Continuous improvement of injection moulding using Six Sigma: case study

Article *in* International Journal of Industrial and Systems Engineering · January 2019
DOI: 10.1504/IJISE.2019.10021839

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Abstract: Plastic injection moulding is considered as one of the very challenging processes to obtain output with a good quality and low cost. This paper presents a case study of the deployment of Six Sigma in plastic injection moulding to improve the quality of the final product by eliminating major defects occurred using cost effective methods. The main objective is to identify the major quality problems and to eliminate root causes by adopting Six Sigma define, measure, analyse, improve and control (DMAIC) methodology. The proposed Six Sigma approach effectively integrates quantitative and qualitative tools such as statistical process control (SPC) charts, Pareto chart, histogram, Ishikawa diagram, measurement system analysis, hypothesis test and checklist to achieve the desired goal. The results reveal that the implementation of the proposed Six Sigma approach can reduce the rejection rate significantly. It is found that the quality of the final products is substantially improved in terms of sigma level which increased from 4.06 to 4.5 and the cost of poor quality (COPQ) is reduced by 45%.

Keywords: Six Sigma; define, measure, analyse, improve and control; DMAIC; statistical process control; SPC; injection moulding.

Reference to this paper should be made as follows: Maged, A., Haridy, S., Kaytbay, S. and Bhuiyan, N. (2019) 'Continuous improvement of injection moulding using Six Sigma: case study', *Int. J. Industrial and Systems Engineering*, Vol. 32, No. 2, pp.243–266.

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1 Introduction

Injection moulding is one of the most important manufacturing processes for the mass production of plastic parts with complex geometries (Birley, 2012). Injection moulding has been widely used to manufacture large and heterogeneous types of parts, from the smallest components to huge body panels of cars. It is considered as the most common technique for plastic production.

Most governments nowadays are addressing regulations for environmental and waste management issues revolving around the efficient disposal of defective material. The plastic injection moulding is one of the industries that have been burdened with these regulations. Many plastic injection moulding operations cannot avoid scrapping large amounts of non-conforming parts that cannot be reused again. Injection moulding waste, such as plastic scrap, can be very costly as well as time consuming to reclaim and reuse.

Plastic injection moulding defects can be described as: measurable, (e.g., dimensions) and attribute defects (mechanical properties) (Rosato and Rosato, 2012). The factors that affect the quality of a moulded part can be classified into six categories: part design, labour skills, mould design, machine performance, materials used and processing conditions. The part design is assumed to be established and fixed. The problems due to mould design can be minimised by using computer aided design (CAD)/computer aided manufacturing (CAM), injection moulding simulation and prototyping (Beaumont et al., 2002). Therefore, this article will not focus neither on part design nor mould design.

The relation between the inputs and outputs of the plastic injection moulding process was widely studied using regression analysis and analysis of variance (ANOVA) in order to identify its optimal parameters (Chen et al., 2014; Akbarzadeh and Sadeghi, 2011). Shen et al. (2007) optimised the parameters of the injection moulding process using a combination of artificial neural network and genetic algorithm method. Altan (2010) used a neural network generated model as a predictive tool for the shrinkage of the injected part. Timans et al. (2014) provided an optimisation method for improving the injection moulding processes in small and medium sized enterprises using design of experiments (DoE). Although these studies optimised the process stability, most production processes, quality characteristics may deviate from their target because of noise factors (Timans et al., 2014). These noise factors could be due to environmental conditions, (e.g., humidity), or small variations in machine settings, (e.g., variations in controlled set-points over successive machine cycles) or variations in material properties, (e.g., tensile strength). The high quality specifications in case of uncontrollable changes in processing conditions could not be satisfied.

This research proposes an integrated framework of both qualitative and quantitative analysis by which we can lower the effect of uncontrollable changes in processing conditions. The proposed framework will enhance the product quality and reduce the defective rate, which would in turn increase the customer satisfaction and profitability.

In this research, we aim to lower the output defective rate of the plastic injection moulding process using the Six Sigma methodology. The common types of defects are studied and their root causes are investigated. Recommendations for improvement are suggested and applied. The resulting defective rate is compared to the historical one and a control plan is proposed to sustain the enhanced quality and gain obtained.

2 Six Sigma

Six Sigma can be simply defined as a methodology used to reduce the defects by identifying sources of variation and eliminating them and to mistake proof the processes that create value for the customer. This will lead to yield improvement and higher quality of the final product which accordingly will increase customer satisfaction (Su and Chou, 2008). Naumann and Hoisington (2001) pointed out that the concept of Six Sigma is the development of a regular way to measure and monitor the performance and set extremely high expectations and improvement targets.

Six Sigma focuses on optimising input variables to improve a process using proper data collection and statistical analysis which results in achieving the three main goals of Six Sigma: improve customer satisfaction, increase profitability and increase productivity (Lo et al., 2009). When operating at the Six Sigma level, the number of defects should be 3.4 defects per million opportunities (DPMO) (Sanders and Hild, 2000). Six Sigma has two main methodologies, define, measure, analyse, improve and control (DMAIC) which is used for existing processes and define, measure, analyse, design, verify (DMADV) which is used for designing new processes (De Feo and Barnard, 2003).

Since its initiation in industry by Motorola's Bill Smith two and a half decades ago relying on the philosophy, principles and methods of total quality management, Six Sigma has penetrated into most disciplines of today's business world (Bharti et al., 2011; Brady and Allen, 2006). Dedhia (2005) studied several firm experiences, including Samsung Electronics, American Express, Motorola, General Electric, the National Science Foundation and Du Pont and found that companies save an average of $100,000–200,000 per each implemented improvement project using the Six Sigma approach. Six Sigma has been applied in many manufacturing industries. Krishna and Dangayach (2007) implemented Six Sigma at an auto component manufacturing plant. Falcón et al. (2012) proposed the application of the Six Sigma methodology to improve the energy efficiency in a distillation unit of a naphtha reforming plant. The results showed a significant savings of around 150,000€/year.

Six Sigma usage has been extended to cover service providing corporations, (e.g., banking, healthcare, etc.). Wyper and Harrison (2000) deployed the Six Sigma methodology in human resources functions. Vijay (2014) reduced the patients discharge cycle time in a multidisciplinary hospital process using the Six Sigma DMAIC model. Gutierrez-Gutierrez et al. (2016) analysed the application of Six Sigma framework for supporting continuous improvement (CI) in logistics services which resulted in a significant improvement for the company and positively influenced its annual income.

The increasing interest of Six Sigma has led to an extensive study of its tools both statistical and managerial (Uluskan and Antony, 2016; Haridy et al., 2016; Sarkar et al., 2013).

3 Plastic injection moulding process

Injection moulding is a manufacturing technique to transform raw thermoplastic material into designed parts of a particular shape (Beaumont et al., 2002). In this process, the plastic is melted and injected at a high pressure into a mould. The mould is designed to be the inverse of the desired part shape. Based on type and grade, each plastic material is usually processed within a certain range of temperature and pressure correctly (Whelan and Craft, 2012). These are the key parameters of plastic processing.

