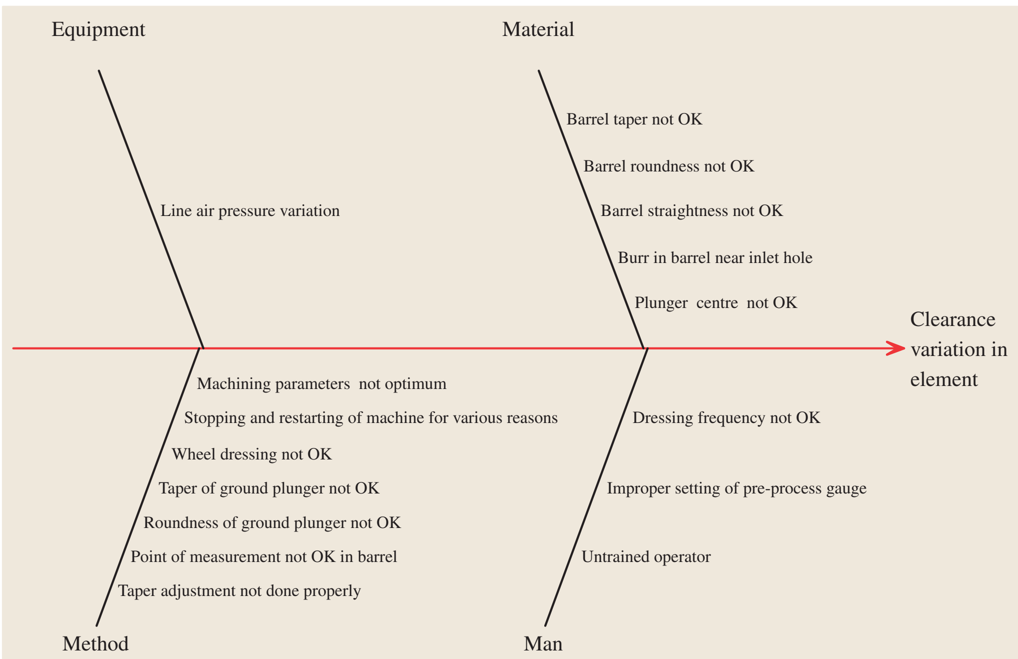

Figure 3. Cause and effect diagram for clearance variation.

characteristics: barrel size, barrel roundness, barrel taper, barrel bore straightness, plunger size, plunger run out, plunger taper and ground plunger taper with corresponding clearance values. As all these variables are continuous, the effect of these input dimensional characteristics on the clearance value needs to be validated by a multiple regression analysis. If the regressors are linearly related, the inference based on a regression model can be misleading or erroneous (Montgomery and Peck 1982). When there are near linear dependencies between the regressors, the problem of multicollinearity is said to exist (Montgomery

Table 2. Cause validation plan.

S. no.	Causes	Validation method
1	Barrel taper not OK	Regression analysis/CART
2	Barrel roundness not OK	Regression analysis/CART
3	Barrel straightness not OK	Regression analysis/CART
4	Burr in barrel near inlet hole	GEMBA
5	Plunger centre not OK	GEMBA
6	Untrained operator	GEMBA
7	Improper setting of pre-process gauge	GEMBA
8	Dressing frequency not OK	Design of experiments
9	Line air pressure variation	GEMBA
10	Taper adjustment not done properly	Data on plunger taper after grinding
11	Point of measurement not OK in barrel	GEMBA
12	Roundness of ground plunger not OK	Validation by checking using the gauge
13	Taper of ground plunger not OK	Regression analysis/CART/design of experiments
14	Wheel dressing not OK	First piece inspection/design of experiments
15	Stopping and restart of machine for various reasons	First piece inspection after restarting of machine
16	Machining parameters not optimum	Design of experiments

and Peck 1982). Hence, before performing the multiple regression analysis, the variables were tested for multicollinearity. The multicollinearity can be studied by a matrix plot of the data. Multicollinearity can also be studied through the variance inflation factor (VIF). The VIF for each term in the model measures the combined effect of the dependencies among the regressors on the variance of that term. One or more large VIF indicates multicollinearity. If any one of the VIFs exceeds 5 or 10, it is an indication that the associated regression coefficients are poorly estimated because of multicollinearity (Montgomery and Peck 1982). From the matrix plot (Figure 4) as well as from the VIF of the regression analysis (Tables 3 and 4), it is evident that multicollinearity is not present in the data (Draper and Smith 2003). Since the *p*-values for barrel roundness, barrel taper and ground plunger taper from the regression analysis were found to be less than 0.05, it was concluded that these variables significantly affect the clearance (Draper and Smith 2003). To identify the best operating ranges for these variables, the CART analysis (Breiman *et al*. 1984) was done with the help of statistical software JMP 8.0. The output of the regression tree analysis obtained from the JMP software is presented in Figure 5. During this analysis, the variable is split into two partitions or *nodes* according to cutting values (Gaudard *et al*. 2009). Initially, the entire data is considered as one group and the optimal split is done with respect to the variable with maximum sum of squares (Breiman *et al*. 1984). After the first split, the entire data set is divided into two groups based on the optimal split identified for the variable with largest sum of squares. Thus, two *nodes* are being formed after the first split. Next, the program identifies the variable for further split based on largest sum of squares between these two *nodes*. After every split, each node gives the average and standard deviation for that group of data. The JMP software provides only a minimal *stopping rule*, that is, a criterion to end splitting; this is based on a defined minimum node size (Gaudard *et al*. 2009). From Figure 5, it can be observed that the first split was based on *barrel taper*. The optimum split point identified in this case was −1. There were six observations with *barrel taper* below −1 and 53 observations with *barrel taper* above −1. The second node was further split with respect to *barrel straightness* and the split point was 4.5. This splitting continues till the node size reduces to 5. From this analysis, it can be concluded that the best operating ranges for the input characteristics are as follows:

(1) *Barrel straightness* less than 0.5 µm, *barrel roundness* less than 0.5 µm and *barrel taper* greater than zero (non-negative taper).
(2) *Ground plunger taper* greater than 0.25 µm and *barrel straightness* between 0.5 and 2 µm.

