International Journal of Enhanced Research in Science, Technology & Engineering
ISSN: 2319-7463, Vol. 4 Issue 7, July-2015

Reduce short filling problem in Injection Molding

Ajit Singh[1], Lokesh Kumar[2]

[1,2]R.P.S.G.O.I, Mahendergarh, Haryana, India

Abstract

Purpose: To reduce short filling problem of doors in injection molding process at supplier end. This problem definition was studied over a six – month period and included an analysis of production yield and manufacturing costs.

Design/Methodology/Approach:

- What is the current state of short filling rejection in injection molding process?
- Determine the process capability of Shot weight, Core temperature, and cavity temperature.
- Calculate the Measurement system analysis and agreement of operators with the measurement instruments.
- Determine the source of variability that influences the short filling problem in doors used in HVAC assembly.

Findings: Total in house rejection PPM of Molding shop is 9150 PPM for the year 13~14 (June-13 to Mar-14) against budgeted target of 8,000 PPM. There are different parts making in the injection molding shop e.g., covers, doors, bracket, expansion valve etc. There is high rejection in Doors. Further scoping down the problem, we find that we have different models i.e., XA, XB, XC, Car and others. In model XA having the high rejection as compared to other models. In XA model we have five different parts i.e., 191, 192, 193, 195, 195. The part having 191 and 195 more rejection ppm as compared to other. Short filling, flow mark, flatness are the common defects in the doors named XA. Short filling problem is thus selected for the six sigma project.

Keywords: Six Sigma, Quality, Yield, injection molding.

1. Problem definition

To reduce short filling problem of doors in injection molding process at supplier end. This problem definition was studied over a six – month period and included an analysis of production yield and manufacturing costs.

2. Objectives

- What is the current state of short filling rejection in injection molding process?
- Determine the process capability of Shot weight, Core temperature, and cavity temperature.
- Calculate the Measurement system analysis and agreement of operators with the measurement instruments.
- Determine the source of variability that influences the short filling problem in doors used in HVAC assembly.

3. Selection of the problem

Total in house rejection PPM of Molding shop is 9150 PPM for the year 13~14 (June-13 to Mar-14) against budgeted target of 8,000 PPM. There are different parts making in the injection molding shop e.g., covers, doors, bracket, expansion valve etc. There is high rejection in Doors. Further scoping down the problem, we find that we have different models i.e., XA, XB, XC, Car and others. In model XA having the high rejection as compared to other models. In XA model we have five different parts i.e., 191, 192, 193, 195, 195. The part having 191 and 195 more rejection ppm as compared to others. Short filling, flow mark, flatness are the common defects in the doors named XA. Short filling problem is thus selected for the six sigma project. The graphs of the problem selection are shown below.

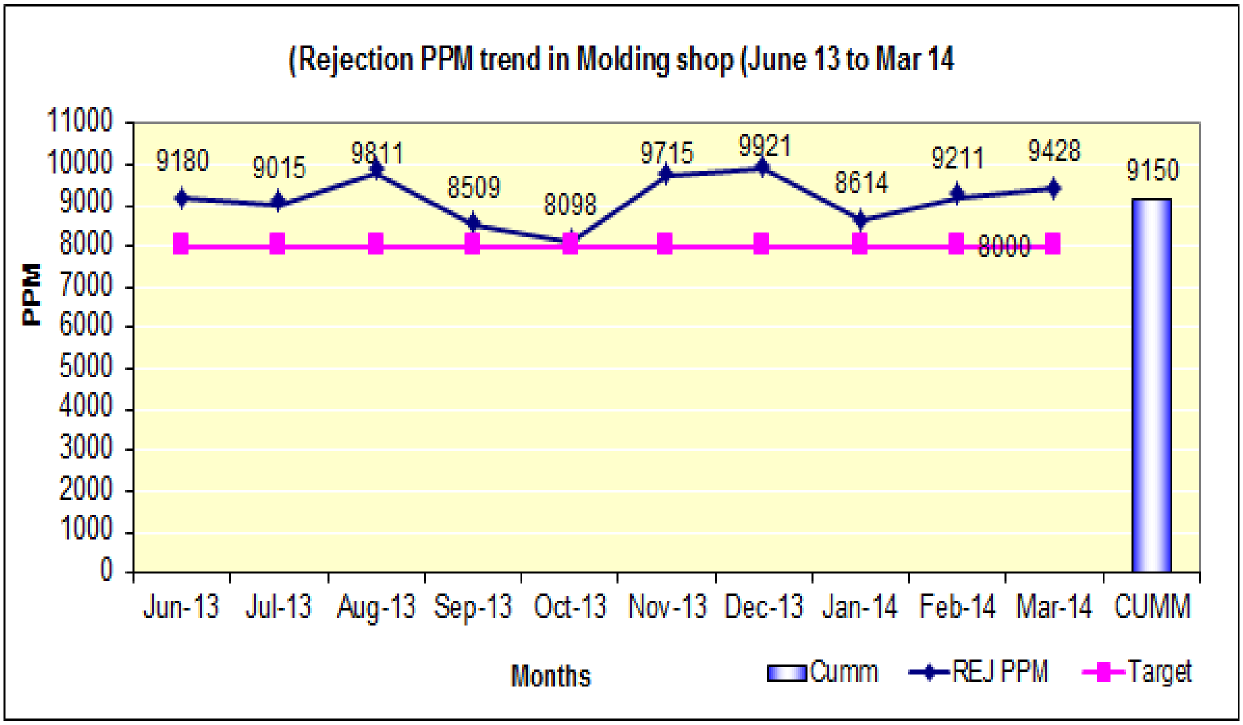


Figure 3.1 Run chart for rejection PPM (june 13 to march 14)

From the trend chart shown above we conclude that our rejection PPM is 9150 as compared to our budgeted target of 8000 PPM. Then we find the area where the problem exists in the company. This can be targeted by the scoping tree. We find that our main problem area is injection molding process. In injection molding process we have five main parts. Doors have the section in which the problem is more. We make doors for the five different models. The model named XA has the pain area. In XA we have five different parts, but 191 and 195 have the short filling problem. So, we select these two parts for short – filling problem.