Figure 1 Plastic injection moulding machine (see online version for colours)

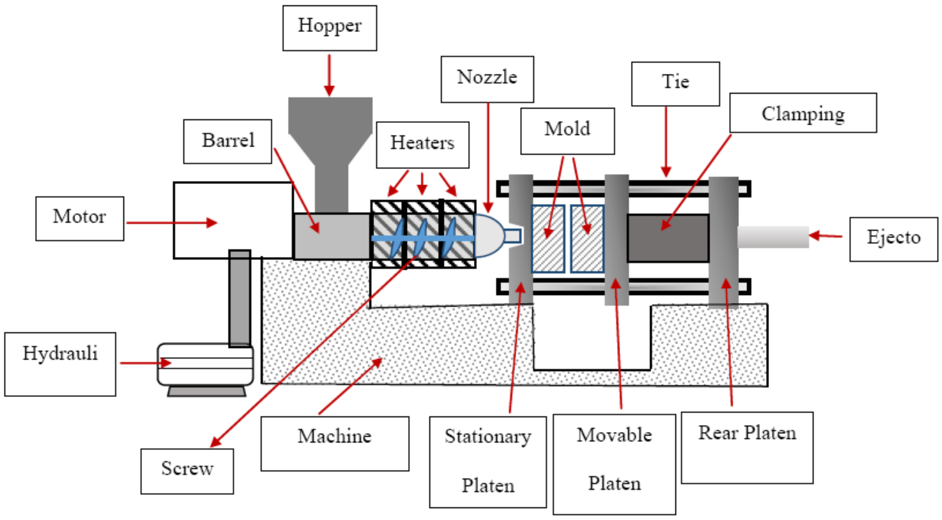


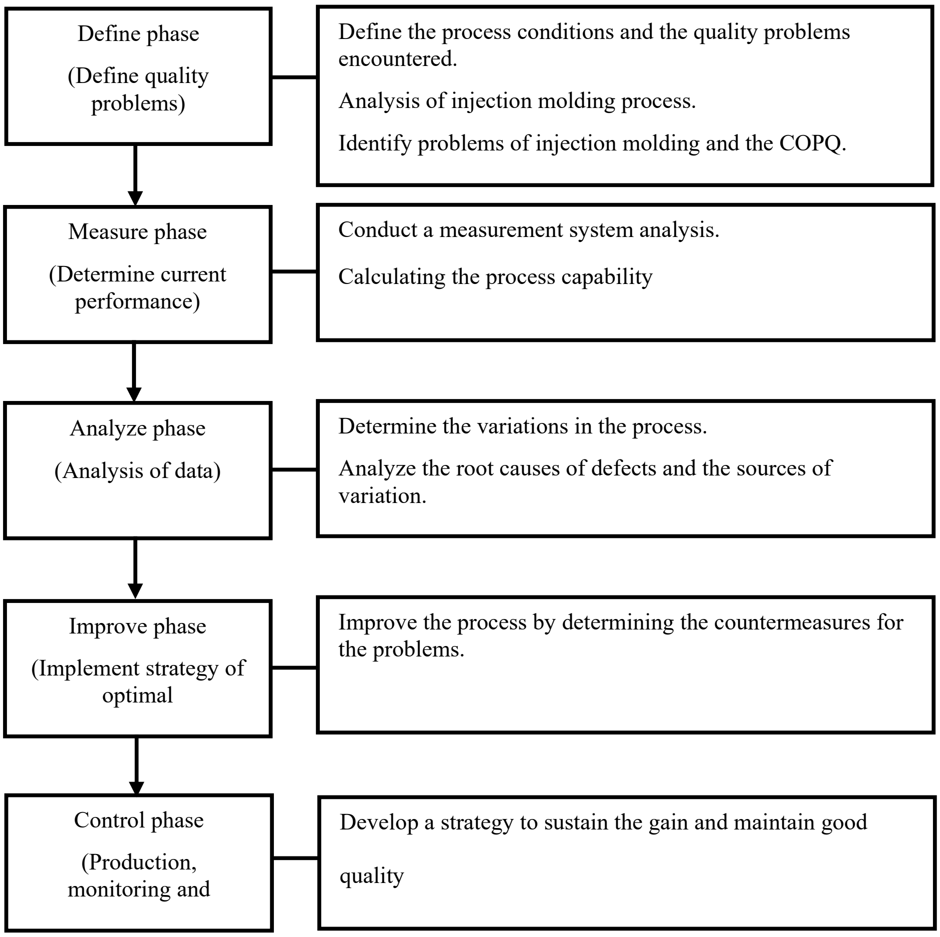
Figure 1 illustrates the parts of the plastic injection moulding machine. In the injection moulding machine, the raw material is fed to a hopper into a highly heated barrel with a reciprocating screw.

The raw material is melted by the heaters and the screw forces the molten plastic through a check valve to be injected to the mould at a high velocity and high pressure. The pressure is not lowered until the gate (cavity entrance) solidifies. The mould cavity temperature is reduced by a cooling line containing circulating water or cooling oil. Once the required temperature is achieved, the mould opens and the part is ejected and the cycle repeats (Malloy, 1994).

4 Case study

A case study was conducted in an engineering company in Egypt. This company has many sales outlets all over Egypt. The main products the company are blenders, choppers, irons, blowers and fans. Most of these products are mainly made of plastic parts. Consequently, plastic injection moulding has the largest share of all the manufacturing operations in this company. Due to the high cost of the scrap and the environmental regulations, it was necessary for the company to stop the money bleeding by lowering the scrap rate. Therefore, the company sought to use Six Sigma to lower the scrap rate and create an environmentally safe workplace. Figure 2 shows the Six Sigma DMAIC architecture used in this study. It can be considered as a road map for the process improvement (Kwak and Anbari, 2006).

Figure 2 Flow for DMAIC steps



4.1 Define

Three tasks must be undertaken during the define phase: finding a feasible project scope, setting up goals for the project and defining the project conditions. Due to the limitations of resources, the duration of this Six Sigma project cannot exceed six months. In this study, the essential goal of this project is to ensure a stable and robust production process, with a reduced number of non-conforming parts.

The process diagram of the injection moulding process is illustrated in Figure 3. The current problem of high rejection rate is defined. Table 1 shows the total number of rejected and accepted items and the cost of poor quality (COPQ). COPQ are the costs that would disappear if systems, processes and products were perfect (Harrington, 1987), The COPQ can be calculated by the multiplication of the number of defective items and the cost associated with each item. For example, COPQ of part FH447 = 2.213 × 3669 = 8120.