There were few causes related to the machine parameters of the process. During the discussion, the team felt, there was no scientific methodology adopted for fixing these process parameters. Hence it was decided by the team along with the Champion and Master Black Belt that a scientifically proven design of experiment methodology can be used during the improve phase to identify the optimum operating levels for these parameters. The other causes listed in

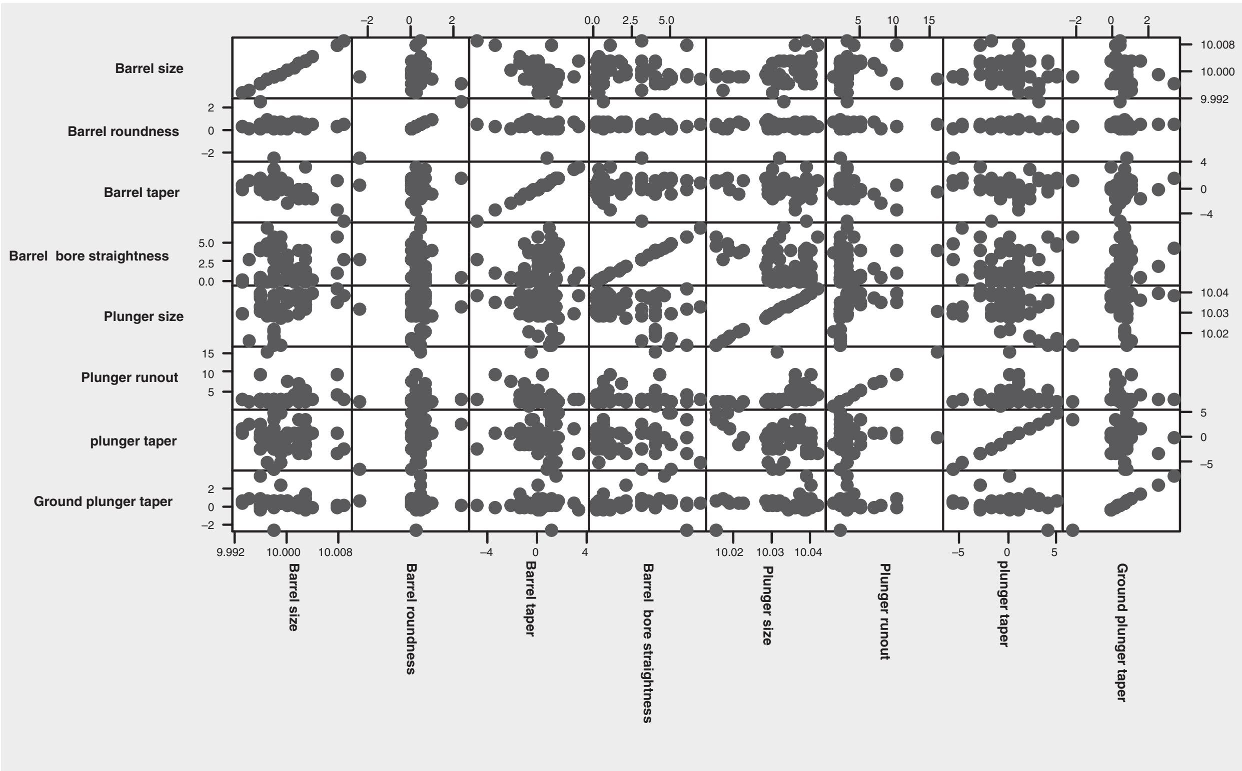

Figure 4. Matrix plot.

Table 3. Minitab output of regression analysis.

Predictor	Coefficient	SE of coefficient	t-Statistic	p-Value	VIF
Constant	501.3	400.6	1.25	0.217	–
Barrel size	−43.86	40.82	−1.07	0.288	1.6
Barrel roundness	−0.7647	0.2319	−3.30	0.002*	1.2
Barrel taper	0.33057	0.09941	3.33	0.002*	1.4
Barrel bore straightness	−0.09547	0.06096	−1.57	0.124	1.2
Plunger size	−6.14	23.39	−0.26	0.794	2.0
Plunger run out	−0.03903	0.0771	−0.51	0.615	1.5
Plunger taper	0.01283	0.05598	0.23	0.820	1.5
Ground plunger taper	0.5835	0.168	3.47	0.001*	1.1

Notes: [a]Implies that these factors are significant at 5% level of significance.

Table 4. ANOVA table for regression analysis.

Source	DF	SS	MS	F	p-Value
Regression	8	39.3785	4.9223	6.87	0.00006
Residual error	50	35.8087	0.7162		
Total	58	75.1873			

the cause and effect diagram were validated by *GEMBA* analysis. The detail of validation of all causes is summarised in a tabular format and is given in Table 5.

3.4. *The improve phase*

During this phase of the Six Sigma project, solutions were identified for all root causes selected during the analyse phase and implemented after studying the risk