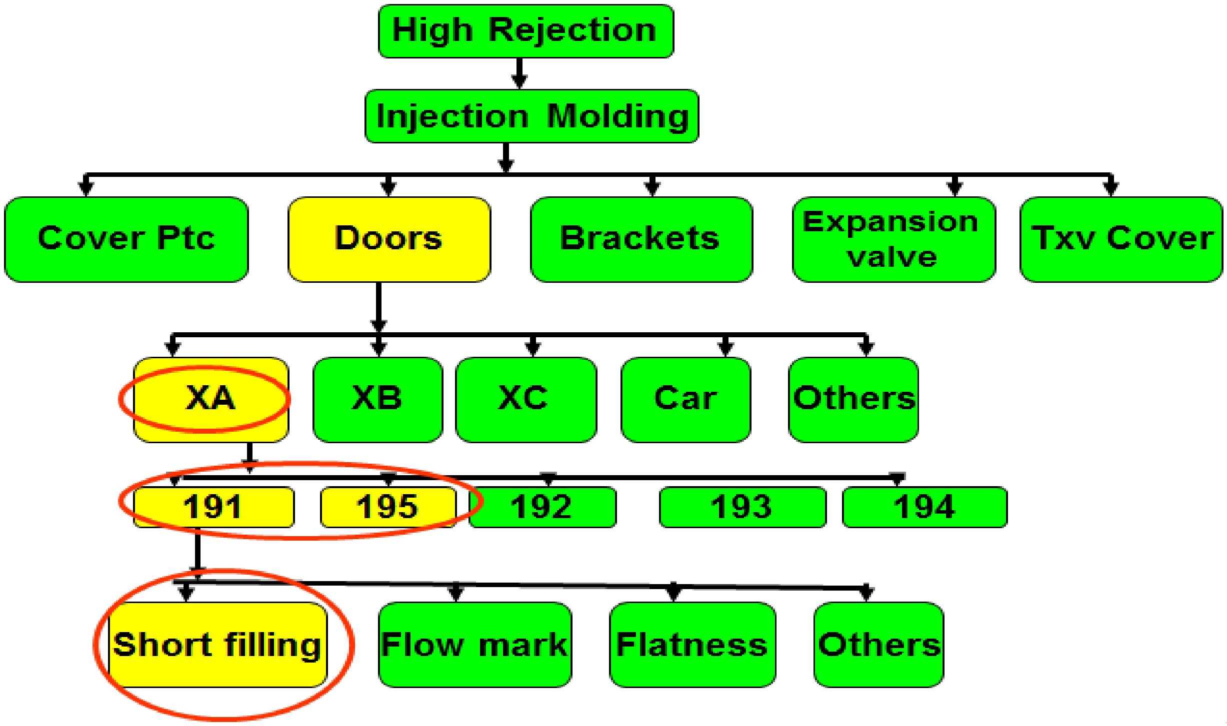


Figure 3.2 Scoping tree for the problem selection

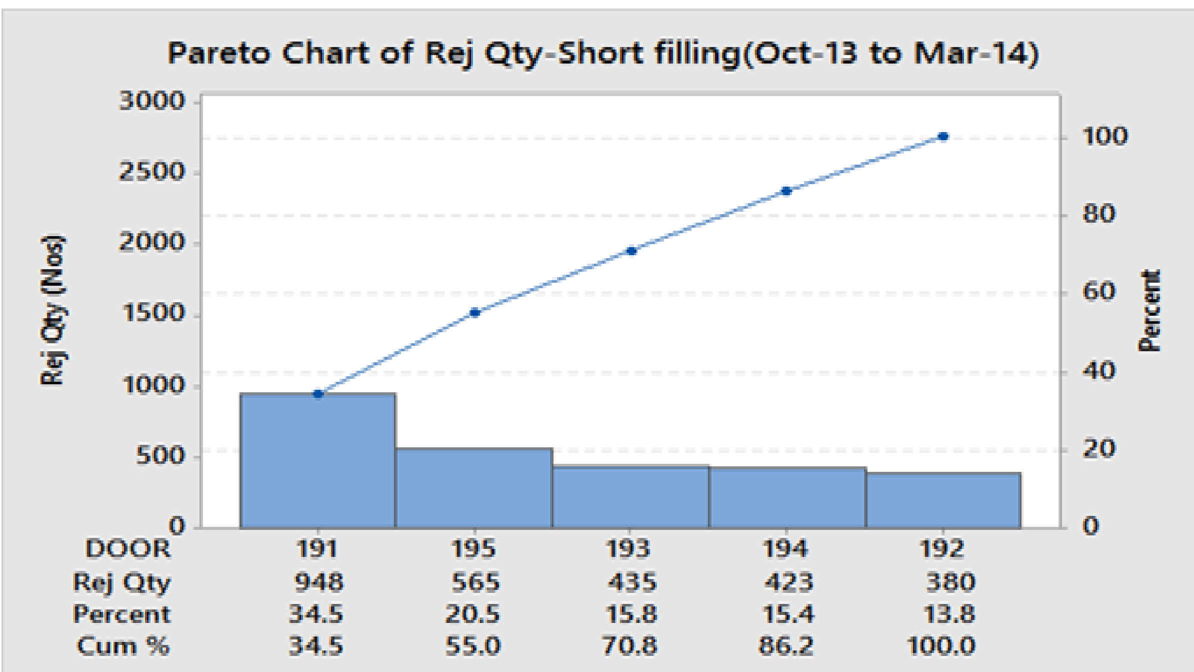


Figure 3.3 Pareto chart for rejection in Short-filling process (june 13 to march 14)

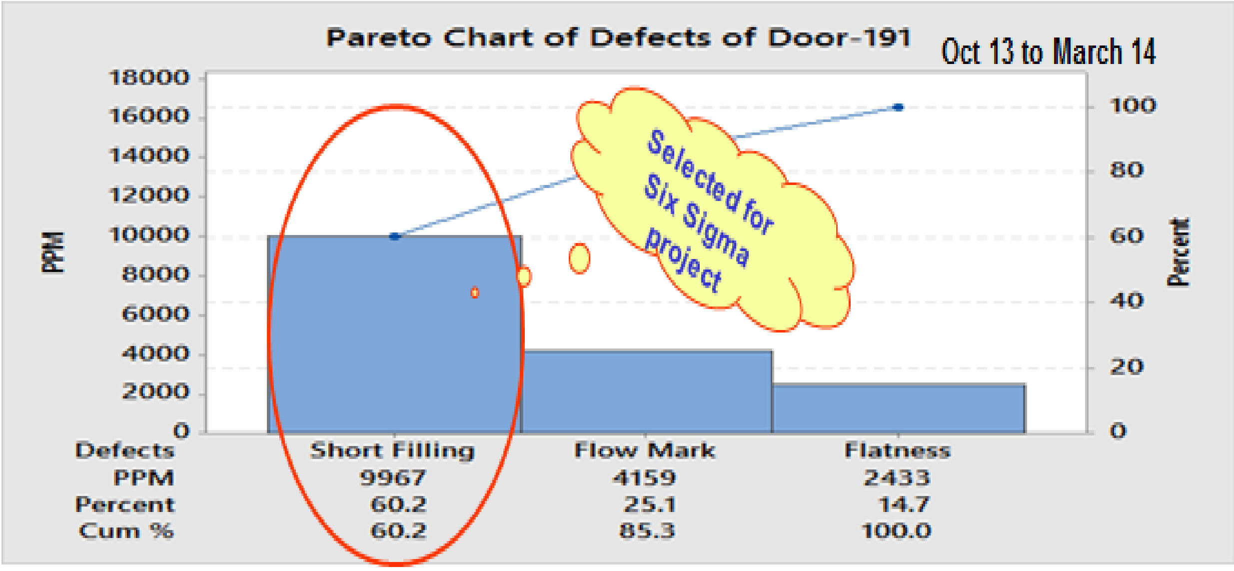


Figure 3.4 Pareto chart for the defect of Door 191.

4. Product detail

Doors are used to control air direction and flow in heating ventilation and air conditioning system (HVAC) assemblies of AC system of cars.

Figure 3.5 Product detail (a)

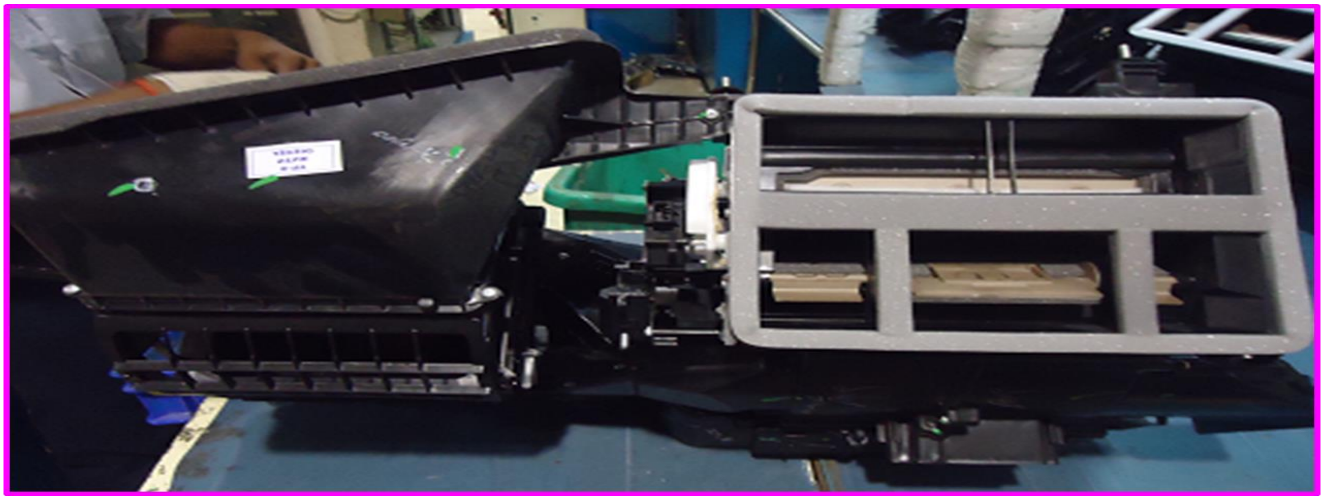


Figure 3.6 Product detail (b)

After selecting the problem area, we collect the data for the last six month and plot there trend chart. From there, we found that the problem is consistent outside the criteria having high PPM. We plot the trend chart for both the parts i.e., 191 and 195 shown in the figure below.

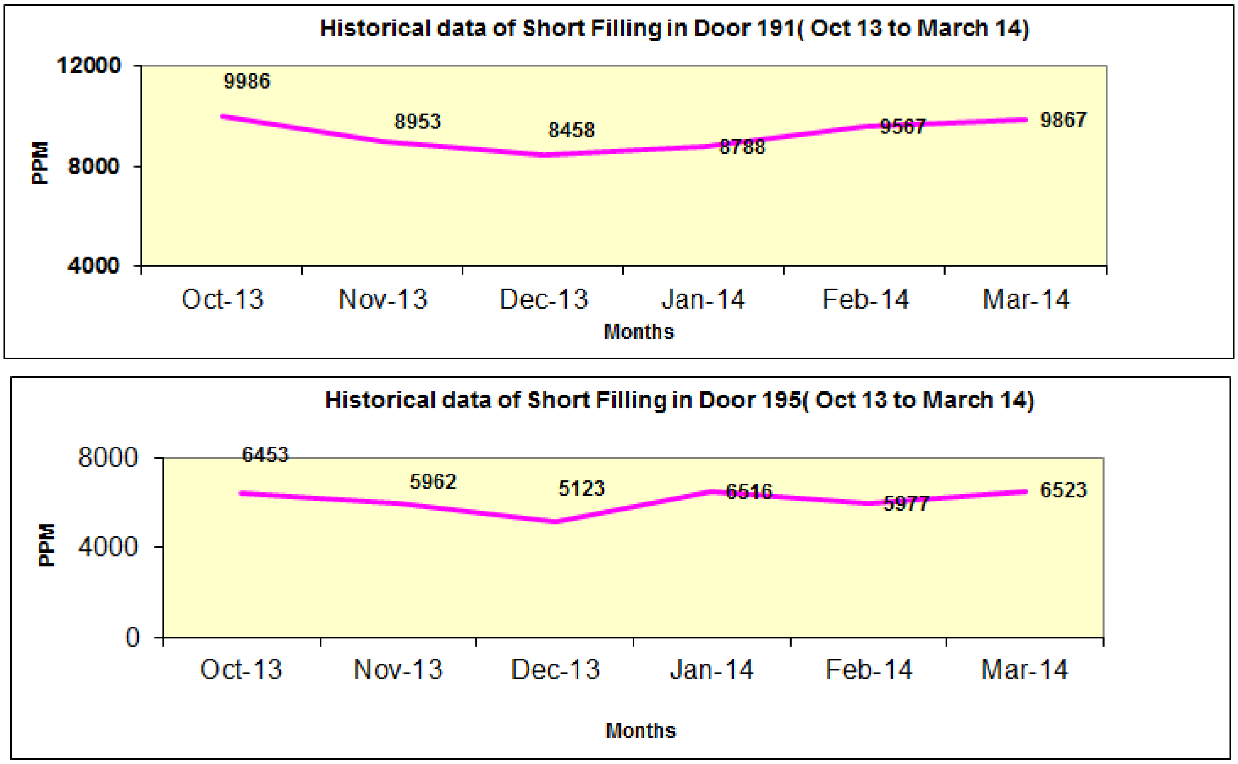


Figure 3.7 Historical data for the short filling problem.