Table 1 Rejection data of the parts produced by injection moulding machines

Model no.	*Cost ($)*	*No. of rejected parts*	*No. of accepted parts*	*COPQ ($)*
FH5	4.435	774	30,663	3,433
FH7	0.358	466	22,637	167
MX10	0.175	215	9,092	38
FH9511	0.107	207	9,011	22
B293014	0.901	87	4,584	78
MX54	0.149	282	12,522	42
MBG104	4.268	78	3,813	333
FE109	0.206	1,326	56,691	273
FH95129	2.213	276	12,417	611
FE195	0.072	1,515	63,663	109
RG227	13.215	317	13,314	4,189
RG312	0.710	36	1,434	26
MX335	0.275	252	10,825	69
MX344	0.901	84	3,390	76
FE366	1.636	147	7,109	241
FH447	2.213	3,669	137,691	8,120
BXS536	0.854	27	1,342	23
GR594	0.072	150	5,904	11
BS605	13.215	480	22,050	6,343
DB610	0.710	228	9,528	162
Others	0.116	1,027	48,141	119

Figure 3 Injection moulding process diagram

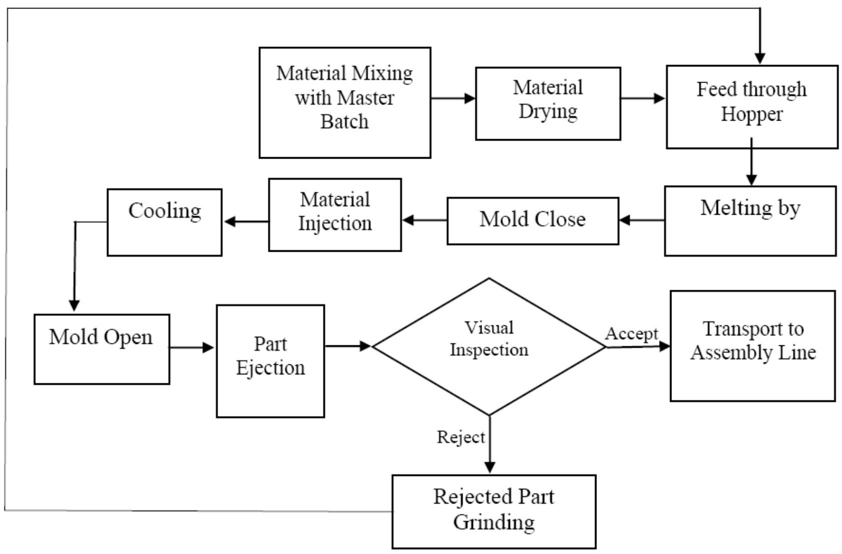


Table 1 reveals that the part named FH447 has the highest number of rejections which represents 33.2% of the total loss. Since this part has both the largest number of rejections and the highest COPQ, it will be our first priority and taken as the main studying element in this research.

Figure 4 3D model of part FH447 (see online version for colours)

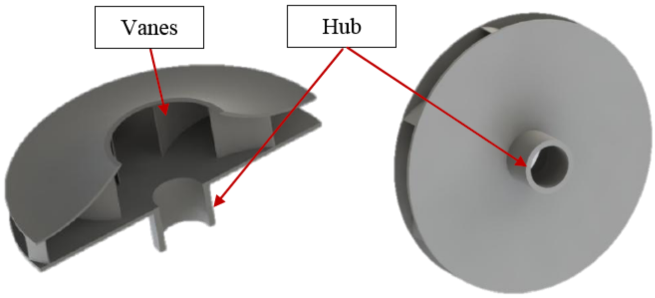
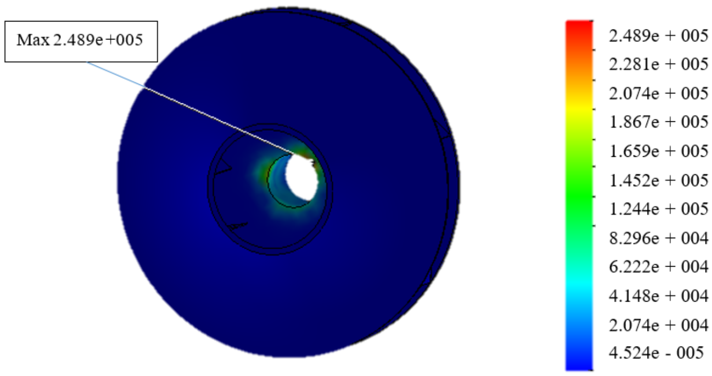
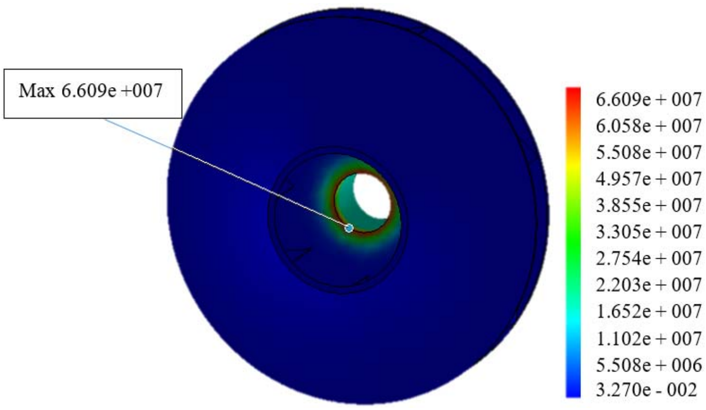


Figure 5 FEA for the impeller, (a) diameter of 10.90 mm (b) diameter of 10.89 (see online version for colours)



(a)



(b)

In order to be able to define the problem encountered by part FH447, the critical to quality (CTQ) characteristics should be clearly defined first. CTQs are the primary measurable characteristics of a product or a process. CTQs include the upper and lower specification limits or any other factors related to the product. Part FH447 is an impeller which is mounted on a shaft connected to a compressor. Consequently, the important CTQs in our case are that the internal diameter of the hub shown in Figure 4 meets the specification limits and that the part does not show any of the injection moulding defects that may affect the functionality of the impeller.

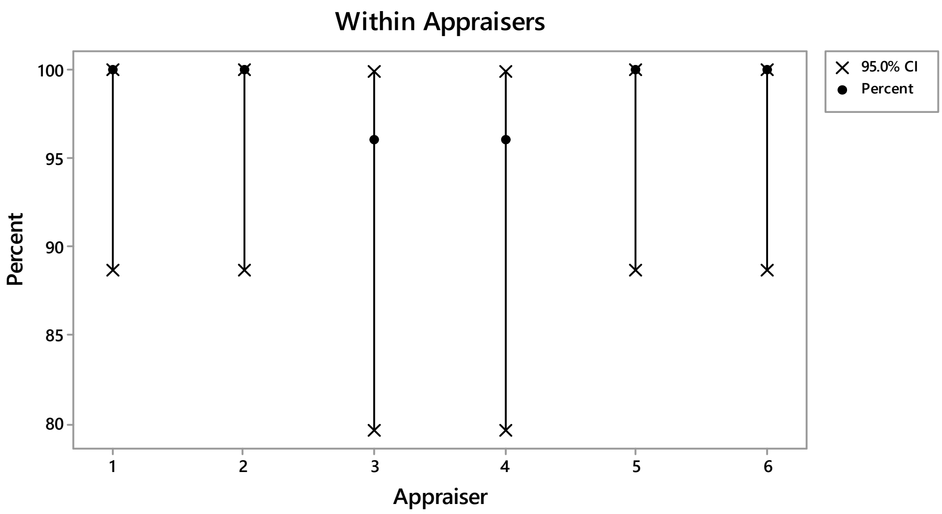
The upper and lower specification limits are defined by finite element analysis (FEA) (Stamatis, 2002; Meeker and Escoba, 2004). The lower specification limit is the lowest acceptable diameter and has a value of 10.90 mm as presented in Figure 5(a). A diameter lower than 10.90 can cause the crack shown in Figure 5(b) to appear and propagate, which will lead eventually to the failure of the impeller. The upper specification limit is the largest acceptable diameter that allows the impeller to be properly mounted on the shaft and it is equal to 11.09 mm.

