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Quality Assurance through Process Improvement—A Concise Review

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Abstract. The past two decades have seen the realization of the manufacturing firms towards quality consciousness. The various firms worldwide employed the statistical tools for minimizing the deviations and subsequently the number of rejects of the manufactured parts. In this process, more prominence is laid on prevention of defects rather than detecting and rejecting the defect in the usual traditional end inspection quality check. This review paper witnesses the procedures involved in the improvement of the manufacturing process capability and focuses on achieving quality assurance through sustained improvement in the manufacturing process. The different methodologies for sustained improvement in manufacturing process across varied industrial sectors, are identified, discussed and presented. The nuances of enhanced product quality levels through process capability improvement work performed in varied areas of industrial manufacturing are also captured.

Keywords: Statistical Process Control (SPC), Define-Measure-Analyse-Improve-Control (DMAIC) procedure, process capability, Critical to Quality (CTQ) characteristic, Quality Assurance (QA).

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1. Introduction

With increasing customer demands, the thrust on the quality products for low costs has become the call of the hour. This is achievable only by reducing the number of manufacturing process rejections at first hand. Apart from this, to sustain the competition, the manufacturing firms must curtail the defects at the very first instance by standardizing the production set-up changeover procedures. Many firms focused on process improvements and curtailed down the process rejections. Hence, emphasis is laid on greater process control through mapping the critical to quality characteristics onto the process monitoring charts. An attempt has been made to capture the finer aspects of the manufacturing process improvements over the recent times.

The structure of this paper is elaborated as follows. The paper starts with an introductory note stating the importance of process improvements in quality assurance. The review of various methodologies employed in achieving quality assurance focusing on process improvements forms the main content of the paper. Here, the different methods responsible for the achievements in quality assurance through focused improvement in the manufacturing processes are traced and discussed at length. Finally, the conclusion forms the last part of the paper. The list of references from varied facets of manufacturing are referred in this paper.

2. Methodologies Employed in Achieving Quality Assurance Focusing on Process Improvements

The quality improvement cycle starts with recognizing the voice of the customer as a part of Quality Function Deployment (QFD) [1] wherein the customer requirements are finally incorporated in the product functional design and reflected in the manufacturing process in the form of critical-to-quality characteristics. To improve the product quality and sustain the fierce competition, the manufacturing firms curtailed down the manufacturing costs. This was possible only through focused improvement in the manufacturing process and closing down the process rejects at the first instance. Continuous improvements in the manufacturing process through the formation of Quality Circles were achieved. The Cross Functional Teams (CFTs) were formed and the end product quality was assured by removing the flaws in the related manufacturing process. Various Quality Assurance (QA) tools and methodologies focusing on the improvements in related manufacturing process were employed. Root cause analysis was performed and the pitfalls in the process parameters were identified and corrective measures were taken. Preventive maintenance was given priority in order to prevent any unexpected shut-downs. Process related issues were given top priority, as it was realized that any kind of sustainable improvement is possible only through improvements in the manufacturing process. Table 1 summarizes the methodologies employed for achieving Quality Assurance through process improvement.

Different methodologies for achieving Quality Assurance through process improvements, are adopted and are discussed as follows. In all the works referred, statistics form a very important aspect in quality improvement [2] particularly in the six sigma DMAIC improvement works [3].

2.1. PCMC (Process Capability Monitoring Chart)

The Process Capability Monitoring Chart (PCMC) interprets multi-characteristics process capabilities and hence is a useful tool to evaluate the manufacturing process performance [4]. PCMC is an effective and efficient tool for examining the process capabilities of a product of multiple processes. Process capability zone marked on the PCMC checks whether process capabilities satisfy preset level or not. An extension to PCMC is PCMF (process capability monitoring figure) [5] which guides the process engineers in establishing the process parameters for maintaining the process quality. PCMF adopts a color management method where the process monitoring chart is divided into unique color bands for assisting the frontline machine operator in regulating the deviations of Critical-To-Quality characteristic under observation. PCMF also helps the process engineers in predicting the process capability for the subsequent production batch by time series analysis approach.

Table 1. Methodologies employed for achieving Quality Assurance through process improvement.