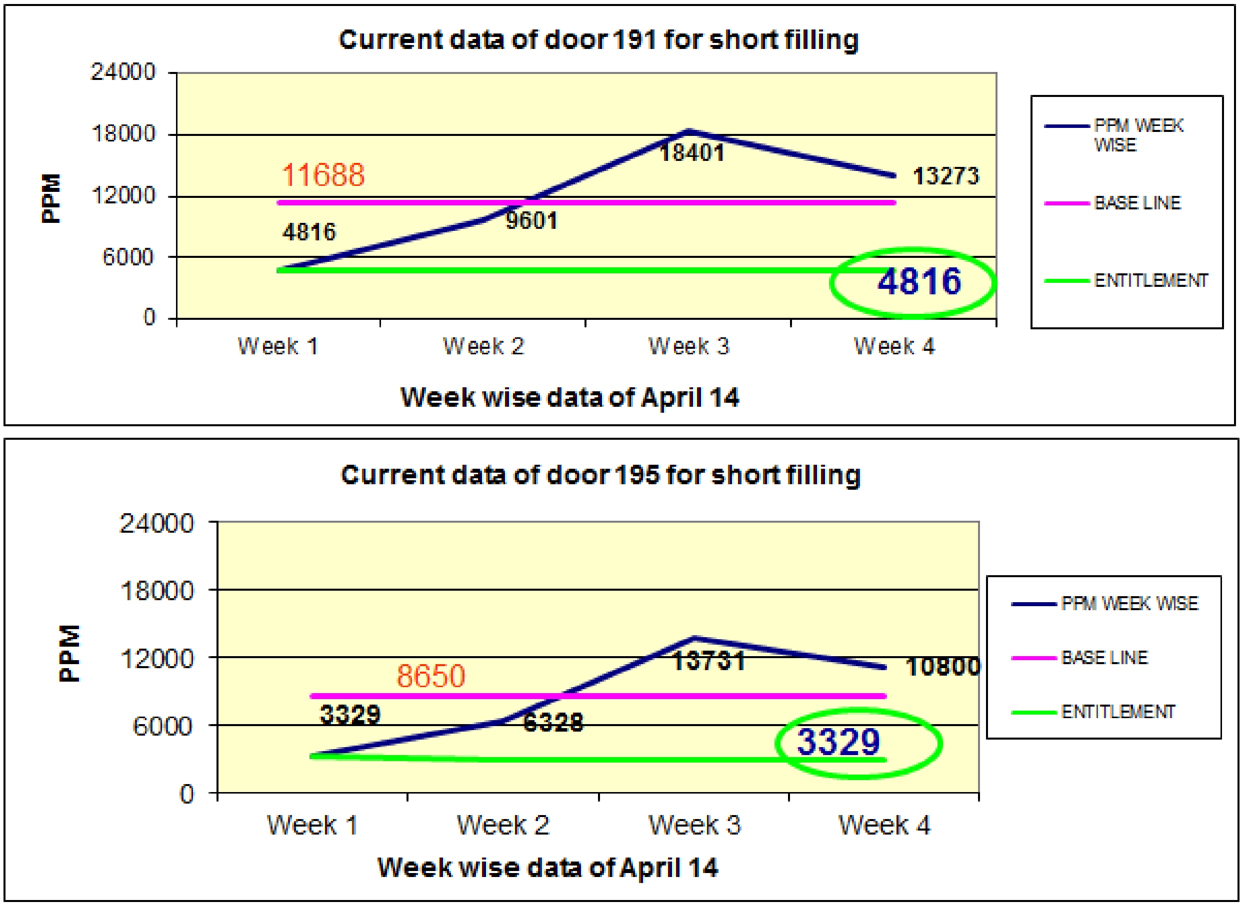


Figure 3.8 Current data for the short filling problem.

From the above trend chart we conclude that the door 191 has the 11688 PPM and door 195 has 8650 PPM. We select the target for both doors, 11688 to 2104 and 8650 to 2163 PPM.

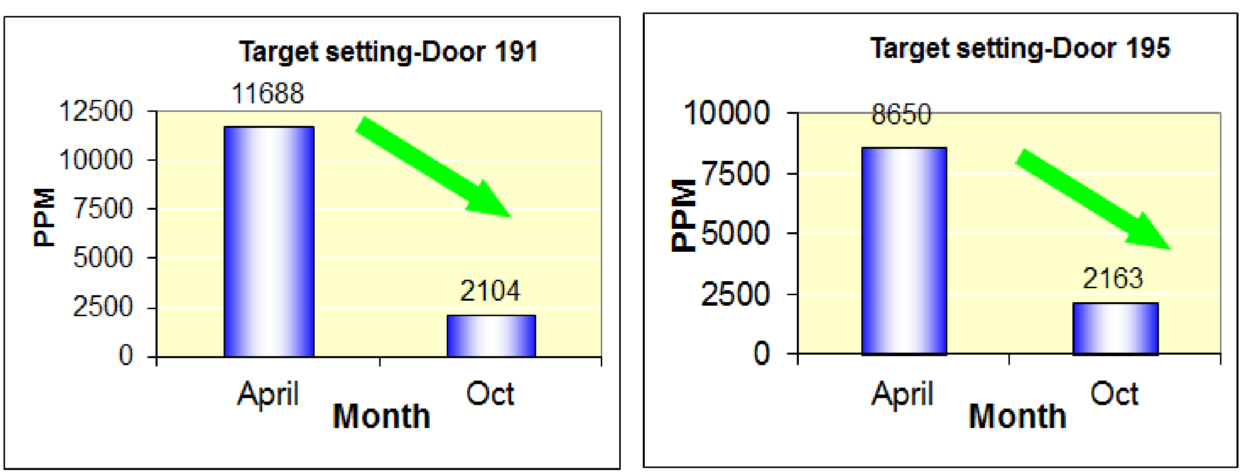


Figure 3.9 Target setting.

5. Process flow diagram

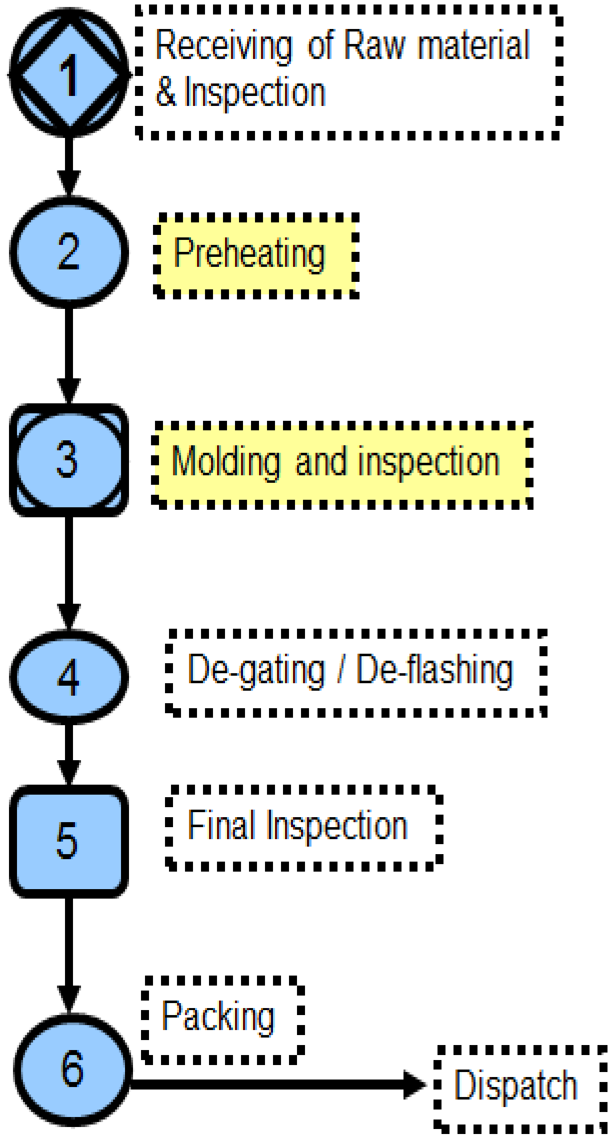


Figure 3.10 Process flow diagram.

The above figure shows the process flow diagram for the process. We see that preheating and molding and inspection are our main focus area for investigation. We study the process thoroughly and check the preset standards for these two standards. Input/output sheet also contains the details of the process. By focusing on the input/output sheet we select the main factors on which we have to work.