4.2 Measure

The measure phase is attentive on selecting one or more essential product characteristics. Then, applying measurement system analysis (MSA), a measurement system (MS) is the collection of instruments, gages, operations, methods, software and personnel (Burdick et al., 2003). At last, making the necessary measurements and establishing a touchstone for evaluating the process performance.

The number of rejected parts having the code FH447 was collected for five months from January to May 2015 to track down the problems encountered. The part is inspected visually first and then a calliper tool is used to measure the hub diameter in millimetre.

Figure 6 Within appraiser variation



We need to determine if a MS is capable of assessing process performance in an effective and proper way. This can be achieved by conducting two studies, the first is attribute gage agreement analysis which is used to assure the appraiser's ability of discovering any attributed defect, (e.g. short shots, cracks, etc…) through the visual inspection and the second is gage repeatability and reproducibility (GR&R) for the calliper.

For the attribute gage agreement analysis, a sample of 15 items was inspected twice by six operators to decide whether the part is accepted (represented by A) or rejected (represented by B). The data are shown in Table 2.

Table 2 Results from visual inspection for agreement test

Sample no.	*Appraiser*											
	Appraiser A		*Appraiser B*		*Appraiser C*		*Appraiser D*		*Appraiser E*		*Appraiser F*	
	A-1	*A-2*	*B-1*	*B-2*	*C-1*	*C-2*	*D-1*	*D-2*	*E-1*	*E-2*	*F-1*	*F-2*
1	A	A	A	A	A	A	A	A	A	A	A	A
2	A	A	A	A	A	A	A	A	A	A	A	A
3	A	A	A	A	A	A	A	A	A	A	A	A
4	A	A	A	A	A	A	A	A	A	A	A	A
5	A	A	A	A	A	A	A	A	A	A	A	A
6	R	R	R	R	R	R	R	R	R	R	R	R
7	R	R	R	R	R	R	R	R	R	R	R	R
8	A	A	A	A	A	A	A	A	A	A	A	A
9	A	A	A	A	A	A	A	A	A	A	A	A
10	A	A	A	A	A	A	A	A	A	A	A	A
11	A	A	A	A	A	A	A	A	A	A	A	A
12	A	A	A	A	A	A	A	A	A	A	A	A
13	A	A	A	A	A	A	A	A	A	A	A	A
14	A	A	A	A	A	A	A	R	A	A	A	A
15	R	R	A	A	R	R	R	R	R	R	R	R
16	A	A	A	A	A	A	A	A	A	A	A	A
17	R	R	R	R	R	R	R	R	R	R	R	R
18	R	R	R	R	R	R	R	R	R	R	R	R
19	A	A	A	A	A	A	A	A	A	A	A	A
20	A	A	A	A	A	R	A	A	A	A	A	A
21	A	A	A	A	A	A	A	A	A	A	A	A
22	A	A	A	A	A	A	A	A	A	A	A	A
23	A	A	A	A	A	A	A	A	A	A	A	A
24	A	A	A	A	A	A	A	A	A	A	A	A
25	A	A	A	A	A	A	A	A	A	A	A	A

The results illustrated in Figure 6 show six vertical lines, one for each appraiser. The analysis is done using 95% confidence interval (CI). The graph shows that all six appraisers had the same decision they had in their previous judgment. Operators 3 and 4 showed the least agreement (about 95%). This score is more than the recognised standard for an attribute gage agreement analysis of 80% (Hung and Sung, 2011).

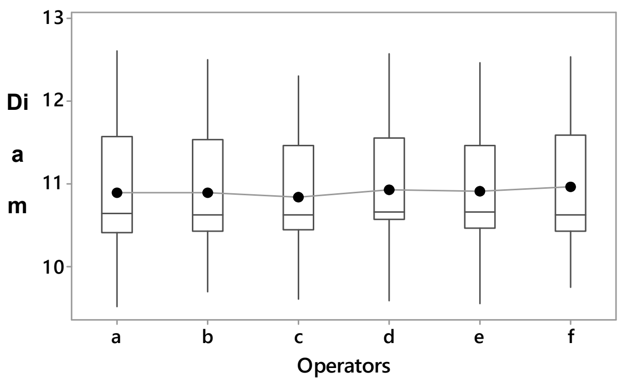
Table 3 Kappa statistics of the MSA

Appraiser	*Response*	*Kappa*
1	R	1.00000
	A	1.00000
2	R	1.00000
	A	1.00000
3	R	0.88345
	A	0.88345
4	R	0.88345
	A	0.88345
5	R	1.00000
	A	1.00000
6	R	1.00000
	A	1.00000

The results in Table 3 reveal that the lowest Kappa value is 0.88345 for both acceptance and rejection of measured parts. Kappa coefficient is a statistic which measures inter-rater agreement (Gwet, 2002; Cohen, 1960). It is considered to be a more realistic measure than simple percent agreement calculation, since it takes into account the possibility of the agreement occurring due to chance (Banerjee et al., 1999). This insures that the measuring system is reliable (Landis and Koch, 1977) and we can rely on it in any further conclusion taken by the measurements of these six operators.

For the GR&R, a good estimate of the process variation and the measurement variation is needed. Process variation is comprised by the part-to-part variation from the parts in the study. A sample size of ten items typically satisfies requirement for GR&R study (Tsai, 1988).

Figure 7 Reproducibility – operator's main effect



Measurement variation is estimated from the parts, it is broken down into Reproducibility and Repeatability. The number of parts in our study is 15 measured by six operators, which is adequate for repeatability and reproducibility estimation. To hold the GR&R study, a sample of 15 items was inspected twice by six operators. The data are shown in

Table 4. The results of the study are illustrated in Figure 7 and Figure 8. The reproducibility (main effect of the operator) is expressed in six whiskers each for one appraiser (Figure 7). It can be seen that all of them had the same readings excluding the outliers. Figure 8 shows the repeatability expressed by parts ranges and operator's ranges.