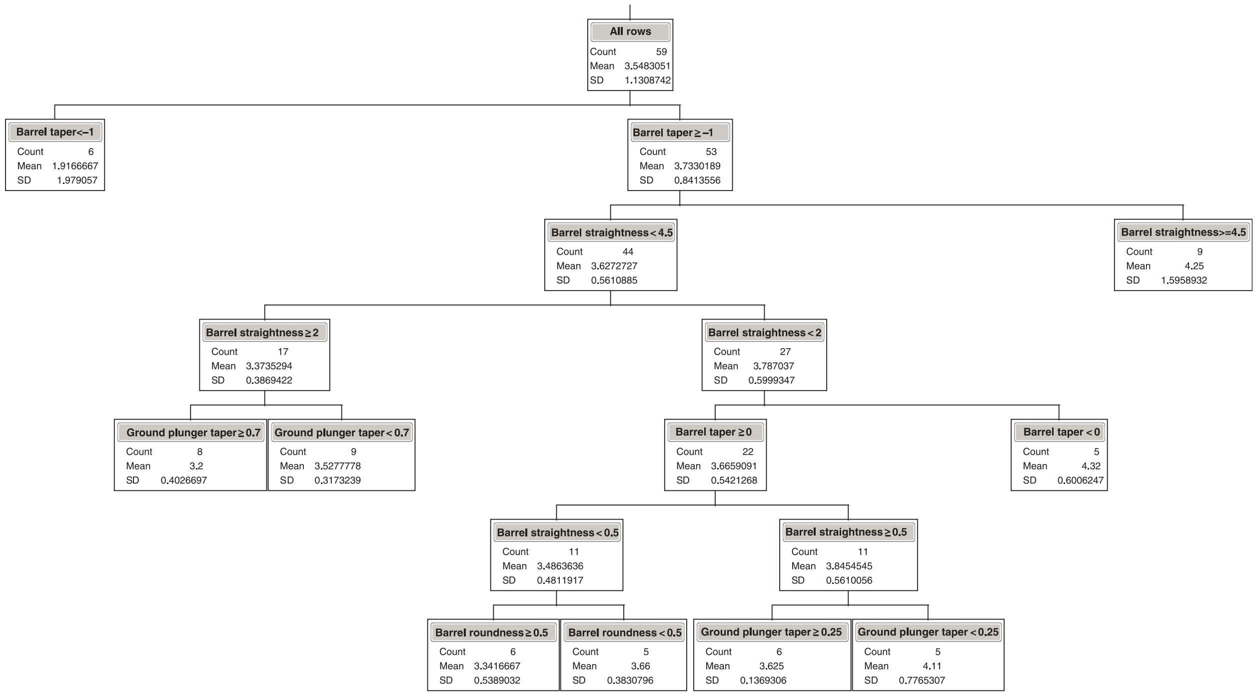

Figure 5. Output of regression tree analysis.

involved in implementation and results were observed. The team had detailed discussions involving all the stakeholders of the process for identifying the solutions for all selected root causes.

As decided earlier, it was planned to conduct a design of experiment for optimising the operating levels of the machine parameters. A meeting was conducted with the operating personnel of the process along with the project team to identify the factors and levels for experimentation. The team, operating personnel of the process, the Champion and the Master Black Belt together selected the following factors for experimentation – *dressing frequency*, *grinding stock*, *grinding feed* and *dressing feed rate*. It was also felt by the team that there might be a possible interaction of *dressing frequency* with *grinding feed* and *grinding stock* with *grinding feed*. Hence, it was also decided to estimate the effect of these two interactions. Since the relationship between these variables and the clearance value was not established as linear, it was decided to experiment all these factors at three levels. The factors and their levels for experimentation are presented in Table 6. Four factors at three levels and two interactions with replications require a huge number of components for conducting a full factorial experiment (Montgomery 1991). Hence, it was decided to use $L_{27}(3^{13})$ orthogonal array for conducting this experiment. A design layout for the experiment (Table 7) was prepared by allocating all the experimental factors in $L_{27}(3^{13})$ orthogonal array (Gijo 2005). The experimental sequence given in the master plan was randomised and experimentation was done. Each experiment was replicated 10 times and the clearance was measured.

The experimental data were analysed by Taguchi's *signal-to-noise* (S/N) ratio method (Acharya *et al.* 2010). Since clearance is nominal-the-best type of characteristic, the S/N ratio formula used for analysis was $10 \times \log((Y^2)/s^2)$, where Y is the average and s, the standard deviation for each experiment (Taguchi 1988, Gijo and Perumallu 2003). Analysis of variance (ANOVA) was carried out for the S/N ratio values and the Minitab output of the same is presented in Table 8. From the ANOVA table, it is clear that the factor dressing frequency and interactions of dressing frequency with grinding feed and grinding stock with grinding feed are significant at 5% level of significance. The factor dressing feed rate is significant at 10% level of significance. Main effect and interaction plots were made for the S/N ratio values (Figures 6 and 7). The level that maximises the S/N ratio was selected as the best level for that factor (Wu and Hamada 2000). Thus, the best levels for the factors dressing frequency, grinding feed and grinding stock were selected from the interaction plot and the best level for dressing feed rate was selected from the main effect plot of the S/N ratio (Ross 1996, Chen and Lyu 2009). These identified

Table 5. Summary of validated causes.

S. no.	Causes	Validation method	Conclusion
1	Barrel taper not OK	Regression analysis/CART	Root cause
2	Barrel roundness not OK	Regression analysis/CART	Root cause
3	Barrel straightness not OK	Regression analysis/CART	Not a root cause
4	Burr in barrel near inlet hole	Burr not found in 500 components after inspection	Not a root cause
5	Plunger centre not OK	Plunger centre found OK after inspection in 500 nos	Not a root cause
6	Untrained operator	Only trained associates work on this machine	Not a root cause
7	Improper setting of pre-process gauge	Validated by setting ring and master barrel	Not a root cause
8	Dressing frequency not OK	Design of experiments	Root cause
9	Line air pressure variation	Line pressure ensured three to four bars	Not a root cause
10	Taper adjustment not done properly	Measurement of plunger taper after grinding	Not a root cause
11	Point of measurement not OK in barrel	Validated by using master setting barrel/POKA-YOKE	Root cause
12	Roundness of ground plunger not OK	Validated by checking using the gauge	Not a root cause
13	Taper of ground plunger not OK	Regression analysis/CART/design of experiments	Root cause
14	Wheel dressing not OK	First piece inspection/design of experiments	Root cause
15	Stopping and restart of machine for various reasons	First piece inspection after restarting of machine	Root cause
16	Machining parameters not optimum	Design of experiments	Root cause

Table 6. Factors and their levels for experimentation.