				Process Outputs/Features					Process Inputs(s)				
Process Steps	VA/NVA	SOP	Equipment	Output	Feature (Y)	Specification	MSA	Capability	Input(X)	C/N	Feature	Specification	Test(s) / Analysis
Moulding	VA	SA-PROD-WI-51	Injection Moulding Machine	Moulded door	Fitment	Fitment as per Matting part	NA	IPY = 100%	Operator	N	Skill Level	Min. Level3	OK
					Appearance	Apperance as per limit sample	**Attribute, App. Vs Std. result is > 70%**	IPY = 99%	Machine	C	Injection pressure	16 ± 5 Kg/cm2	**16**
					Shot Weight	144 ± 3 gram	NA	Cpk =0.63		C	Holding pressure	5 ± 2 Kg/cm2	5
										C	Inj.speed	14 ± 4	**14**
										C	Holding speed	4±1	4
										C	Clamping Pressure	90 ± 5	90
										C	Clamping Speed	15 ± 5	15
										C	Screw position	95 ± 5 MM	95
										C	Barrel temprature	240,220,200,186 ± 10ºC	234,221,198,190
										C	Injection time	4± 2 sec	**4**
										C	Holding time	1+ 1 sec	**1**
										C	Cooling time	25± 2 sec	25
										C	Total cycle time	40 ± 3 sec	39
										C	Mold temprature	Core 41 °C & Cavity 41 °C	As per attached data

Table 3.1 Input/output sheet

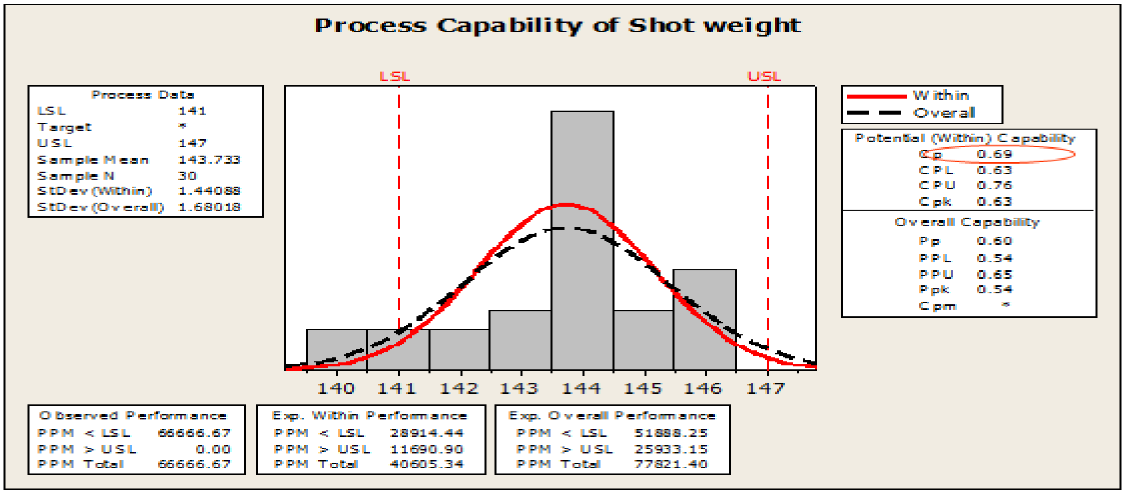
6. Inference of input output sheet

1) Total numbers of factors = 57
2) Controllable factors = 50
3) Non controllable factor = 7
4) Quick win opportunities identified 6
5) Process capability is less than 1.33 for the following
   a. Shot weight
   b. Mold temperature (core and cavity)

7. Process Capability for Shot weight

Process capability for the shot weight process is not good. The Cp value is 0.69 and Cpk is 0.63 for the shot weight process. We have to improve the capability of this process to produce the good parts, and lowers the PPM level.

Process Capability for Shot Weight



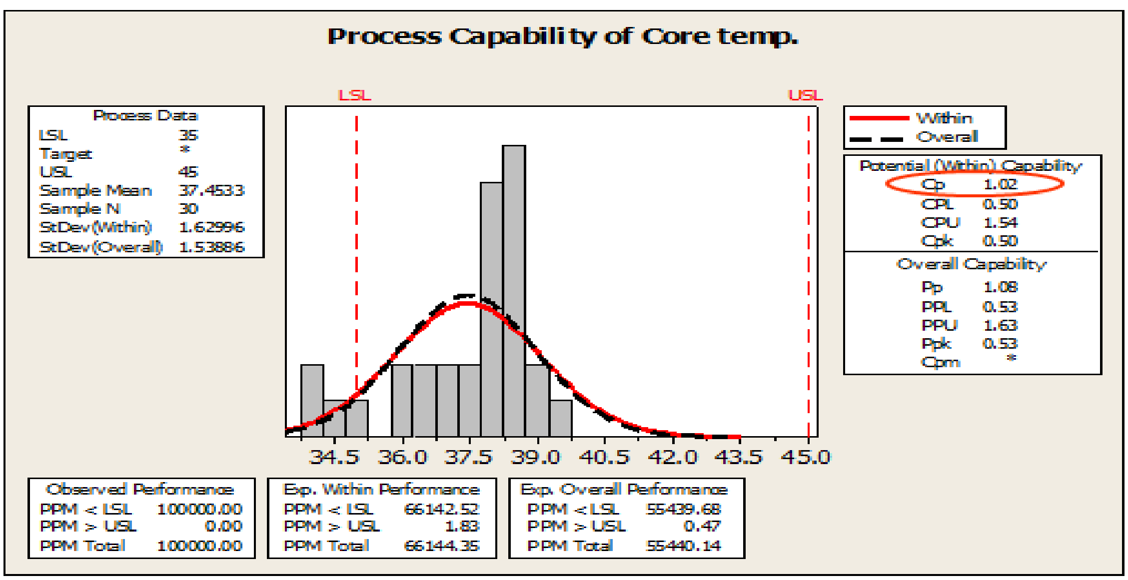
Inference : Cp is 0.69 & Cpk is 0.63 due to shifting / out of tolerance in both side

Figure 3.11 Process capability for shot weight

8. Process Capability for Core Temperature

Process capability for the core temperature is less. It shifts towards the Lower specification limit. The Cp value is 1.02 and Cpk is 0.50 for the core temperature process. We have to improve the capability of this process to produce the good parts, and lowers the PPM level.

Process Capability for core temperature



Inference : Cp (1.02) & Cpk (0.50) both are less, due to shifting in lower side/out of tolerance.

Figure 3.12 Process capability for core temperature

9. Process Capability for Cavity Temperature

Process capability for the cavity temperature is less. It shifts towards the LSL and not centered. The Cp value is 1.02 and Cpk is 0.50 for the core temperature process. We have to improve the capability of this process to produce the good parts, and lowers the PPM level.

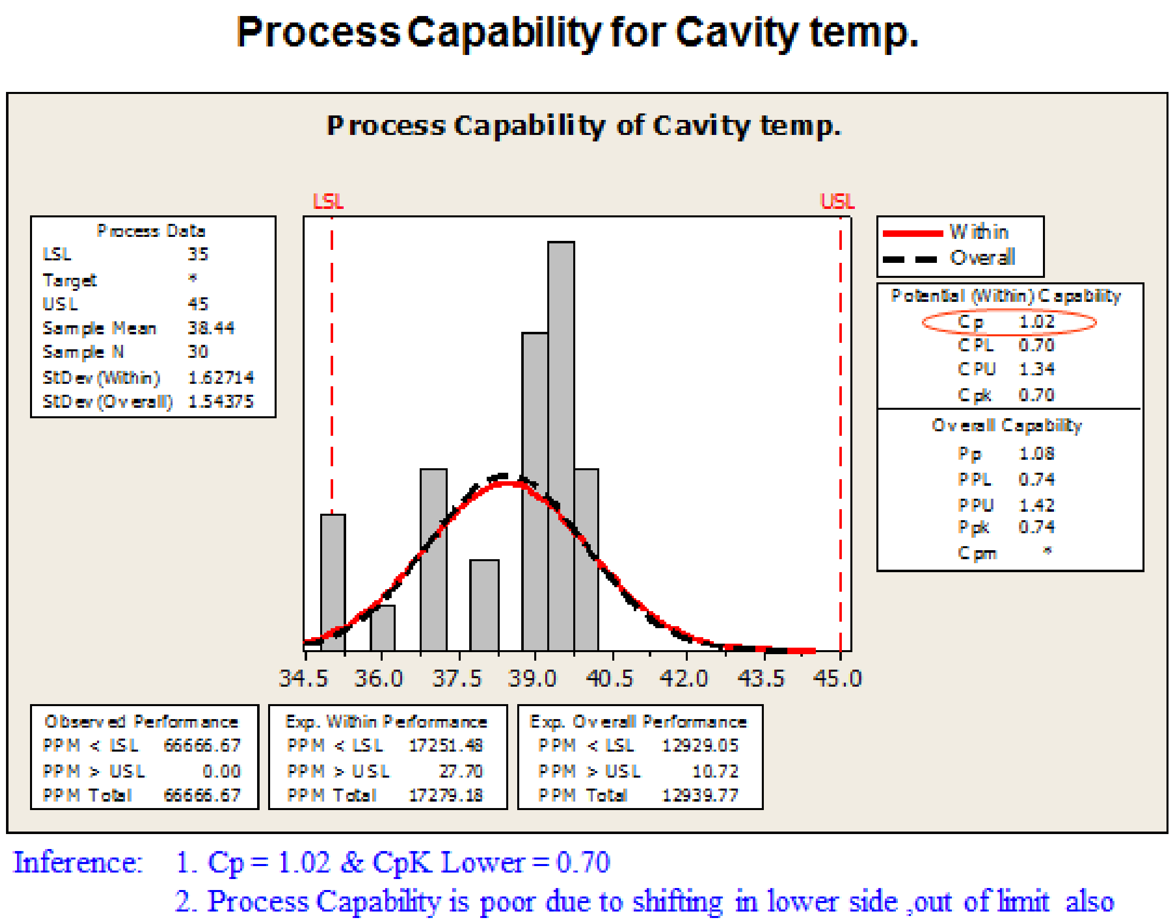


Figure 3.13 Process capability for cavity temperature.

10. Measurement System Analysis

Measurement system analysis for the attribute measurement is not acceptable. The assessment agreement within the appraisers has lower kappa value. The appraiser versus standard also has less agreement. There will be need to train the appraisers and also familiar with the measurement system. After completion of training to the operators again MSA will be conducted to check whether the operators are skilled or not.