Table 4 Measurements of hub diameter using calliper for GR&R

Part no.	*Appraiser*					
	Appraiser A		*Appraiser B*		*Appraiser C*	
	A-1	*A-2*	*B-1*	*B-2*	*C-1*	*C-2*
1	11.604	11.585	11.539	11.637	11.619	11.424
2	11.459	11.548	11.106	11.509	11.713	11.658
3	12.608	12.077	12.022	12.280	12.309	12.163
4	11.772	11.672	11.553	11.540	11.205	11.268
5	10.503	10.439	10.465	10.324	10.486	10.377
6	10.402	10.127	10.577	10.332	9.974	10.489
7	10.136	10.526	9.916	10.537	9.950	10.487
8	10.036	9.963	9.968	10.376	9.625	9.722
9	10.591	10.631	10.540	10.647	10.615	10.660
10	10.640	10.643	10.606	10.563	10.604	10.614
11	10.599	10.655	10.605	10.635	10.599	10.616
12	10.716	10.700	10.707	10.695	10.700	10.712
13	9.540	9.705	9.718	9.941	9.831	9.793
14	11.108	11.073	10.965	11.002	10.881	11.440
15	12.145	11.813	12.195	12.518	11.932	12.265
Part no.	*Appraiser D*		*Appraiser E*		*Appraiser F*	
	D-1	*D-2*	*E-1*	*E-2*	*F-1*	*F-2*
1	11.611	11.499	11.530	11.348	11.553	11.602
2	11.520	11.546	11.460	11.645	11.687	11.604
3	11.915	11.959	12.141	12.250	12.049	12.158
4	11.589	10.640	11.170	11.575	11.539	11.632
5	10.597	10.661	10.389	10.505	10.509	10.389
6	10.809	10.649	10.401	10.517	10.417	10.442
7	10.110	10.469	10.496	9.574	10.291	10.110
8	9.824	10.616	10.288	9.719	10.596	10.291
9	10.680	10.547	10.654	10.718	10.638	10.646
10	10.627	10.572	10.591	10.605	10.612	10.623
11	10.618	10.611	10.583	10.641	10.621	10.557
12	10.711	10.708	10.718	10.704	10.698	10.714
13	9.765	9.614	9.743	9.747	9.762	9.786
14	11.641	10.943	11.445	11.465	11.288	11.528
15	12.383	12.587	12.408	12.480	12.459	12.545

Figure 8 Repeatability expressed by ranges

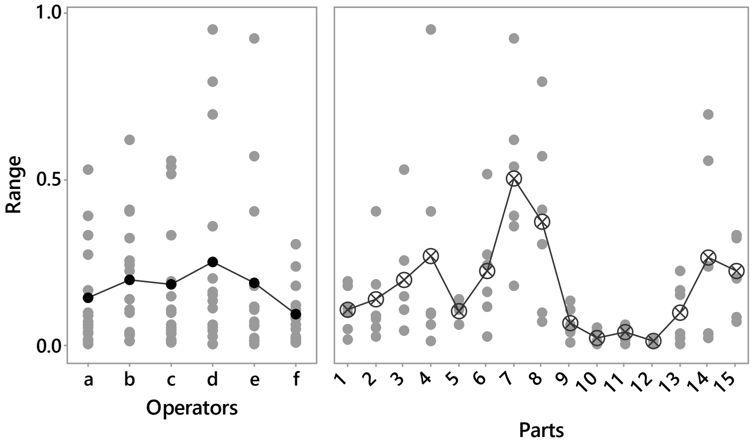


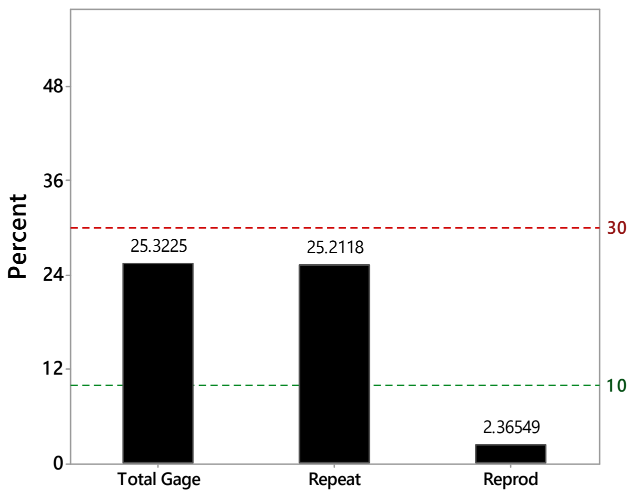
Table 5 ANOVA of the GR&R analysis

Source	*DF*	*SS*	*MS*	*F*	*P-value*
Part	84	98.042	1.16717	31.0686	0.000
Reproducibility	5	0.242	0.04843	0.0415	0.999
Repeatability	90	3.381	0.03757		
Total	179	101.665			

The results of the ANOVA for GR&R study are indicated in Table 5 where DF, SS and MS stand for degrees of freedom, sum of squares and mean of squares respectively.

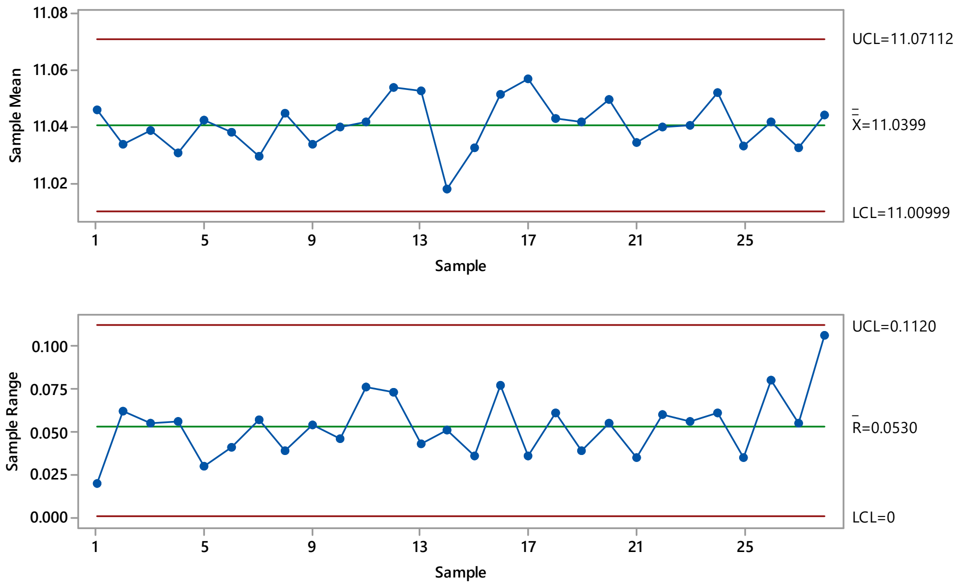
The output reveals that 'part' is the source with the lowest p-value which means that most of the variation in the measurement is due to the part to part variation. This insures that the measuring system is reliable and we can rely on it for any further conclusions.

Figure 9 Contribution of repeatability, reproducibility and total gage in the system (see online version for colours)



The GR&R analysis is summarised in Figure 9 which emphasises the contribution of repeatability and reproducibility in the overall variance due to gauge and the contribution of the gauge to the variance in the whole system.