		Level		
S. no.	Factor	1	2	3
1	Dressing frequency	30	45	60
2	Grinding stock (μm)	25	35	45
3	Grinding feed (μm)	1	2	3
4	Dressing feed rate (mm/min)	80	100	120

optimum factor level combinations are presented in Table 9. These factor level combinations are considered as solutions to the causes related to machine parameters.

Finally, the selected solutions for all the root causes are presented in Table 10. A risk analysis was conducted for identifying possible negative side effects of the solutions during implementation. The team has concluded from the risk analysis that there is no significant risk associated with any of the identified solutions. After the risk analysis, an implementation plan was prepared for all solutions with responsibility and target date for completion for each solution. The time frame defined for completing all these solutions were 3 weeks. The solutions were implemented as per the plan and results were observed. The data on clearance were collected from the process after the project. A sample of 350 observations was recorded over a period of 2 weeks. The process capability evaluation was done through Minitab software (Figure 8). The ppm level of the process was 5715. A dot plot (Figure 9) was made for comparing the process before the project, which shows a significant reduction in clearance variation after the project. The summarised results are presented in Table 11.

3.5. *The control phase*

Once the results are achieved, the challenge for any process owner is to sustain the improvement in the achieved results. This is true in the case of Six Sigma implementation also. Due to many organisational reasons like people changing the job, etc. quite often maintaining the results is extremely difficult (Gijo and Rao 2005). Standardisation of the improved methods and continuous monitoring of the results alone can ensure sustainability of the results. It is also important

Table 7. Design layout for the experiment using L_{27} orthogonal array.

Experiment no.	Dressing frequency in nos	Grinding stock (μm)	Grinding feed (μm)	Dressing feed rate (mm/min)
1	30	25	1	80
2	30	25	2	100
3	30	25	3	120
4	30	35	1	100
5	30	35	2	120
6	30	35	3	80
7	30	45	1	120
8	30	45	2	80
9	30	45	3	100
10	45	45	1	80
11	45	45	2	100
12	45	45	3	120
13	45	25	1	100
14	45	25	2	120
15	45	25	3	80
16	45	35	1	120
17	45	35	2	80
18	45	35	3	100
19	60	35	1	80
20	60	35	2	100
21	60	35	3	120
22	60	45	1	100
23	60	45	2	120
24	60	45	3	80
25	60	25	1	120
26	60	25	2	80
27	60	25	3	100

Table 8. ANOVA table for S/N ratios (Minitab output).

Source	DF	Sequential SS	Adjusted SS	Adjusted MS	F	p-Value
Dressing frequency	2	154.192	154.192	77.096	8.83	0.006*
Grinding stock	2	40.266	40.266	20.133	2.31	0.150
Grinding feed	2	30.716	30.716	15.358	1.76	0.221
Dressing feed rate	2	60.846	60.846	30.423	3.49	0.071**
Dressing frequency × grinding feed	4	162.069	162.069	40.571	4.65	0.022*
Grinding stock × grinding feed	4	142.826	142.826	35.706	4.09	0.032*
Error	10	87.279	87.279	8.728		
Total	26	678.195				

Notes: * and ** denote significance at the 5% and 10% levels, respectively.

to ensure that the operating personnel in the process feel ownership of the solutions implemented, so that without any external intervention the process can be maintained (Gijo and Rao 2005).

The process changes were documented in the procedures of the quality management system of the organisation. This has helped standardise the improvements due to this project. The CTQ of the projects were added to the audit checklist and were verified by internal auditors during the three monthly internal audit processes. Deviations, if any, were reported and corrective actions were initiated.

An $\overline{X}$-R control chart (Figure 10) was introduced for monitoring the process along with a reaction plan (Grant and Leavenworth 2000). This reaction plan helps the operators to take action on the process in case assignable causes occur. Training was provided for the people working with the process about the improved operational methods so that their confidence level in working with the new process increases.

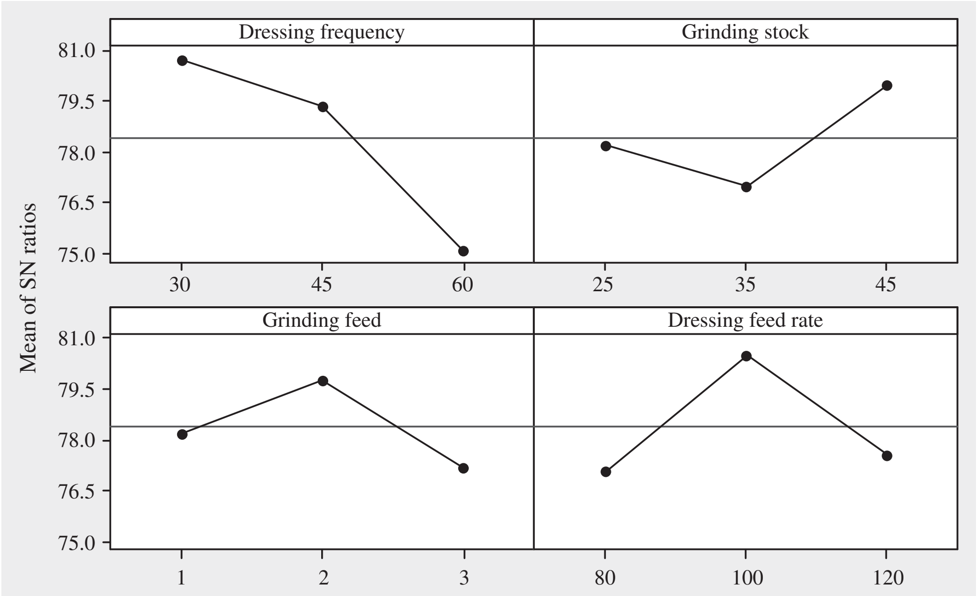

Figure 6. Main effects plot (data means) for S/N ratios.