S. No.	Authors	PCMC (Process capability monitoring chart)	PCMF (Process capability monitoring figure)	FMEA (Failure Modes and Effects Analysis)	ANOVA (Analysis of variance)	Gage R & R and Gage compatibility index	DEA (Data Envelopment Analysis)	RSM (Response Surface Methodology)	SPC (Statistical process Control, X bar R , shewart, CUSUM EWMA charts)	Process capability studies of CTQ characteristic	Process capability indices	Quality Function Deployment (QFD)	DoE (Design of Experiments)	DMAIC
1	Schilling (1994)								✓					
2	Locke (1994)								✓					
3	Chen, Li, Liao (2002)									✓				
4	Lin (2004)									✓			✓	✓
5	Tong,Tsung, Yen (2004)												✓	✓
6	Su, Chiang, Chiao (2005)													✓
7	Burlikowska (2005)								✓					
8	Hwang (2006)													✓
9	Chen, Yu, Sheu (2006)	✓												
10	Yu, Sheu, Chen (2006)		✓											
11	Gentili et al. (2006)													✓
12	Li, Refaie, Yang (2008)													✓
13	Aggogeri, Mazzola (2008)													✓
14	Lo, Tsai, Hsieh (2009)													✓
15	Wu, Pearn, Kotz (2009)										✓			
16	Chen, Li, Cox (2009)									✓			✓	
17	Kumar, Sosnoski (2009)													✓
18	Feldner (2009)													✓
19	Liao, Kang, Lee, Wu (2009)									✓	✓			
20	Sokele, Šercer, Godec (2010)									✓				
21	Pepper, Spedding (2010)													✓
22	Hoerl and Snee (2010)													✓
23	Box and Woodall (2011)													✓
24	Tangjitsitcharoen (2011)									✓				
25	Koc, Agcayazi, Carsley (2011)												✓	
26	Singh (2011)									✓				
27	Sahey et al. (2011)									✓				✓
28	Jirasettapong and Rojanarowan 2011								✓					

S. No.	Authors	PCMC (Process capability monitoring chart)	PCMF (Process capability monitoring figure)	FMEA (Failure Modes and Effects Analysis)	ANOVA (Analysis of variance)	Gage R & R and Gage compatibility index	DEA (Data Envelopment Analysis)	RSM (Response Surface Methodology)	SPC (Statistical process Control, X bar R , Shewart, CUSUM, EWMA control charts)	Process capability studies of CTQ characteristic	Process capability indices	Quality Function Deployment (QFD)	DoE (Design of Experiments)	DMAIC
29	Pearn, Hung, Tai, Hou (2011)									✓	✓			
30	Mariappan et al. (2012)				✓	✓							✓	
31	Lin et al. (2012)												✓	✓
32	Gasparin et al. (2012)					✓								
33	Su, Hsiao, Liu (2012)													✓
34	Antony, Gijo, Childe (2012)													✓
35	Kaushik, Khanduja, Mittal, Jaglan (2012)													✓
36	Martowibowo, Wahyudi (2012)												✓	
37	Bilgen, Sen (2012)													✓
38	Chen, Chen, Wang (2012)									✓	✓			
39	Tai (2012)									✓	✓			
40	Hsu, Pearn, Chuang (2012)									✓	✓			
41	Ebadi, Shahriari (2013)									✓				
42	Lin et al. (2013)									✓				
43	Chen, Huang, Huang (2013)				✓		✓				✓			
44	Kumaravadivel, Natarajan (2013)			✓				✓						✓
45	Sharma and Rao (2013)	✓		✓	✓				✓					✓
46	Oke (2013)													
47	Kumar, Satsangi, Prajapati (2013)													✓
48	Sharma and Rao (2014)	✓		✓	✓				✓					✓
49	Ghosh, Maiti (2014)													✓

S. No.	Authors	PCMC (Process capability monitoring chart)	PCMF (Process capability monitoring figure)	FMEA (Failure Modes and Effects Analysis)	ANOVA (Analysis of variance)	Gage R & R and Gage compatibility index	DEA (Data Envelopment Analysis)	RSM (Response Surface Methodology)	SPC (Statistical process Control, X bar R , Shewart, CUSUM, EWMA control charts)	Process capability studies of CTQ characteristic	Process capability indices	Quality Function Deployment (QFD)	DoE (Design of Experiments)	DMAIC
50	**Jirasukprasert, Garza-Reyes, Kumar and Lim (2014)**													✓
51	**Prashar (2014)**													✓
52	**Chang and Wysk (1985) 1st Edition Prentice-Hall Inc.**									✓	✓			