International Journal of Enhanced Research in Science, Technology & Engineering
ISSN: 2319-7463, Vol. 4 Issue 7, July-2015

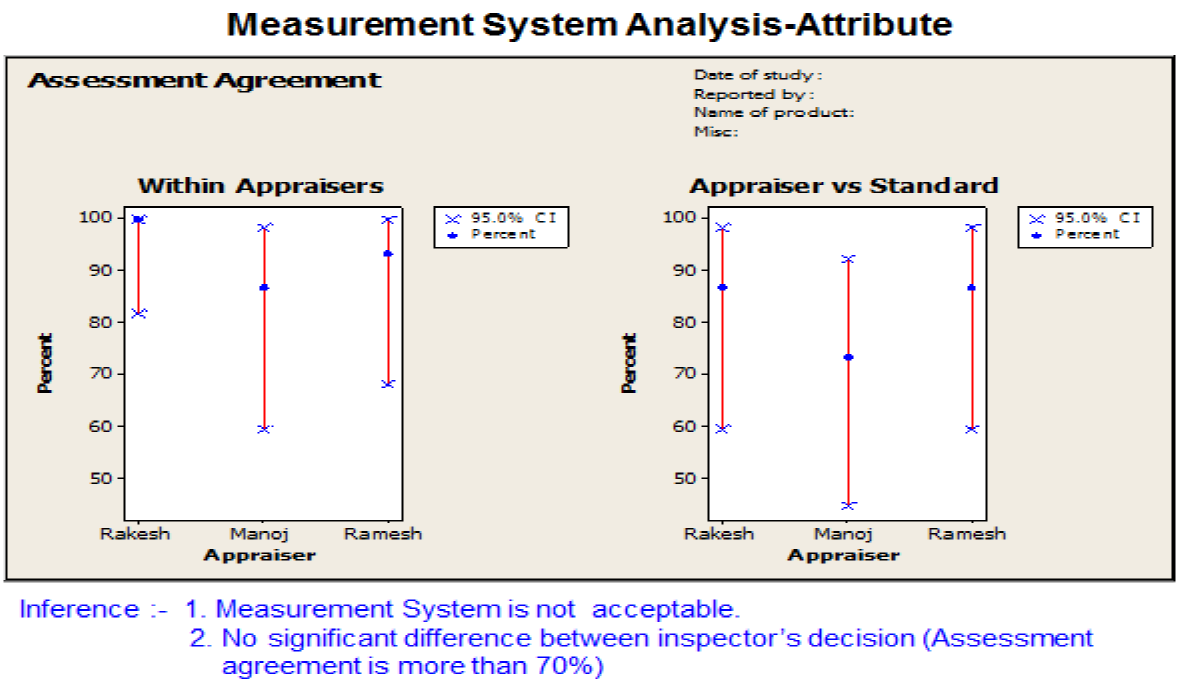


Figure 3.14 Measurement system analysis for attribute system.

11. Cause and effect diagram

Cause and effect diagram for the short filling is shown in the figure below. It is conducted by the operators following brainstorming and nominal group technique. The causes which are highlighted by the red circles are the probable causes for the process. These are further verified by conducting the experiment for the particular cause and its effect. They need to be validated by the process experts.

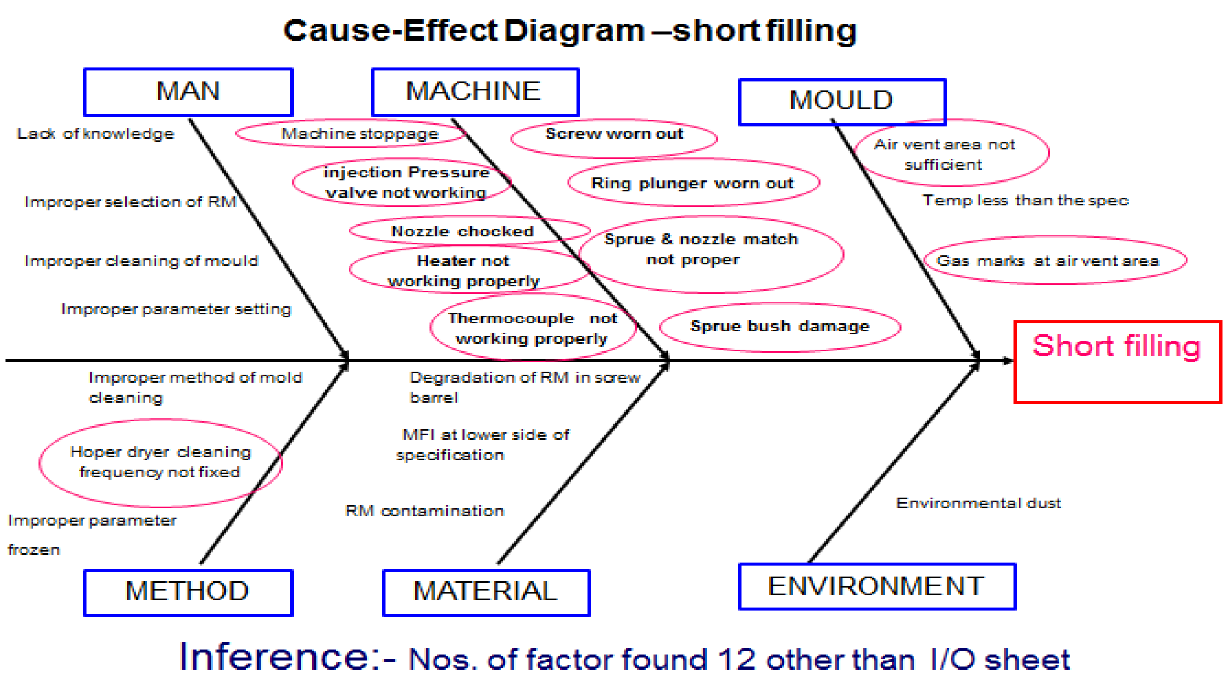


Figure 3.15 Cause and effect diagram for Short filling.

12. Identified Quick Win Opportunities after I/O Sheet (Test/Analysis) & cause & effect diagram

1. Process is not running as per standard parameters e.g. core temperature up to 33.9 ºC & cavity temperature up to 34.8 ºC (Spec-41±5 ºC).
2. Ring & plunger found worn out -was causing less feeding of molted material into mold.
3. Screw found worn out- Effecting feeding of material as per requirement.
4. Hopper filter cleaning is done but no frequency decided for cleaning and no monitoring is done for cleaning.
5. Nozzle condition to be checked on daily basis
6. Frequent Change Over of Mold due to Non Availability of Bins.
7. SOPs are not adequate e.g. contents are not legible clearly, revision details are not mention etc.
8. No Specification of Lux value for lighting at final inspection station.

13. Cause and effect matrix

After completing the cause and effect diagram we need to form a cause and effect matrix, which involves the causes other than the diagram. The possible causes and their rating is shown in the table below, their probable causes are also shown in the table.

Cause-Effect Matrix & Inference from Measure Phase

		Customer priority	9	
S No	Process step	Probable Causes	Rating	Total
1	Raw material preheating	Temperature not as per requirement	9	81
2	Raw material preheating	Time not as per requirement	9	81
3	Raw material preheating	Hopper filter cleaniness	9	81
4	Raw material preheating	Loader filter cleaniness	9	81
5	Paramter setting	operator skill	9	81
6	Paramter setting	Process parameters not set as per std	9	81
7	Moulding	Injection pressure less	9	81
8	Moulding	Mould temperature less	9	81
9	Moulding	clamping pressure less	9	81
10	Moulding	Barrel temperature less	9	81
11	Moulding	Injection Pressure valve not working	9	81
12	Moulding	Nozzle chocked	9	81
13	Moulding	Heaters not working properly	9	81
14	Moulding	Themocouple not working properly	9	81
15	Moulding	Screw worn out	9	81
16	Moulding	Ring plunger worn out	9	81
17	Moulding	Sprue & nozzle mistmatch	9	81
18	Moulding	Mixing of other material	9	81
19	Moulding	Sprue bush damage	9	81
20	Moulding	Improper feeding of raw material	3	27
21	Moulding	Air vent area is not sufficient	3	27
22	Moulding	Gas marks at air vent area	3	27

- Ranking co relation:- 0=none ,1 = week ,3= moderate ,9 = strong
- Here only those factors have been shown which are on priority after filtering
- Inference:- Total no. of inputs found 19 for short filling which are having overall rating 81

Figure 3.16 Cause and effect matrix.

14. Analyze Phase

PFMEA

After completing the cause and effect matrix, we find the causes by the failure mode and effect analysis process as shown in the figure below.

PFMEA

Process Function	Requirement	Potential Failure Mode	Potential Effects of Failure	SEV	class	Potential Cause(s)/ Mechanism(s) of Failure	Current Process Controls prevention	OCC	Current Process Controls detection	DET	RPN
Raw material preheating	Preheated material should be free from moisture	Misture contents in material	Manufacuring & assmbly- Short filling	8	C	1. Less hopper temperature due to thermocouple malfunctioning or wrong setting by operator	1.Parameters monitoring 2.Operator training to set parameters as per standards	6	Recording of parameters in check sheet	7	336
						2. Less time given	Temp. monitoring				
		Overheating of raw material	will cause of brittleness of product,part may get crack	8	C	Excess temp. or time given during process	Temp. monitoring	6		7	336
Injection Moulding	No short filling	No short filling	Less cooling in cabin due to Air leakage in AC sub -unit(HVAC)	8	C	Less temp. of core & cavity due to wrong setting or heaters/thermocouples not working peroperly	-Preventive maintenance of heaters, thermocouples & other parts as per schedule '-PLC controlled '-Operator training to set parameters as per standards & visual inspection	7	-Recording of parameters/actual data in check sheet '-Ist off approal '-100% visual inpection	7	392
					C	Less injection pressure,speed due to wrong setting or leakage in hydraulic system					
					C	Less Barrel temperature due to wrong setting or heaters/thermocouple not working properly					
					C	Ring plunger or/and Screw worn out since not changed as per schedule					
					C	Sprue bush damage,Nozzle choked due to poor maintenance					

Inference:- There are 9 numbers of causes which Occurrence and RPN is More
Note: Cut off no. for RPN Decided 250

Figure 3.17PFMEA for the process.