Figure 10 Phase 1 control chart (see online version for colours)



After performing the MSA and ensuring that the MS is acceptable, a process capability analysis is conducted. Before performing the capability analysis, a phase 1 control chart monitoring the hub diameter is used to ensure that the process is in control as shown in Figure 10. Meanwhile, it is found that the data can be well approximated by a normal distribution (p-value = 0.481) with $\mu_0 = 11.0399$ and $\sigma_0 = 0.021$. The capability analysis is evaluated using the process capability index C_p as follows:

$$C_p = \frac{USL - LSL}{6\sigma} = \frac{11.09 - 10.09}{6 \times 0.021} = 1.42 \quad (1)$$

This ensures that the process is capable of producing conforming items in phase 1 (Montgomery, 2007).

The next task is to find the potential influential factors that caused defects to the part of interest.

Table 6 Rejection data of part FH447

Month	*Output*	*Defective*	*DPMO*	*Sigma level*
January	53,551	1,193	3,713.0	4.18
February	53,850	1,507	4,665.0	4.10
March	57,376	1,203	3,608.0	4.19
April	54,870	1,751	5,319.0	4.06
May	58,412	1,838	5,245.0	4.06
Total	291,059	7,492		

Table 6 displays the total output of part FH447 over five months from January 2015 to May 2015, the number of defective parts produced, DPMO and sigma level for each month. It noticeable that the lowest value of the sigma level is 4.06 which is quite high compared to traditional processes, that is due to the CI track the facility is adopting. This process has already been optimised in a previous project using DoE which significantly increased the sigma level. The data in Table 6 will be used to track down the problems that led to high rejects of the part of study.

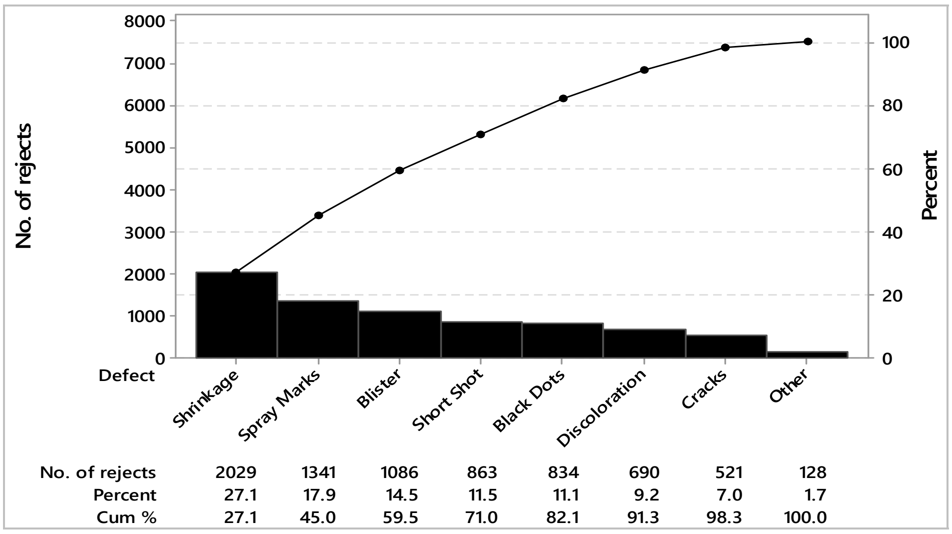
4.3 Analyse

The first step in this phase was to determine which defect to start with. All the defects associated with the part are defined in Table 7. Figure 11 illustrates the Pareto chart for the types of defects occurred in the months of the study and it shows that shrinkage defect is the major contributor to the rejection. Shrinkage contributes to 27.1% of the total rejects compared with other defects.

Table 7 Common defects in plastic injection moulding

Moulding defect	*Description*
Blister	Raised zone on the part surface.
Discoloration	Non-homogeneity in part colours
Black dot	Dirt spots on the surface of the part.
Cracks	Broken part.
Shrinkage	Change in the moulded part dimension while the machine settings remain the same.
Splay marks	Splash on part surface
Short shot	The part is produced but not in complete shape.

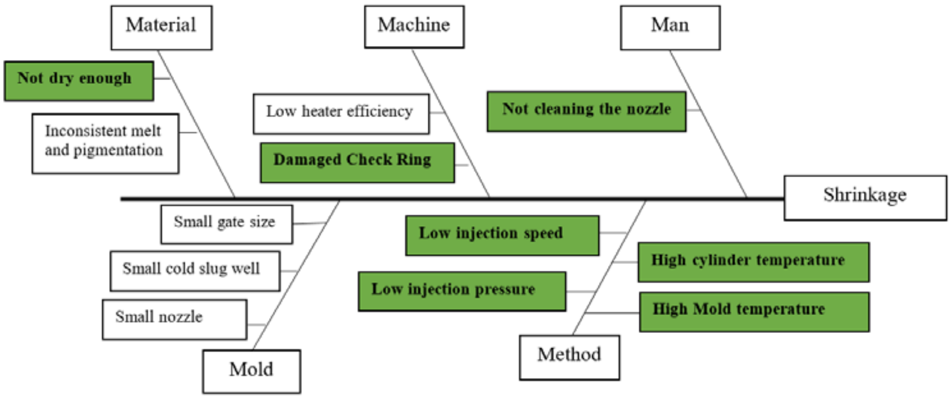
Figure 11 Pareto chart for number of rejects for part FH477



The significant deviation in the diameter of the hub is caused by shrinkage occurring in the injection moulding machine. Hence, the key variables of the injection moulding operation in which a hub hole to be produced had to be studied. Then, the Six Sigma project team participated in brainstorming sessions and identified the causes and key variables that affect it.

Through brainstorming sessions, all the causes and key variables were pictorially plotted using a cause and effect diagram. Then the causes which have no effect on the defect were eliminated. For example, when we suspected that the small nozzle is causing shrinkage defect we measured the nozzle size and rechecked its design specifications which were found to be accurate. The root causes of the defect that need to be taken care of are highlighted in green. The cause and effect diagram is depicted in Figure 12.

Figure 12 Cause and effect diagram of the shrinkage defect (see online version for colours)



At the end of this phase, the team members identified with three actions to be considered, these actions will be discussed in the next section.

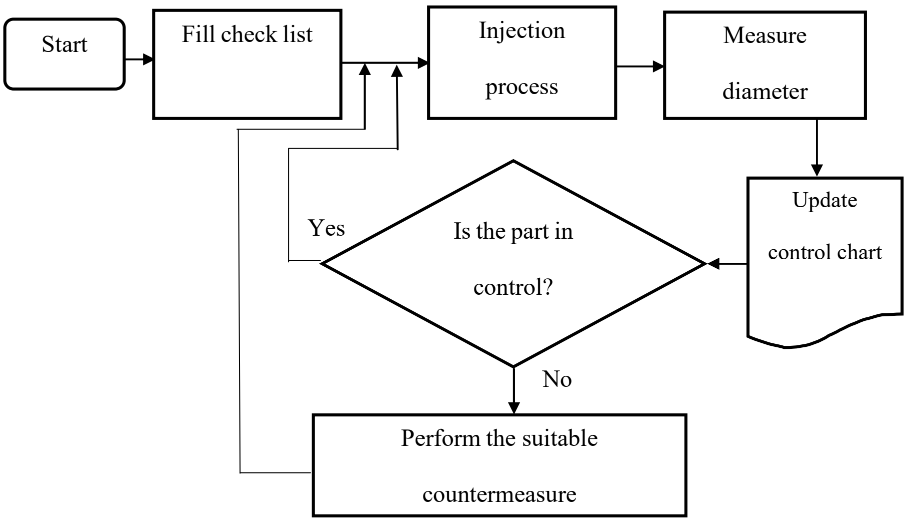
4.4 *Improve*

The most difficult part of the Six Sigma process is perhaps the Improve phase. An action plan is made and executed to eliminate the root causes that led to the shrinkage defect and to increase the ability to detect them as quick as possible.