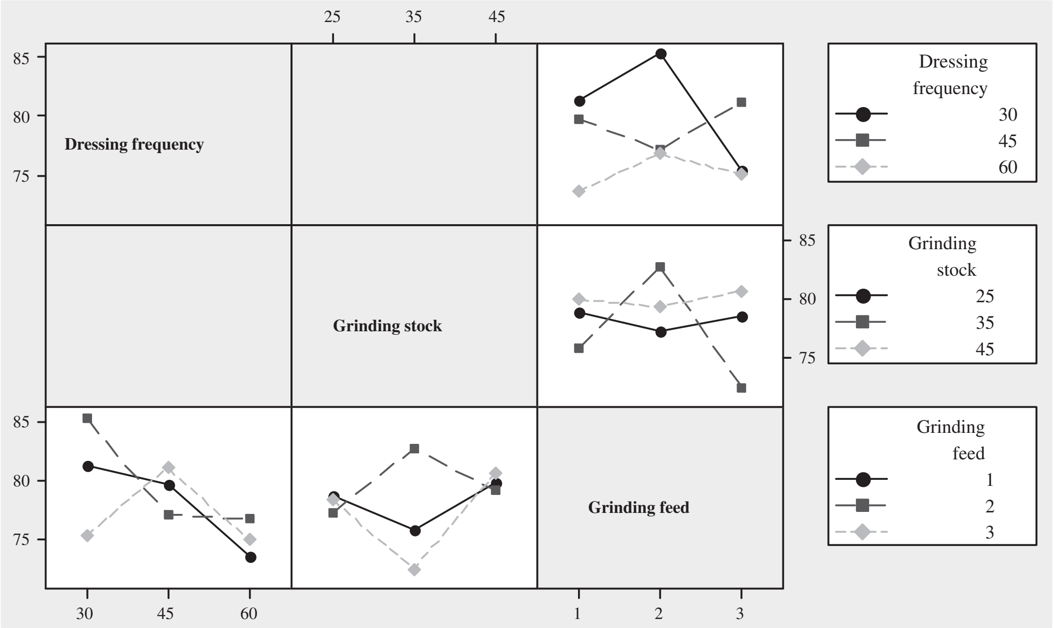

Figure 7. Interaction plot (data means) for S/N ratios.

Table 9. Optimum factor level combination.

S. no.	Factor	Optimum level
1	Dressing frequency	30
2	Grinding stock (μm)	35
3	Grinding feed (μm)	2
4	Dressing feed rate (mm/min)	100

4. Key lessons learned from the study

Six Sigma methodology helped the people in the organisation to understand how a process problem can be addressed systematically. During the project, extensive data collection and analysis were performed to make meaningful conclusions regarding the process. Once data collection started, hidden problems in the 525

Table 10. Validated causes and solutions.

S. no.	Validated cause	Solution
1	Barrel taper and roundness not OK	Control in setting the stroke length during lapping
2	Dressing frequency not OK	Established optimum dressing frequency by DOE
3	Point of measurement not OK in barrel	Introduced Poka–Yoke in barrel pre-process gauge
4	Taper of ground plunger not OK	Established the dressing depth, dressing feed and dressing frequency through DOE Alignment between headstock and tailstock with respect to grinding wheel axis corrected. This is introduced as a parameter to be checked in machine preventive maintenance checklist
5	Wheel dressing not OK	Optimised the dressing parameters by DOE
6	Stopping and restart of machine for various reasons	Introduced Robo-cycle before restarting of the machine
7	Machining parameters not optimum	Optimised parameters introduced through DOE

Note: DOE, design of experiments.

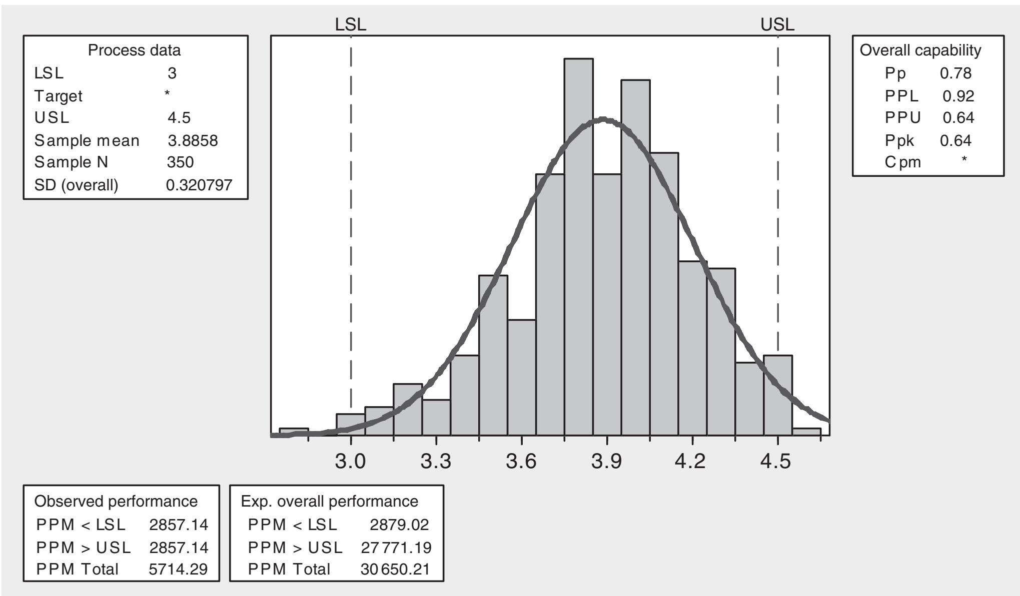

Figure 8. Process capability of clearance.

process were uncovered. Learning statistical software like Minitab and JMP along with Six Sigma has opened a new world of opportunities for making accurate decisions. In this process, everyone in the top management and the team understood the power of scientifically proven data analysis and decision-making.