As a whole, PCMC and PCMF give first-hand information on the existing condition of the manufacturing process and guides the process engineering about the process deviations by identifying the process outliers. Hence PCMC and PCMF are simple and useful methods to evaluate the process capability of a machining center by taking the process precision, accuracy and actual capability into consideration.

2.2. SPC and $\overline{X}$ - R Charts

SPC forms the modern approach towards Quality Assurance where the power of process control is combined with the assurance of acceptance sampling [6]. In SPC, the data acquired from acceptance sampling is used as a feedback of information on the process rather than simple acceptance or rejection of lots. Application of SPC in industry is started by employing a unique ABC plan which discusses about establishing control, establishing capability and maintaining process capability in a phase vise manner. $\overline{X}$ -R charts found a place in Statistical Quality Control [7] where the accuracy and precision capability were also addressed. $\overline{X}$ -R charts gained popularity as a measure of Statistical process control, to measure and minimize the variations that occur in the process and help solving the problems locally by taking collective decisions [8].

In order to monitor the similar multiple stream processes Group Control Charts (GCC) are used which consists of Group $\overline{X}$ and group R charts. Apart from $\overline{X}$ and R charts, the Shewhart, CUSUM and EWMA control charts are employed for Multiple Stream Processes (MSP). CUSUM chart is a cumulative sums of deviations which the observations reflect from the true value and EWMA chart is an exponentially weighted moving average chart. The sensitivity to detect process shift is least for Shewhart when compared to EWMA and CUSUM charts. Jirasettapong and Rojanarowan in their work suggested that in broader terms, where the number of streams in a MSP are less than or equal to 5, then CUSUM charts are aptly suitable, whereas if the number of streams in MSP are greater than 5 then, Shewhart chart in combination with $\overline{X}$ -R charts is suggested [9]. It has been stressed that the type of control chart depends on the interrelation between the process parameters.

Hence, SPC concentrates on process improvement and guides the process engineers to regulate the manufacturing process in order to proactively prevent the occurrence and propagation of defects down the manufacturing line.

2.3. FMEA (Failure Modes and Effects Analysis)

FMEA is an analysis tool that finds versatile applications in wide areas., The cause-and-effect matrix and the failure modes and effects analysis are both together employed for flywheel casting process to find out the potential causes for low process yield [10]. Key process input and output variables are charted. Remedial actions are taken to correct and prevent variations in the process. Another noted area of application of FMEA is the engine manufacturing process [11, 12]. In the area of engine manufacturing, FMEA is carried out for the Failure Modes of the following observed CTQ characteristics namely, thrust face width of connecting rod and crankshaft stub-end hole diameter after boring operation. Severity, Occurrence and detection ratings are allocated and the corresponding risk-priority-numbers (RPNs) are calculated. Based on the RPNs the remedial actions are taken for process standardization.

2.4. ANOVA (Analysis of Variance)

ANOVA (Analysis of Variance) is a statistical tool employed for narrowing down to the root cause for degraded process performance. The Post-hoc test establishes the extent of influence of the causes on the CTQ characteristic of concern. In connecting rod and crankshaft components of engine manufacturing, ANOVA is successfully employed for identifying the major root causes and subsequently for identifying the extent of influence of these root causes on process deviations [11, 12]. Among the varied areas of applications of ANOVA, one such area is manufacturing of shafts used in submersible pumps [13]. The surface finish of the shaft was identified as a critical to quality characteristic and ANOVA finds place as a part in the manufacturing process improvement. During the manufacture of front cover of a digital camera [14], the ANOVA methodology was applied to find the significant process parameters that affect the part's quality indices. The results showed that four out of nine process parameters were significant with a significance level of 0.05.