X's identified for data collection:

1. Mold Core Temperature
2. Mold Cavity Temperature
3. Barrel temperature – Zone-1
4. Barrel temperature – Zone-2
5. Barrel temperature – Zone-3
6. Barrel temperature – Zone-4
7. Injection Pressure
8. Injection Speed
9. Hopper Temperature

Data collection plan

1. Sample size = 5 continuous shots after every 1 hr.
2. Min. 5 defective should be covered in total data set, as min. rejection is 1.1 % so as per np≥5 min. 500 shots data to be collected.

International Journal of Enhanced Research in Science, Technology & Engineering
ISSN: 2319-7463, Vol. 4 Issue 7, July-2015

24/9/2012	10:00 AM	NITYANAND	2	31.3	30.9	92	239	225	200	185	13	12	OK
24/9/2012	11:00 AM	NITYANAND	2	31	30	91	242	224	200	185	11	10	NG
24/9/2012	12:00 PM	NITYANAND	2	33.8	34.8	92	234	221	202	185	11	10	NG
24/9/2012	1:00 PM	NITYANAND	2	33	34.5	91	238	221	200	185	13	12	OK
24/9/2012	2:00 PM	NITYANAND	2	33.5	35.5	91	238	221	200	185	11	10	OK
24/9/2012	3:00 PM	HARIOM	2	33.2	35.6	91	231	216	200	185	11	10	OK
24/9/2012	4:00 PM	HARIOM	2	33.6	35.4	92	233	216	200	185	11	10	OK
24/9/2012	5:00 PM	HARIOM	2	33.5	35.2	92	234	223	200	185	11	10	OK
24/9/2012	6:00 PM	HARIOM	2	33	35.6	91	245	223	200	187	11	10	NG
24/9/2012	7:00 PM	HARIOM	2	33.6	35.4	91	244	223	200	185	13	12	OK
24/9/2012	8:00 PM	HARIOM	2	33.7	35	91	234	223	202	185	11	10	NG

Table 2: Data collection sheet

Note: Total 975 shots data was collected in 32 days.

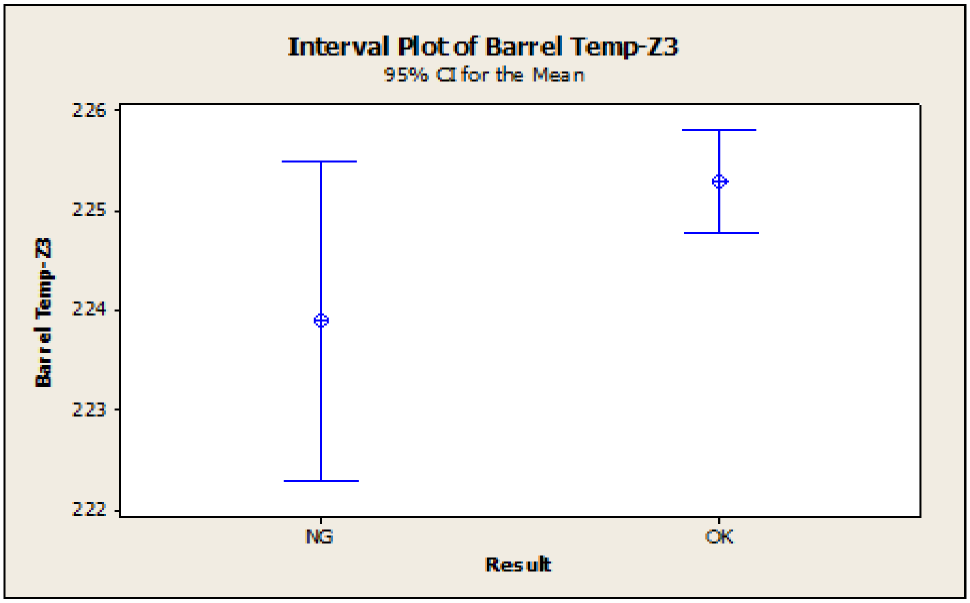
15. Tools identified for graphical analysis

S.No	Parameter (Xs)	Input type	Output type	Tools to be used
1	Mould Core Temperature	C	D	Main effect plot, Interaction plot, Box plot
2	Mould Cavity Temperature	C	D	Main effect plot ,Interaction plot ,Box plot
3	Barrel temperature – Zone-1	C	D	Main effect plot, Interaction plot, Box plot
4	Barrel temperature – Zone-2	C	D	Main effect plot, Interaction plot, Box plot
5	Barrel temperature – Zone-3	C	D	Main effect plot, Interaction plot, Box plot
6	Barrel temperature – Zone-4	C	D	Main effect plot ,Interaction plot, Box plot
7	Injection Pressure	C	D	Main effect plot ,Interaction plot, Box plot
8	Injection Speed	C	D	Main effect plot, Interaction plot, Box plot
9	Hopper Temperature	C	D	Main effect plot, Interaction plot, Box plot

Table 3 Graphical analysis for the factors identified.

Interval plot for Z – 3 Temperature

Interval Plot for Z - 3 Temp.

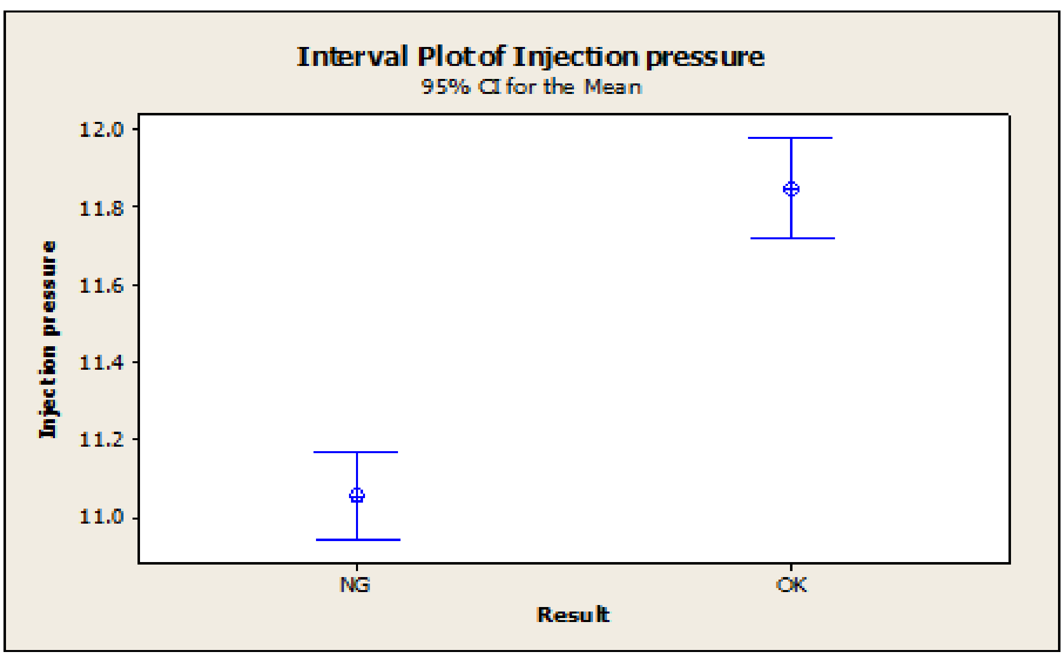


Inference: There seems relationship between Z-3 Temp. and short filling.

Figure 3.18 Interval plot for Z – 3 temperature

Interval plot for Injection Pressure

Interval Plot for Injection Pressure



Inference: There is relationship between mould cavity temp. & short filling. Relationship to be proved with Logistic regression.

Figure 3.19 Interval plot for injection pressure

16. Binary Logistic Regression for Short Filling problem

Binary Logistic Regression for Short Filling

Binary Logistic Regression: Result versus Mould Core T, Mould Cavity, ...