5. Managerial implications

This case study was an eye opener for the management as it gave a significant improvement in the process. Data and its analysis gave confidence to the people and top management for making decisions about the process. This has changed the mindset that 'it is not invented here, hence not applicable to our process'. The success in this project has made them the 'change agents' in the process of cultural transformation of the organisation. There were isolated efforts in the organisation in the past to implement initiatives like statistical process control, quality circles, small group activities, Kaizen, etc. During the implementation of those initiatives, no systematic effort was made to identify the improvement opportunities in line with business priorities or customer requirements. As a

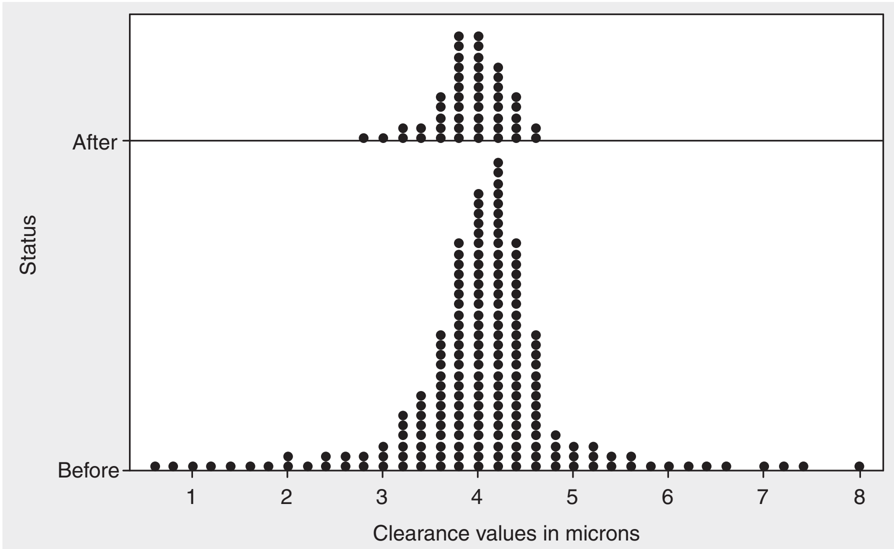

Figure 9. Dotplot of clearance before and after the project.

Table 11. Comparison of results before and after.

	Before	After
DPMO	157,972	5715
Yield (%)	85	99.4
Cycle time (s)	47	42

result, the impact was not very visible in the organisation whereas in Six Sigma, projects were identified with respect to the voice of the business and the customer, and the problems addressed were of highest priority to the organisation. Hence management decided to use Six Sigma methodology for all future improvement initiatives in the organisation. The management introduced a team known as 'Leadership Team' in the organisation to oversee the Six Sigma project selection and execution. All issues related to implementation were also reported to this team for further action.

6. Concluding remarks

The target set for this project was to improve the first pass yield of the match grinding process from 85% to 95%. However, as a result of this study, the first pass yield has improved from 85% to 99.4%. The defect rate after the project is down to 5715 ppm (Table 11). The team with the help of the finance department estimated the tangible savings due to this project. It was found that as a result of this project, the cost associated with scrap, repair and tool has come down drastically. The annualised savings estimated from this project were about US$70,000. This figure no doubt understates the benefits from improved customer perception. This has given an encouragement for the management to implement Six Sigma methodology for all improvement initiatives in the organisation. To encourage the people in the organisation to use Six Sigma methodology, the management decided to suitably reward the successful teams. They planned a twofold activity for this. A certain percentage of the savings reported from the project was shared among the team members. Also, during the annual appraisals due weighting was given for individuals who actively participated in Six Sigma work. This has encouraged more and more people to come forward to take part in the Six Sigma journey. After observing the success in this project, the people were more confident in implementing Six Sigma for addressing any improvement initiative in the organisation.

Even though the case study gave wonderful results, completing the project was not an easy task. Like any other initiative, there were a few people who were initially opposing the movement, but later got convinced about the methodology after observing the results. The project was also affected by the attrition problem in the organisation. There were obvious difficulties when a trained team member left the organisation and was substituted by someone who was not trained in Six Sigma. Quite often in-depth data