The main improvement strategy is centred upon that we should predict when the shrinkage will take place. Then, decide what actions should be taken if it occurs, in order to fix the problem and avoid the occurrence of the defect in future. This procedure will consequently lower the defective rate. In other words, the improvement of the process is based on the early detection of the problem using the optimal control chart, then performing countermeasures. The countermeasures are directly built on the root cause analysis. Instead of working on a single root cause, we found that performing the countermeasures can easily remove the root cause getting the process to be in control again.

An overview of the architecture to control the output quality of the injection moulding machine is presented in Figure 13. At the start, a check list is filled to provide a standard operating procedure (SOP) for every shot; the diameter of the impeller is measured and plotted on a control chart to provide a continuous monitoring of the process output. If the process is out of control, the machine inputs are adjusted so as to improve the quality of the part through better set points, (e.g., melt temperature and melt pressure) providing a feedback of part's quality. If the process is in control, nothing will change and the control process will continue as it is. This will provide more precise control on the shot.

Figure 13 System diagram of injection moulding quality control



The control chart here is used as a monitoring tool based on which we decide whether to apply the countermeasure or not. In other words, if the values of diameter we monitor are within the control limits, no action will be required. On the other hand, if the control chart signals, the operator will need to apply the suitable countermeasure.

In this case study, the team is interested in detecting the two-sided mean shift and an increasing variance shift. The internal quality team currently uses a traditional 3-σ $\overline{X}\&R$ chart (with $n = 5$) for monitoring x. The team investigates designing an optimal $\overline{X}\&R$ chart to detect the process shifts more efficiently.

Using the proposed framework by (Haridy et al., 2016) to carry out the design of any of the above chart, the following three specifications have to be determined beforehand:

1 the minimum allowable value (τ) of the in-control average time to signal ATS0.

2 the allowable inspection rate (r)

3 the mean values μ_{δ_μ} and μ_{δ_σ} of the random shift in mean and standard deviation, respectively.

The value of τ is decided with regards to the tolerable false alarm rate. The value of r is equal to the ratio between the average sample size n and the sampling interval h and depends on the available resources such as manpower and measurement instruments. Usually, only the in-control (or long run) value of r is considered, because a process often runs in an in-control condition for a long period and only occasionally falls into an out-of-control status for a short time period. The inspection rate in the short out-of-control period has little influence on the long run value of r and is of much less concern (Arnold and Reynolds, 2001).

It is assumed that the random shifts δ_μ and δ_σ follow a Rayleigh distribution. This distribution is often used to characterise the positional deviation from a target in geometrical tolerance. It was adopted to model the mean shift of a normally distributed random variable (Wu et al., 2002).

The traditional 3-σ $\bar{X}\&R$ chart used in the factory gives a false alarm rate of 521. Hence, the 3-σ $\bar{X}\&R$ and optimal $\bar{X}\&R$ charts were designed under τ = 521 for a fair comparison and μ_{δ_μ} and μ_{δ_σ} were estimated from the historical out of control data (Haridy et al., 2013) and were found to be 2.532 and 3.541, respectively. The values of the charting parameters can be found in Table 8 where *UCL* and *LCL* are the upper and lower control limits for the $\bar{X}$ chart and H are the upper and lower control limits for the R chart respectively and the average extra quadratic loss (AEQL) values. The index AEQL is a performance measure used to measure the overall performance of the control charts over a wide domain of shifts rather than at a specific shift. The AEQL directly relates the chart performance with the economic outcome based on Taguchi's loss function (Ross, 1988). The AEQL values for both charts are indicated in Table 8. The smaller the AEQL, the better the chart is. It is found that the optimal $\bar{X}\&R$ chart has a sample size n of 2 and outperforms the traditional chart by 59% in terms of AEQL.

Table 8 Comparison between 3-σ $\bar{X}\&R$ and optimal $\bar{X}\&R$ charts

Chart	*Charting parameters*					*AEQL*
	n	*h*	*UCL*	*LCL*	*H*	
3-σ $\bar{X}\&R$	5	5	11.074	11.003	0.134	56.922
Optimal $\bar{X}\&R$	2	2	10.978	11.099	0.125	33.984

It is now the turn to provide some countermeasures to apply whenever a defect takes place. Based on the analysis done, the following countermeasures in Table 9 were executed to correct the problem and reduce number of rejections due to the shrinkage defect. To ensure that all the precautions are taken before the injection moulding process is done; the checklist illustrated in Figure 14 is posted on injection moulding machines and has to be filled out by the operator in each working shift.

Now, we need to determine whether these qualitative and quantitative countermeasures can achieve the desired change and lower the defective rate. Although the workers reported a marked improvement in the machine output, it is necessary to be statistically proven that there is a significant reduction in the number of defects. In order to make sure of that, the number of rejected parts in May (which had the highest number of rejects) and in June (after the improvement phase) is shown in Table 10 and represented by NP control chart in Figure 16. These data were used to hold a hypothesis t-test between the number of defective parts before and after applying the Six Sigma approach, as shown in Table 11. Table 10 shows the day to day number of defective parts and the sigma level in May and June, while Figure 16 illustrates the number of defects in both charts as well.

Table 9 Countermeasures against shrinkage

Countermeasures
Clean the machine with commercial decontamination material or remove screw and clean barrel.
Search for any dirt or contamination sources such as dead spots and remove it.
Remove excessive moisture and ensure that raw material is completely dried.
Keep the raw material away from moisture and in dry inventory.
Reduce regrind input
Inspect the check ring if it is broken or worn out
Make sure the mould temperature is uniform by checking the cooling system.
Decrease cylinder temperature.
Increase holding pressure.
Decrease injection pressure.
Increase injection speed.
Decrease overall cycle time.
Decrease mould temperature.

Figure 14 Check lists of all the precautions taken before the injection moulding process

Check list

Date: / / . **Shift:** . **Part Name:** .