Variable	Value	Count
Result	OK	176 (Event)
	NG	19
	Total	195

Logistic Regression Table

Predictor	Coef	SE Coef	Z	**P**	Odds Ratio	95% CI Lower	95% CI Upper
Constant	33.3824	98.1765	0.34	0.734			
Mould Core Temp.	0.173660	0.147998	1.17	0.241	1.19	0.89	1.59
Mould Cavity Temp	-0.21511	0.245629	-0.88	0.381	0.81	0.50	1.31
Hopper temp	-0.21589	0.368745	-0.59	0.558	0.81	0.39	1.66
Barrel Temp-Z4	0.03997	0.07246	0.55	0.581	1.04	0.90	1.20
Barrel Temp-Z3	0.12186	0.09612	1.27	0.205	1.13	0.94	1.36
Barrel Temp-Z2	0.06542	0.19615	0.33	0.739	1.07	0.73	1.57
Barrel Temp-Z1	-0.49028	0.46438	-1.06	0.291	0.61	0.25	1.52
Injection pressure	2.15713	0.92237	2.34	0.019	8.65	1.42	52.72
Injection speed	0.62868	1.83109	0.34	0.731	1.88	0.05	67.87

Log-Likelihood = -48.133
Test that all slopes are zero: G = 28.306, DF = 9, **P-Value = 0.001**

Figure 3.20 Binary Logistic Regression output for short filling problem

Inference of Statistical Analysis

1. Following Factor are found statistically significant after application of various graphical and statistical tools:
   a. Injection Pressure

2. Following Factors are also taken for improvement based on statistical analysis-

   b. Mould Core Temperature
   c. Barrel Temperature Z3

Remark- DOE will be done on 3 factors

17. Improve Phase

DOE Data Collection Plan

No. of Factors :- 3
Level :- 2
Doe Design :- Full factorial with no replicates
Total Run :- 9
Center Point :- 1

StdOrder	RunOrder	CenterPt	Blocks	Injection Pressure	Mould core	Heater barrel temp-	REJ % - Short filling
2	1	1	1	17	36	210	0.38
9	2	0	1	14	41	220	0.00
7	3	1	1	11	46	230	0.37
3	4	1	1	11	46	210	2.52
5	5	1	1	11	36	230	0.38
8	6	1	1	17	46	230	0.00
1	7	1	1	11	36	210	3.68
6	8	1	1	17	36	230	0.00
4	9	1	1	17	46	210	0.36

Table 3 DOE data collection plan

DOE Result- Main Effect Plot (Short Filling)

Pareto Chart : Short Filling

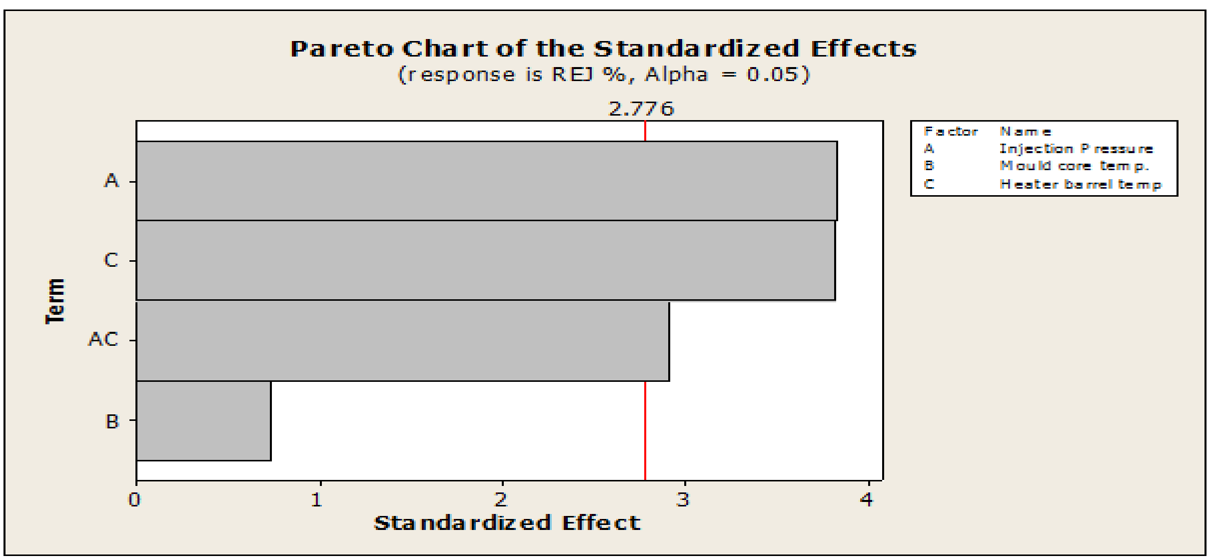


Figure 3.21 Pareto chart for short filling problem.

DOE Result- Main Effect Plot (Short Filling)

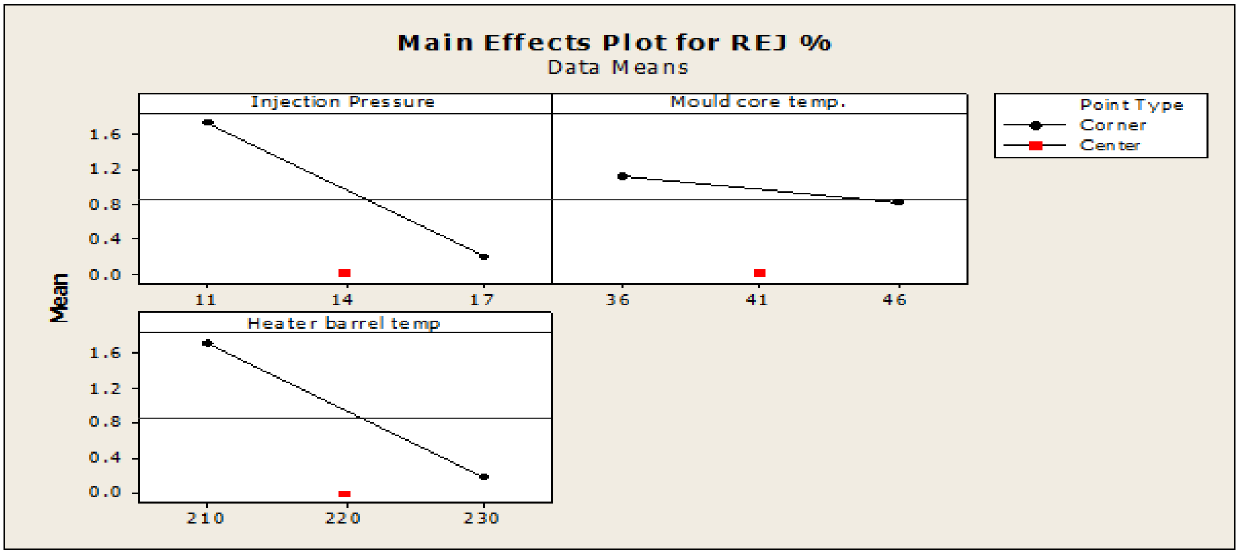


Figure 3.22 Main effect plot for short filling problem.

DOE – Minitab output for Short Filling

Factorial Fit: REJ % versus Injection Pr, Mould core t, Heater barrel temp. (Z 3)

Estimated Effects and Coefficients for REJ % (coded units)

Term	Effect	Coef	SE Coef	T	P
Constant		0.8544	0.1913	4.47	0.011
Injection Pressure	-1.5525	-0.7762	0.2029	-3.83	0.019
Mould core temp.	-0.2975	-0.1488	0.2029	-0.73	0.504
Heater barrel temp	-1.5475	-0.7738	0.2029	-3.81	0.019
Injection Pressure* Heater barrel temp	1.1775	0.5888	0.2029	2.90	0.044

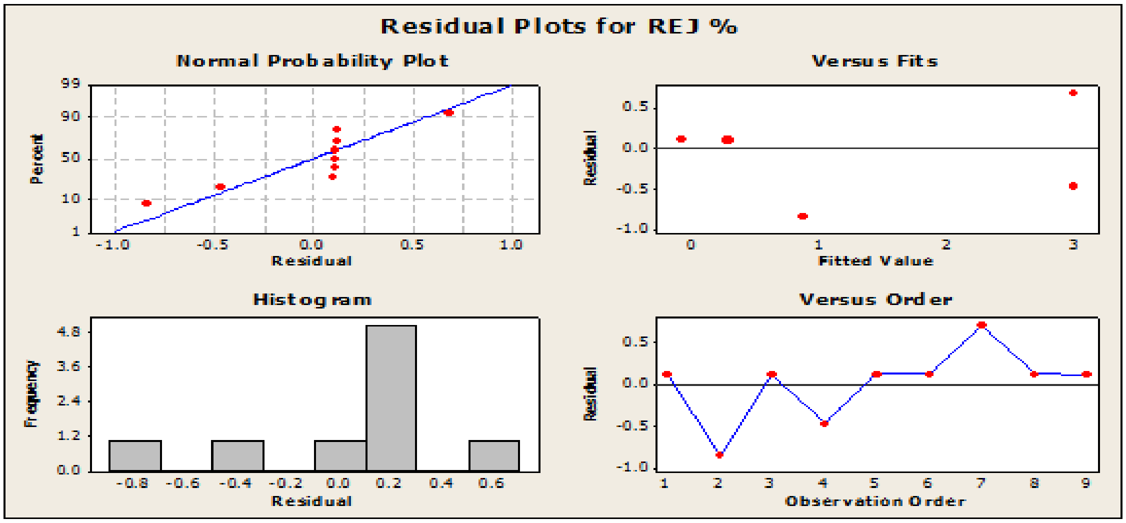
S = 0.573884 PRESS = 4.80735

R-Sq = 90.51% R-Sq (pred) = 65.36% R-Sq (adj) = 81.01%

Figure 3.23 Minitab output for short filling problem.

Model Equation: Short Filling = 0.1822 - 0.7762*(Injection Pressure) - 0.7737*(Barrel temp Z3) + 0.5888*(Injection Pressure*Heater barrel temp Z3)

Residual Analysis for Short Filling



Conclusion : Data is not normally distributed towards zero but random pattern is there.