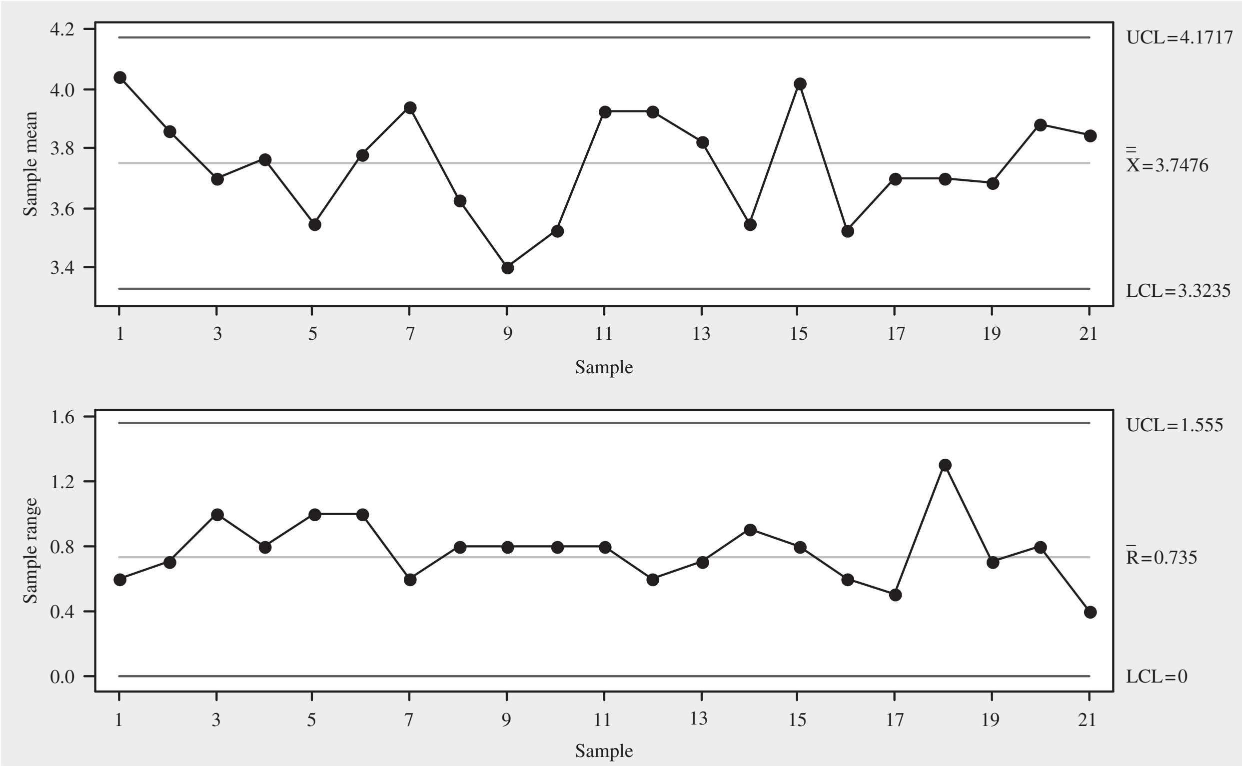

Figure 10. $\overline{X}$-*R* chart for clearance.

collection from the processes was extremely difficult. Sometimes even people are hesitant to give detailed data due to the fear of adverse effect on individuals, if something wrong was identified. A committed and enthusiastic team overcame all these hurdles and successfully completed the project through their teamwork with dedication.

The main learning points from the case study can be stated as follows:

- The Six Sigma exercise provided the company with an example of the benefits of addressing a problem systematically.
- Extensive data collection was essential to the success of the project, but this had to be focussed on the key areas identified in the study. Also, no amount of data collection would be valid without the Gauge R&R study.
- Statistical software was essential for the analysis. However, these packages require use by people with the correct training.
- Management and staff began to believe in their own ability to implement advanced methods. The good example set by this project, supported by making Six Sigma a factor in staff appraisal, has encouraged staff to accept the use of the technique.
- Over the time period of the project, difficulties from loss of trained staff delayed the project. Future projects would benefit from training additional staff beyond initial requirements.
- The cultural issues associated with collecting detailed quality data (related to peoples' performance) must be addressed. A culture of openness is required to remove fear of blame.
- Six Sigma succeeded in a process where previous improvement attempts had failed. This is attributed to the structured data collection that focussed attention on the true causes of the problem.

We hope that this case will encourage managers to use the Six Sigma method to deal with difficult problems, especially where causes are not obvious. A high level of technical ability is required for the benefits to be gained, but the success of such projects also depends on the correct aims being set, the correct team being selected, and the correct atmosphere being created for the project; thus there are both technical and management challenges to ensure Six Sigma project success.

Notes on contributors

Jiju Antony, director of the Centre for Research in Six Sigma and Process Improvement (CRISSPE) and director of Knowledge Exchange within Strathclyde Institute for Operations Management. In his 10 years of research career, he has published more than 200 refereed journal and conference papers and five textbooks in the area of Reliability Engineering, Design of Experiments, Taguchi Methods, Six Sigma, Total Quality Management and Statistical Process Control. He has successfully launched the *First International Journal of Lean Six Sigma* in April 2010. Prof Antony has been invited several times as a keynote speaker to national conferences on Six Sigma in China, South Africa, Netherlands, India, Greece, New Zealand, South Africa and Poland. Antony has also chaired the First, Second and Third International Conferences on Six Sigma and First and Second International Workshops on Design for Six Sigma. The recent work of Prof Antony includes collaborations with organisations such as Thales Optronics Ltd., Scottish Power, Rolls-Royce, Tata Motors, Bosch, Nokia, GE Domestic Appliances, Scottish Widow, 3 M, Land Rover, GE Power Systems, NHS Ayr and Aaran, Kwit Fit Financial Services, Clydesdale Bank, etc. in the development of Six Sigma, Lean and Continuous Improvement programmes within these organisations. He is on the Editorial Board of over eight International Journals and a regular reviewer of five leading International Journals in Quality, Operations and Production Management.

E.V. Gijo is a faculty in the Statistical Quality Control and Operations Research Unit of Indian Statistical Institute, Bangalore, India. He holds a Master's degree in Statistics from M.G. University, Kottayam, Kerala and a Master's degree in Quality, Reliability and Operations Research from Indian Statistical Institute, Kolkata. He is an active consultant in the field of Six Sigma, Quality Management, Reliability, Taguchi Methods and allied topics in a variety of industries. He is a certified Master Black Belt and trainer in Six Sigma and qualified assessor for ISO-9001, ISO-14001 systems. He has published many papers in reputed international journals. He also teaches in the academic programs of the Institute.

Stephen Childe is a senior lecturer in Engineering Management at the University of Exeter. He is a chartered engineer and member of the Institution of Engineering and Technology and a member of the IFIP Working Group (5.7) in Integrated Manufacturing Systems. He was formerly a vice chairman of the UK Institution of Operations Management and is the editor of the *International Journal Production Planning and Control*: The Management of Operations which addresses operations management in all sectors, especially focusing on research that addresses or identifies problems experienced in industry (The peer review and decision process for research papers authored by Dr Childe for this Journal is handled independently by the co-editor).

References

Acharya, U.H., Gijo, E.V., and Antony, J., 2010. Quality engineering of a traction alternator by robust design. *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture*, 224 (2), 297–304.

Antony, J., Knowles, G., and Roberts, P., 1999. Gauge capability analysis: classical versus ANOVA. *Quality Assurance: Good Practice, Regulation and Law*, 6, 173–181.

Breiman, L., *et al*., 1984. *Classification and regression trees*. Monterey, CA: Wadsworth Inc.