Note that these checks are done at the start of each shift or change of mold

- [ ] Clean the nozzle
- [ ] Clean the cylinder
- [ ] Check for the standard cylinder temperature
- [ ] Check for the standard runner temperature
- [ ] Check for the standard injection speed
- [ ] Check for the standard rotating speed
- [ ] Check the cooling system

Labor Name

Table 10 The daily number of rejected parts before (in May) and after the improvement phase (in June)

																Total	*Sigma level*
Before	61	58	63	74	65	60	58	59	61	54	53	63	65	61	64	1,838	4.06
	56	62	66	49	59	57	63	64	64	59	56	71	58	70	65		
After	22	9	11	21	13	18	17	22	16	26	20	20	12	24	19	526	4.50
	18	11	17	16	13	18	14	14	27	16	18	23	20	17	14		

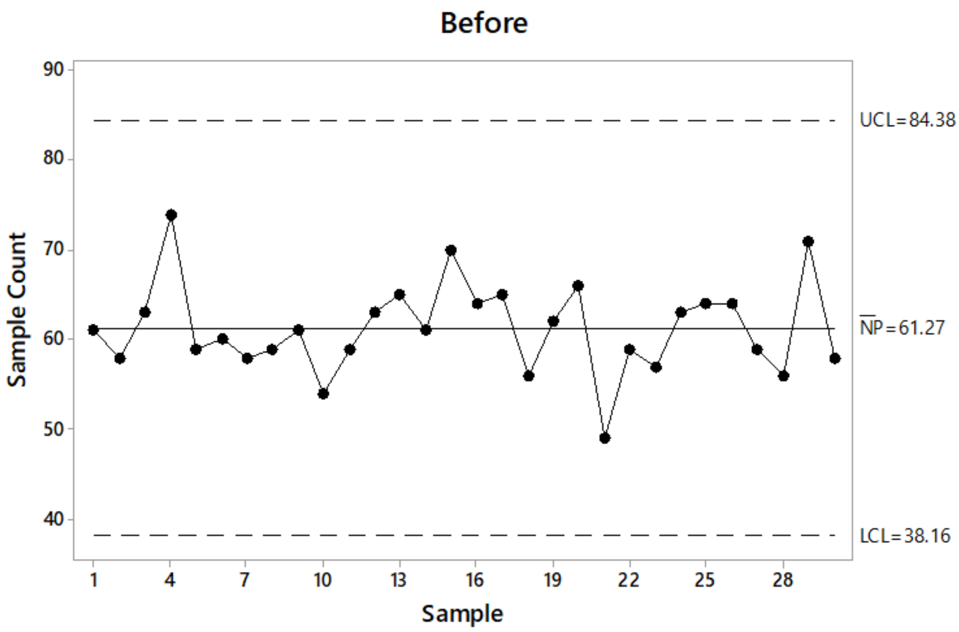
The results in Table 11 showed a low p-value which implies that we should reject the null hypothesis (H_0) and accept the alternative hypothesis (H_1), hence there is a significant difference between the number of defectives before and after the improvement action.

Table 11 T-test between the monthly amount of rejection before and after applying Six Sigma

N	*Mean*	*Standard deviation*	*Difference*	*95% lower bound*	*T-value*	*P-value*	
Before	30	61.27	5.09	43.74	41.66	35.33	0.000
After	30	17.53	4.48				

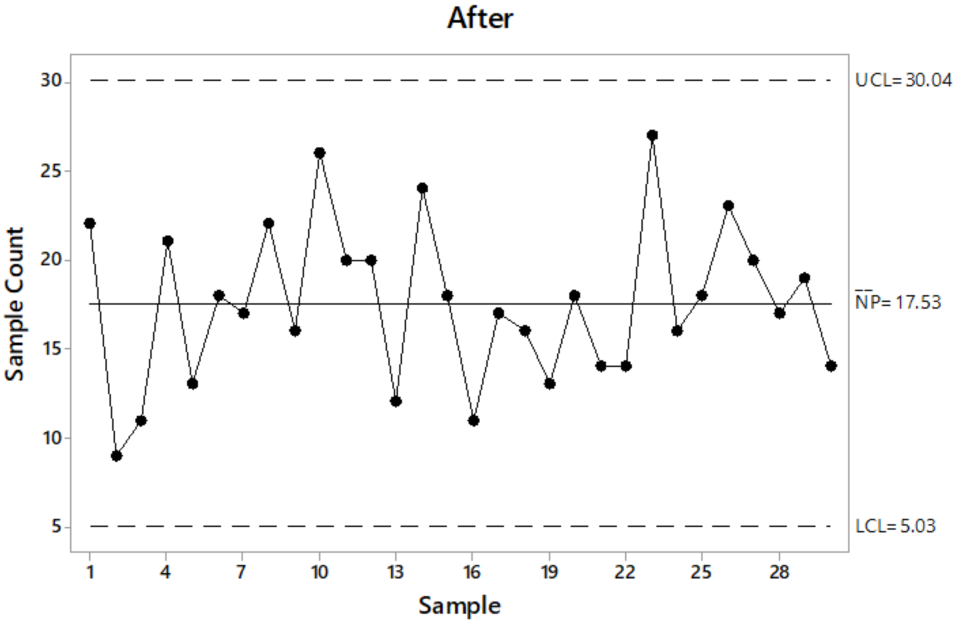
The test indicates that the monthly number of rejections after applying the Six Sigma project is less than the monthly number of rejections before the Six Sigma project. In summary, by increasing the detection effectiveness and eliminating the root causes for the shrinkage, the reduction in rejections is three times better than it was before the project.

Figure 15 NP chart of defects before and after implementing six sigma



(a)

Figure 15 NP chart of defects before and after implementing Six Sigma (continued)



(b)

4.5 Control

The control phase is the last and final phase. Its sole purpose is to sustain the optimised results which are the real challenge for the Six Sigma methodology. This demands standardisation, constant monitoring and control of the optimised process.

Control charts are made so that the operator can take preventive action before the number of defective parts goes outside the control limits or have an improper trend. Monitoring the process helps to detect out-of-control signals and take the proper corrective action to avoid customer dissatisfaction.

An NP chart is used to capture the voice of the process as a whole. The NP chart works as an aiding tool beside the optimal $\bar{X} \& R$ chart to monitor the number of defective parts produced and to ensure that the whole process is on the right track. The NP chart was constructed as shown in Figure 15(b). It demonstrates that all the points are in control and falls within the specifications and that the variability has been significantly reduced. The NP chart here is used to monitor the

5 Conclusions

This study aims to improve the quality of the final product of a plastic injection moulding in a manufacturing plant and to lower the number of defective items produced through deploying the Six Sigma methodology. In this sense, the contribution of this research is to describe the impact of the Six Sigma approach integrating qualitative and quantitative tools to improve the performance of a plastic injection moulding process.

The main goal of the study is to implement the proposed approach easily without mathematical complication. However, the proposed approach was applied to only one defect and one part (FH447) and it showed very good results.

It is found that the quality of the final products is substantially improved in terms of sigma level which increased from 4.06 to 4.5; the COPQ is reduced by 45%. In summary, the implementation of the Six Sigma structure lowered the rejection rate significantly.

Applying the proposed approach for different parts and different types of defects should be further investigated for generalising the approach.

Moreover, the developed Six Sigma approach can be extended to cover other manufacturing and service industries for the sake of enhancing the quality and eliminating the major defects.

Acknowledgements

This research is supported by the University of Sharjah, UAE, under Seed Research Project No. 1702040568-P. The authors sincerely thank the editor and reviewers for their constructive suggestions and valuable comments.

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