2.5. Gage R & R (Gage Repeatability and Reproducibility)

Gage Repeatability and Reproducability (Gage R & R) is an important aspect of the measurement system analysis where the measuring instrument capability indices, or also known as the gauge capability indices Cg and Cgk are established [15]. Wrong Gage R & R readings lead to incorrect conclusions and subsequently rejecting good components from the production line. For example, while dimensional verification of micro injection-molded components measured using an optical coordinate measuring machine (OCMM), a difference of 10 μm between the different optical set-ups represents a huge gap of about 33 to 50% of the tolerance range for micromechanical parts. Hence, the measuring instrument capability study was through Gage R & R registers a better control on production process.

Gage R&R is equally effective for single sided geometrical tolerances of the larger-the-better or smaller-the-better type. The surface finish of the shaft while manufacturing of shafts used in submersible pumps [13] is a single sided geometrical tolerance of larger-the-better type where Gauge R&R is carried out to make the process stable

2.6. DEA (Data Envelopment Analysis)

DEA is basically and linear programming tool for finding the efficiency of multiple decision making units involving multiple inputs and outputs. In the field of quality assurance, DEA is employed for simultaneous optimization of multiple interrelated quality indices, leading to product quality improvement [14]. Multiple regression equations are set up and used to produce the dataset for DEA analysis. Through this analysis efficient frontier of process parameters can be found with only a few experimental iterations.

2.7. RSM (Response Surface Methodology)

RSM (Response Surface Methodology) is a mathematical tool for optimizing a response (output variable) which is under the influence of several independent variables (input variables). In the field of flywheel casting process [10], in order to reduce part rejection of green sand castings operations, RSM is employed. Before applying RSM, the casting defects were 6.94% and after applying RSM, the casting defects got reduced to 4.69%. Out of the various process parameters for given conditions, the green strength was identified as the dominant process parameter followed by moisture content, for the major chunk of casting defects. Finally, the optimal combination of casting process parameters satisfied the real requirements of casting operation.

2.8. Process Capability

Process capability is the database of knowledge for each process which includes, the shapes and size a process can produce, the dimensions and geometric tolerances that can be obtained by various processes, the surface finish attainable, the metal removal rate, the relative cost and other cutting characteristics and constraints [16]. The more exhaustive is this knowledge base, the more complete the process study shall be. The process capability is measured by process capability indices which have wide applicability and importance in quality assurance [17]. Process capability indices have various applicational aspects like gage measurement, supplier selection, multiprocess performance analysis chart and asymmetrical tolerances. It is emphasized that, whatever may be the process capability index (PCI) employed, they are to be used only after the process has been completely brought under statistical control. If the process data set obtained is non-normal process data with a skewed distribution [18], then the data must be first converted to the equivalent normal values and subsequently solve for process mean and standard deviation of the obtained normal and folded normal distribution data. The measurement of process capability of simple linear profiles also better known as linear regressing models constitutes of two methods [19]. The first method uses the average percentage of non-conforming parts to be transformed into a process capability measure. The second method uses a multivariate approach to determine the process capability. The simulation results indicate that both proposed methods perform well.

The applications of manufacturing process capability improvement studies covers wide areas namely, engine manufacturing process [11, 12], crane hook manufacturing process [20], plasma machining [21], CNC turning process [22], blow moulding process [23], polyjet printing [24], brake lever manufacturing [25] aircraft turbine engine blade manufacturing [26], photolithography process control in wafer fabrication [27], manufacture and process capability evaluation of square bumps [28], golf club-shaft manufacture in leisure sport industries [29], tool condition monitoring for grinding wheel in IC manufacturing of silicon wafer [30] and LED assembly in electronics industry [31]. All the works cited depict the process improvement procedure and fosters the fact that any noticeable permanent improvement is possible only through in-process control and not through end inspection. In all the above works, firstly the CTQ characteristic has been identified in the respective areas of study. Table 2 lists down the identified CTQ characteristic corresponding to the respective manufacturing process. This is succeeded by the collection of data pertaining to the CTQ characteristic and followed by calculation of the process capability indices. Continuous improvement is achieved by taking corrective actions for a lower value of capability index, until the targeted capability index value is reached.

Table 2. List of identified CTQ characteristic corresponding to the respective manufacturing process.