Breyfogle, F.W., 1999. *Implementing Six Sigma: smarter solutions using statistical methods*. New York, NY: John Wiley.

Bryman, A. and Bell, E., 2006. *Business research methods*. New Delhi: Oxford University Press.

Chen, M. and Lyu, J., 2009. A lean Six-Sigma approach to touch panel quality improvement. *Production Planning and Control: The Management of Operations*, 20 (5), 445–454.

Draper, N.R. and Smith, H., 2003. *Applied regression analysis*. 3rd ed. New York: John Wiley.

Dudewicz, E.J. and Mishra, S.N., 1988. *Modern Mathematical Statistics*. New York: John Wiley.

Gaudard, M., Ramsey, P., and Stephens, M., 2009. Interactive data mining informs designed experiments. *Quality and Reliability Engineering International*, 25 (3), 299–315.

Gijo, E.V., 2005. Improving process capability of manufacturing process by application of statistical techniques. *Quality Engineering*, 17 (2), 309–315.

Gijo, E.V. and Perumallu, P.K., 2003. Quality improvement by reducing variation: a case study. *Total Quality Management and Business Excellence*, 14 (9), 1023–1031.

Gijo, E.V. and Rao, T.S., 2005. Six Sigma implementation – hurdles and more hurdles. *Total Quality Management and Business Excellence*, 16 (6), 721–725.

Gijo, E.V. and Scaria, J., 2010. Reducing rejection and rework by application of Six Sigma methodology in manufacturing process. *International Journal of Six Sigma and Competitive Advantage*, 6 (1/2), 77–90.

Grant, E.L. and Leavenworth, R.S., 2000. *Statistical quality control*. 7th ed. New Delhi: Tata McGraw-Hill.

Harry, M. and Schroeder, R., 1999. *Six Sigma: the breakthrough management strategy revolutionizing the world's top corporations*. New York: Doubleday.

Hoerl, R.W., 2001. Six Sigma Black Belts: what do they need to know? *Journal of Quality Technology*, 34, 391–406.

Keller, P.A., 2001. *Six Sigma deployment*. Arizona: Quality Publishing House.

Kumar, M., *et al*., 2006. Implementing the lean Sigma framework in an Indian SME: a case study. *Production Planning and Control: The Management of Operations*, 17 (4), 407–423.

Lee, T.W., 1999. *Using qualitative methods in organizational research*. Thousand Oaks, CA: Sage.

Montgomery, D.C., 1991. *Design and analysis of experiments*. 3rd ed. New York: John Wiley.

Montgomery, D.C., 2002. *Introduction to statistical quality control*. 4th ed. New York: John Wiley.

Montgomery, D.C. and Peck., E.A., 1982. *Introduction to linear regression analysis*. New York, NY: John Wiley.

Pande, P., Neuman, R., and Cavanagh, R., 2000. *The Six Sigma way: how GE, Motorola and other top companies are honing their performance*. New York, NY: McGraw-Hill.

Pande, P., Neuman, R., and Cavanagh, R., 2003. *The Six Sigma way team field book: an implementation guide for process improvement teams*. New Delhi: Tata McGraw-Hill.

Phadke, M.S., 1989. *Quality engineering using robust design*. Englewood Cliff, NJ: Prentice Hall.

Ross, P.J., 1996. *Taguchi techniques for quality engineering*. New York: McGraw-Hill.

Snee, R.D. and Hoerl, R.W., 2003. *Leading Six Sigma: a step by step guide based on experience at GE and other Six Sigma companies*. Upper Saddle River, NJ: Prentice-Hall.

Taghizadegan, S., 2006. *Essentials of lean Six Sigma*. New Delhi: Elsevier.

Taguchi, G., 1988. *Systems of experimental design. Volumes 1 and 2*. New York: UNIPUB and American Supplier Institute.

Treichler, D.H., 2005. *The Six Sigma path to leadership*. New Delhi: Pearson Education.

Tsou, J.C. and Chen, J.M., 2005. Case study: quality improvement model in a car seat assembly line. *Production Planning and Control: The Management of Operations*, 16 (7), 681–690.

Wu, C.F.J. and Hamada, M., 2000. *Experiments – planning, analysis, and parameter design optimization*. New York: John Wiley.

Yin, R.K., 2003. *Case study research: design and methods*. 3rd ed. Thousand Oaks, CA: Sage.

Annexure 1

Project charter

Project title: First pass yield improvement of match grinding process		
Background and reasons for selecting the project: The first pass yield is only 85%, losing approximately 3500 units per month due to rejection and scrap. Average 34 customer complaints per month due to product failure in the field. Process is very complex. Unsuccessful in finding solution in previous attempts		
Aim of the project: To improve the first pass yield from 85% to 95% and increase the output		
Project champion:	Business Head	
Project leader:	Production Manager	
Team members:	Maintenance Manager Production Planning Engineer Production Supervisor Quality Control Inspector Operator – Shift I, Operator – Shift II	
Characteristics of product/process output and its measure		
CTQ Clearance between barrel and plunger	Measure and specification Clearance measured in microns, 3.0–4.5 μm	Defect definition Unit is defective if clearance value less than 3.0 μm or more than 4.5 μm
Expected benefits:	Reduction of internal rejections and customer complaints	
Expected customer benefits:	Reduction of field failure and improving on time delivery	
Schedule:	Define: 3 weeks, Measure: 4 weeks, Analyse: 6 weeks, Improve: 6 weeks, Control: 8 weeks	

Annexure 2

SIPOC along with process map

Supplier	Input	Process	Output	Customer
Supplier	Barrel	Finish match grinding	Finished parts	Assembly shop
Supplier	Plunger	process		
Planning department	Setting parameters		Production reports	Manufacturing department
Planning department	Dressing method			
Planning department	CNC program		Quality reports	Quality department
Calibration department	Gauges			
Planning department	Tooling			

Process steps