Figure 3.24 Residual analysis for short filling

Global Solution

Injection Pressure = 13.6911Heater barrel temp (Z3) = 230

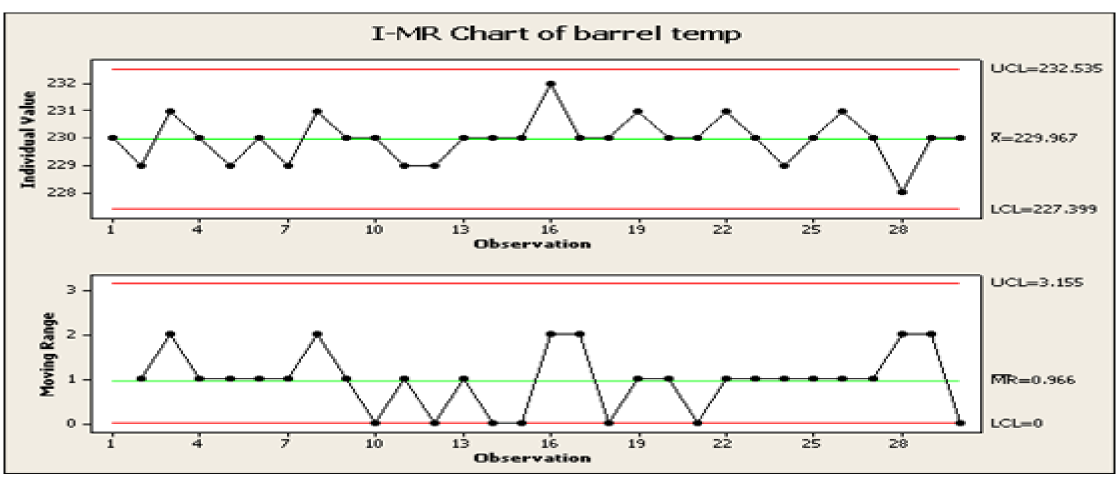
Predicted Responses REJ % = 0.1 desirability = 1.000000

Composite Desirability = 1.0

18. Control Phase

After improving the process, we take the regular data to monitor the process that the process is running the prescribed conditions or not. In control phase, we regular plot the control charts of the process which are variable parameters. The I-MR chart of the Barrel temperature of zone – 3 is shown in the figure. It seems within the control limits.

I-MR Chart for Barrel Temperature Z3



Inference: Temp. is being maintained against requirement of 230 +/- 5 °C, UCL & LCL are defined 233 & 227 °C.

Figure 3.25I – MR chart for Barrel Temperature.

19. Result

After implementing the solution the results of the process are shown in the below graphs. The first graph is the rejection trend for short filling on door 191 and the second graph is rejection PPM for the door 195. Both the charts shows that after implementing the solution the PPM trend is decreasing day by day. This is approximate to the target which is taken in the define phase.

Rejection PPM Trend for Short filling-Door 191

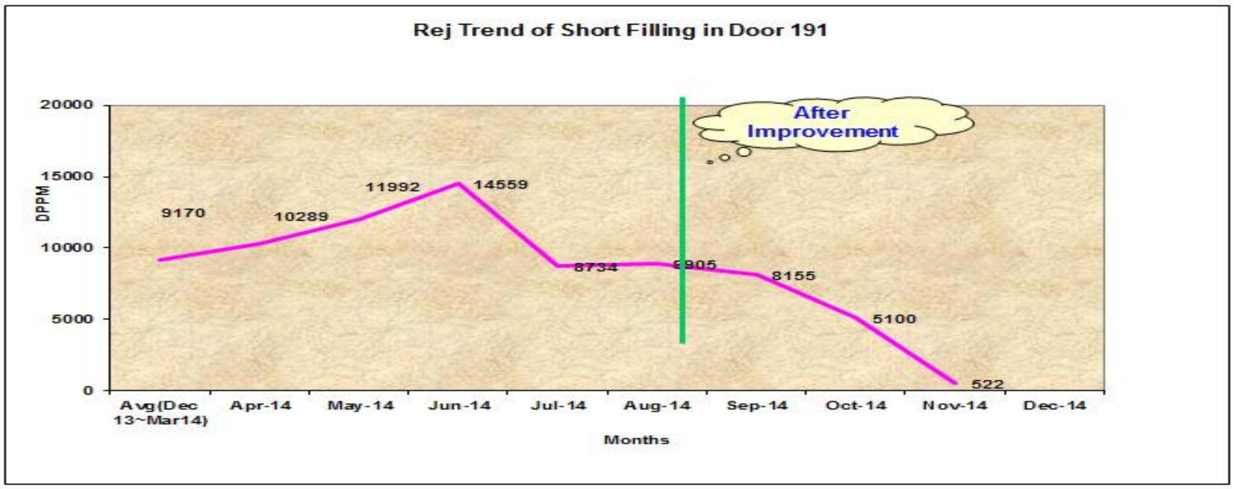


Figure 4.1 Rejection PPM trend for short filling door 191.

Rejection PPM Trend for Short filling-Door 195

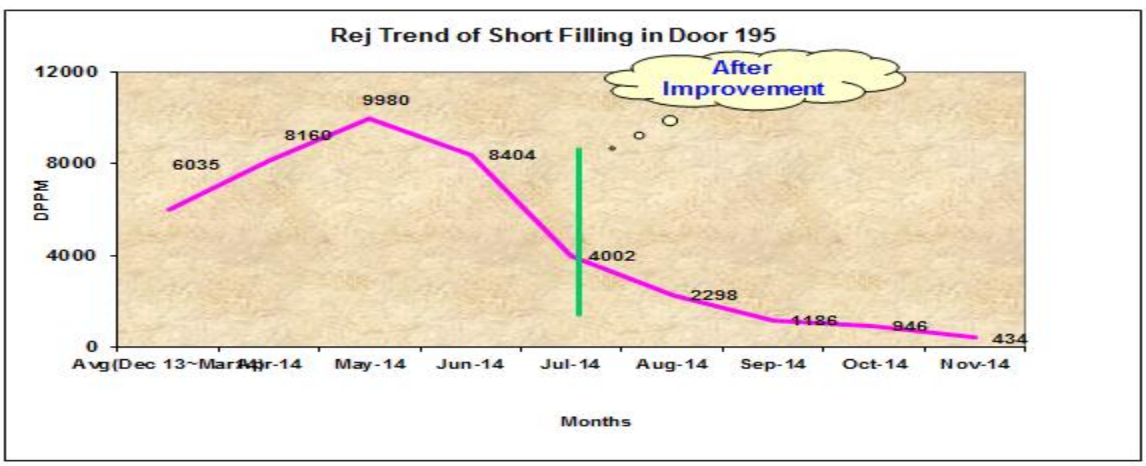


Figure 4.2 Rejection PPM trend for short filling door 195.

References

[1]. Aguavo, R. 1990. Dr. Deming: the American who taught the Japanese about quality. Carol Publishing Group. New York, NY. 289 p.

[2]. Blakeslee, J.A., Jr. 1999. Implementing the "six sigma" solution. Quality Progress. 32(7):77-85.

[3]. Breyfogle, F.W. III. 1999. Implementing "six sigma": smarter solutions using statistical methods. John Wiley and Sons. New York, NY. 791 p.

[4]. Deming, W.E. 1950. Some theory of sampling. Dover Publication, Inc. New York, NY. 601 p.

[5]. Deming, W.E. 1986. Out of crisis. Massachusetts Institute of Technology, Center

[6]. for Advanced Engineering Study. Cambridge, MA. 507 p. 148

[7]. Deming, W.E. 1993. The new economics. Massachusetts Institute of Technology, Center for Advanced Engineering Study. Cambridge, MA. 240 p.

[8]. Fadum, O. 1987. Process information and control systems: a technology overview. Tappi. 70(3):62-66.

[9]. Feigenbaum, A.V. 1991. Total quality control. McGraw-Hill. New York, NY. 863 p.

[10]. Feigenbaum, A.V. 1996. Connecting with customers and other sage advice. Quality Progress. 29(2):58-61.

[11]. Feigenbaum, A.V. 1997. Changing concepts and management of quality worldwide. Quality Progress. 30(12):45-48.

[12]. Harry, M. 1997. The vision of six sigma: application resource. Volumes I, II and III. Tri-Star Publishing. Phoenix, AZ.

[13]. Harry, M. 1997. The vision of six sigma: a road map for breakthrough. Volumes I and II. Tri-Star Publishing. Phoenix, AZ.

[14]. Harry, M. 2000. A new definition aims to connect quality with financial performance. Quality Progress. 33(1):64-66.

[15]. Harry, M. 2000. Six sigma focuses on improvement rates. Quality Progress. 33(6):76- 80.

[16]. Ishikawa, K. 1985. What is total quality control? Prentice-Hall, Inc. Englewood Cliffs, NJ. 215 p.

[17]. Ishikawa, K. 1987. Guides to quality control. Asian Productivity Organization. New York, NY. 226 p.

[18]. Juran, J.M. and F.M. Gryna, Jr. 1951. Juran’s quality control handbook. McGraw- Hill Book Company. New York, NY. 1117 p.

[19]. Juran, J.M. and F.M. Gryna, Jr. 1993. Quality planning and analysis. McGraw-Hill Book Company. New York, NY. 684 p.

[20]. Kilian, C.S. 1992. The world of W. Edwards Deming. SPC Press. Knoxville, TN. 385 p.

[21]. Pande, P.S., R.P. Neuman and R.R. Cavanagh. 2000. The six sigma way. McGraw-Hill Publishing. New York, NY. 422 p. 151

[22]. Pyzdek, T. 1999. The complete guide to six sigma. Quality Publishing. Tucson, AZ. 711 p.

[23]. Shewhart, W.A. 1931. Economic control of quality of manufactured products. D. Van Nostrand Company, Inc. New York, NY. 501 p.

[24]. Shewhart, W.A. 1939. Statistical methods – from the viewpoint of quality control. The Lancaster Press. Lancaster, PA. 155 p.

[25]. Taguchi, G. 1993. Taguchi on robust technology development. American Soc. Mechanical Engineers Press. New York, NY. 136 p.