S.No	Author/year	Manufacturing process	CTQ characteristic
1	K.S.Chen, R.K.Li, S.J.Liao (2002)	Crane hook manufacturing	Strength of the crane hook
2	Joseph C.Chen, Ye Li, Ronald A.Cox (2009)	Plasma machining	Roundness of the holes
3	Somkiat Tangjitsitcharoen (2009)	CNC turning process	Cutting chip profile
4	Maja Rujnić-Sokele, Mladen Šercer, Damir Godec (2010)	Blow moulding process	Volume of blow moulded bottle

S.No	Author/year	Manufacturing process	CTQ characteristic
5	Rupinder Singh (2011)	Polyjet printing	Profile-accuracy and surface finish
6	Chittaranjan Sahey et al. (2011)	Brake lever manufacturing	Brake lever strength
7	S.J.Lin et al. (2013)	Aircraft turbine engine blade manufacturing	Blade profile
8	G.V.S.S.Sharma and P.Srinivasa Rao (2013)	Connecting rod manufacturing	Connecting rod thrust face thickness
9	G.V.S.S.Sharma and P.Srinivasa Rao (2014)	Crankshaft manufacturing	Crankshaft stub-end hole diameter

2.9. DoE (Design of Experiments)

Design of Experiments (DoE) is basically an experiment oriented optimizing tool for optimizing the output parameter by controlling the input variables. DoE knows no boundaries and is equally effective in almost all fields of engineering and technology. In the field of electronics engineering, DoE is carried out to find the optimum settings of the factors involved in solder paste thickness characteristic of the PCB screening process [32]. In electrical manufacturing industry, the Design of Experiments with a total of 36 experiments is conducted for finding the optimal setting combination for roundness of the holes cut by an aging plasma-cutting machine [21]. In the warm sheet hydroforming process, DoE is employed to determine the optimal process conditions for maximum formability of Aluminum Alloy 5754-O (AA5754-O) [33]. In optical fibre industry, DoE finds a place for enhancing the process of optical fiber and for determining the interrelated factors that affect the process quality of optical fiber [34]. In manufacturing of shafts used in submersible pumps [13], DoE is conducted for improving the surface finish of the shaft. In non-conventional metal removal process of wire EDM, the Taguchi DoE forms a effective tool for optimizing the input process parameters to achieve maximum metal removal rate and minimum surface roughness [35]. Hence, DoE is a powerful experimental optimizing tool for determining the optimal process parameters and stabilizing the process.

2.10. DMAIC Methodology

The DMAIC approach is a part of six sigma philosophy and is a step-by-step approach consisting of five layered stages. Hwang [36] elaborated on the detail process of DMAIC and formulated simple flowcharts showing the different phases of DMAIC path. Generalized results were obtained in the form of a guiding tool for tracing the DMAIC path for obtaining improvements in quality assurance sector of any firm. Table 3 describes the different stages of DMAIC methodology.

Table 3. Stages in DMAIC methodology.

Stage No.	Abbreviation	Stage	Description
1	D	DEFINE	Defines the problem and the project charter along with the timelines. Identification of the CTQ characteristic.
2	M	MEASURE	Collection and measurement of raw data pertaining to the identified CTQ characteristic.
3	A	ANALYZE	Processing of data collected in the Measurement phase and employing analytical and optimizing tools.
4	I	IMPROVE	After Analysis phase, experiments are re-conducted and fresh data is collected to register noticeable improvement in the manufacturing process.
5	C	CONTROL	Controls the process by employing process monitoring charts and control charts, in order to prevent the process from degeneration.

In electronics industry DMAIC approach is traced for quality improvement in printed circuit board (PCB) [32]. Here the focus is set on improving the process capability levels of printed circuit board screening process, to greater than or equal to 1.33 i.e., up to 4 sigma levels, which is the industrial benchmark. In the similar lines, DMAIC finds its application in improving the capability of the solder paste printing process of printed circuit boards (PCBs) [37], by reducing the solder paste thickness from a nominal value. The problem of integrated circuit (IC) delamination poses a major challenge in the quality assurance of electronic component manufacturing industry [38]. DMAIC approach is followed for suppressing this problem and for achieving a better quality control plan for the IC assembly process. With the advent of touch-screen products, the thin-film transistor liquid crystal displays (TFT-LCDs) imposes a major problem of fracture resistance property [39]. The six-sigma DMAIC methodology is followed for increasing and optimizing fracture resistance of the TFT-LCDs displays.

In optical fibre industry [34], product quality improvement is achieved by improving the process of strip force of optical fiber and by determining the correlation factors that affect the processes of quality of optical fiber. DMAIC procedure is employed for achieving the same. In the injection molding of optical lens with good surface contour precision [40], process parameters are standardized using the DMAIC procedure.

Gentili et al. [41] applied the DMAIC procedure for a mechanical manufacturing process flow, which manufactures knives. Sahey et al. [25] once again brought the DMAIC approach into use for analyzing the manufacturing lines of a brake lever manufacturing company at Connecticut. Six sigma DMAIC methodology is combined with Lean production techniques [42] for realizing process improvements in brass extrusion and drawing production lines. Further to this, the DMAIC application is seen in various streams namely: reduction of defects in rubber gloves manufacturing process [43], improvement in shopfloor production quality by amending heat-treatment fixtures [44], reduction of cost of poor quality due to deviations in bearing fitment of cooling fan [45], reduction in rejection rate of cycle chain bush in a cycle chain manufacturing unit [46].

DMAIC framework is adopted for improving foundry quality [47]. Two decision tree algorithms namely, Classification and Regression Tree and Chi-squared Automatic Interaction Detection are adopted for reduction in casting defects. The Taguchi's method of experimental design is combined with DMAIC [48] for improving the green sand casting process and reducing process variations.

The field of engine manufacturing involves multi CTQ characteristics for simultaneous control. This is made possible by tracing the DMAIC approach to solve the deviations in the thrust face grinding operations of the connecting rod machining process [11] and deviations in the crankshaft stub-end hole diameter of the crankshaft manufacturing process [12]. The valve guide length and valve stem clearance are the CTQ characteristics which are needed to be maintained during the exhaust valve manufacturing [49]. DMAIC procedure is traced for achieving the desired process capability levels during the exhaust valve manufacturing.

Examinations are conducted to integrate lean Principles with six-sigma DMAIC methodology [50], as a coherent approach to continuous improvement. Standard framework for lean six sigma has been devised. On a whole, in automotive industry, selection of six sigma project is very crucial. In this process, a Fuzzy Analytic Hierarchy Process (FAHP) technique is devised for project selection in the Define Phase of six sigma DMAIC process [51].

It can be summarized that, the six sigma DMAIC process started with an initiation of change in the outlook of the manufacturing companies from final quality inspection to the in-process inspection. The manufacturing companies initiated the thought of, in-process control and statistical process control. Through the six sigma DMAIC philosophy, a tremendous change in the outlook of the manufacturing companies from final quality inspection to the in-process inspection is observed. In order to sustain the fierce competition, the firms started the cost-cutting measures by improving the related process. This leaded to change in thinking of managers from, after the defect "detecting" ideology to before the defect "preventive" ideology, which is the life-line of six-sigma DMAIC philosophy [52].

3. Conclusion

In-process inspection is by-far better than end inspection of components for acceptance sampling in the manufacturing sector. On realizing this fact, many manufacturing firms have started employing the process monitoring charts for in-process control. The basic process capability indices namely the process potential capability index (Cp) and the process performance capability index (Cpk) were then calculated and compared with the industrial benchmark. Hence, the industrial trend started a strategic shift from the acceptance sampling to in-process control, with the philosophy that if the process at every stage is capable of manufacturing dimensionally correct components, then the final product or outcome of the process is bound to be matching the set quality standards. This work captures enhancement in quality assurance through process capability improvement work performed in varied areas of industrial manufacturing. In every research paper referred here it has been observed as a whole, that, there is a strategic shift from end inspection to in-process control for minimizing the defects. The further scope of study is in developing a self-sustaining process capability model wherein the bottom line operators and workers of the manufacturing sectors are trained to be as knowledgeable employees. These front-line knowledge employees are the ones who anticipate the changes in the process beforehand in order to prevent the process from deviations and bring in the concept of zero defects into reality.

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