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Research Article

OPTIMIZATION OF FLEXIBLE POLYURETHANE FOAM HARDNESS BY REDUCING PROCESS VARIANCE

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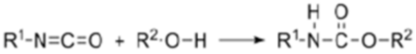
ABSTRACT

The changing global world and accordingly, the increasing consumer demands and needs indicate that companies should adopt continuous improvement as a principle in order to stand sustainable on their sector. Lean Six Sigma (LSS) provides effective and sustainable solutions to meet world standards with the tools and techniques it uses. In this study, which focuses on process improvement, it is aimed to optimize the costly flexible polyurethane foam production process conditions and find out which factors are effective on the hardness of flexible polyurethane foam produced according to slabstock method by reducing variability on this process. At the end of the study, it was understood that the significant factors in the foam process were TDI index and polyol. This study improves the process approximately 15 Newton. This means better use of resources, quality and happy customers.

Keywords: Taguchi experimental design, process optimization, flexible polyurethane foam manufacturing process, measurement systems analysis.

1. INTRODUCTION

In 1937, along with having discovered Polyurethane (PU) by Otto Bayer, "a new way in macromolecular chemistry" began [1]. PU foams are generally formed by the reaction of an isocyanate and polyol with the help of catalysts, blowing agents and surfactants. In the polymerization process, foam is obtained by adding some blowing agent [2]. The generalized PU reaction [3] made up of isocyanate and polyols in PU production is shown in Figure 1.



$$R^1\text{-}N{=}C{=}O + R^2\text{-}O\text{-}H \longrightarrow R^1\text{-}\overset{H}{N}\text{-}\overset{O}{\overset{\|}{C}}\text{-}O\text{-}R^2$$

Figure 1. Generalized PU reaction.

PU foams, first presented to the market in 1950s, have grown rapidly over the years [4]. In 2015, polyurethane market size of $ 53.94 billion is projected to grow at a CAGR (Compound Annual Growth Rate) of 7% until 2025 [5]. Among the products, flexible polyurethane foams are the most widely used and have the largest share in production [6] such as furniture, cushioning, packaging, bedding [7]. It needs "a variety of chemicals and additives" during production [8].

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Polyols are high molecular weight compounds containing more than one hydroxyl group. Choosing right grade of polyol is important since they are main part of formulation. By varying functionality of polyol, desired results for variety of foam can be achieved. If polyol functionality increases, provided that their molecular weight remains constant, a slight increase in foam hardness occurs. Isocyanates have lower molecular weight than polyols. TDI (toluene di-isocyanate) and MDI (methylenediphenyl diisocyanate) are commonly employed in isocyanate species. They form a very strong cross-linking structure with polyols. While air improves cell structure of foam, surfactants control cell formation of foams and their structure [4]. In the absence of this material, reaction results in foam collapse [6]. Amine catalyst energizes reaction of water and TDI, which helps formation of CO_2 and rise of foam, while tin catalyst energizes reaction of polyol with TDI [4]. Water acting as a blowing agent reacts with isocyanate group which results in primary amine and carbon dioxide. As water content rises, gas reaction will increase and this will cause density of foam to decrease. In cases where other components remain constant, load-bearing properties do not change much by increasing water content [8]. effects of TDI index on foam properties examined [9]. TDI index is the "amount of isocyanate used relative to the theoretical equivalent" amount. Increasing this index increases the amount of isocyanate reacted, thereby increasing the number of cross-linking and hardness of foam. In addition, increasing the TDI index more than necessary will not change the hardness and also damage the foam structure [3]. In this study, it is aimed to optimize process factors and process quality characteristic of flexible polyurethane foam produced by slabstock method containing toluenediisocyanate by Taguchi experimental design technique. This research advances application on DMAIC (Define, Measure, Analyze, Improve, Control) by demonstrating that the process measurement capability should be confirmed as precision and accuracy before process optimization studies. Moreover, this research provides a unique practical contribution to DMAIC approach by advancing our understanding of the process improvement. There has not been any other research clearly in the literature combining measurement system analysis and design of experiment before.

2. MEASUREMENT SYSTEM ANALYSIS AND TAGUCHI DESIGN OF EXPERIMENT

There are two variation sources consisting of part-to-part and measurement system in measuring a product. Variation of measurement system may depend on some reasons such as process, personnel, tools/equipment, items to be measured, environmental factors. Unless we can not measure, we can not get reliable data. Thus, process can be neither control nor manage. A poor measurement system can provide bad parts to be accepted and good parts to be rejected, resulting in unhappy customers and scrap. Making some mistakes in measurement will prevent sustainable improvement of business and capability of process. The significant reason of variation in a good measurement system should come from product, not the measurement system. So, it can effective distinguish differences between parts. Measurement in DMAIC process improvement cycle has a crucial importance to improve the process conditions. There are two important concepts used in scientific measurements as accuracy and precision. Accuracy influenced by resolution, bias, linearity and stability is the closeness of a measured value to a standard or known value whereas Precision having an effect on repeatability and reproducibility of the measurement system shows how the closeness of two or more measurements to each other. The evaluation of gauge capability, isolation of variability sources, knowing of how much of total observed variability comes from gauge are the main aims of measurement systems capability studies. Measurement systems variability consist of two components regarded as repeatability and reproducibility. We cannot make an accurate measurement if our equipment is not calibrated properly. Simply, measurement systems analysis (MSA) assesses adequacy of a measurement system. Calibration is important as it guarantees that an instrument is capable of measuring to specifications for which it is rated. Many instruments lose their calibration or accuracy over time therefore it is necessary to get them recalibrated on a regular basis. The goal of calibration is to minimise any measurement uncertainty by ensuring accuracy of test equipment. Because of poor metrology, a robust process can be seen unstable and incapable. Repeatability is the variation which occurs when same operator repeatedly measures same sample on same instrument under same conditions whereas Reproducibility is the variation which occurs between two or more instruments or operators measuring same sample with same measurement method in a stable environment [10], [11]. Once MSA indicates that the measurement method is both sufficiently accurate and capable, it can be integrated into the remaining steps of DMAIC process to analyse, improve and control the characteristic. Gage R&R threshold values are given in Table 1.

Table 1. Gage R&R metric features.

Gage R&R Metric	Bad	Acceptable	Good
%P/T Ratio	≥30%	10%<Ratio<30%	≤10%
Number of Distinct Categories (NDC)	<2	2≤NDC<5	≥5

A capable measurement system is a requirement of conducting design of experiments (DOE) [12]. Generally, this issue is overlooked in the practical studies belonging to literature. Experimental design as an important quality tool is a statistical method that aims to find relationship between response and factors [13]. Developing innovative technologies for production and making it as cost-effective and faster as possible has become important in today's world [14]. Quality engineering consists of off-line and on-line methods. While offline is employed in the design phase, online is in the production phase [14], [15]. Taguchi method is a fractional factorial design method that uses a special sequence known as orthogonal arrays (OA) for a small number of experiments and experimental designs in investigating a large number of variables [16]. It minimizes impact of so-called noise factors and by adjusting control factors to reduce variability in response [17]. Robust Design is a powerful tool to design a high-quality system [18] that uses experimental design techniques focused on improving quality, while also taking into account the loss of quality, which seeks to find an effective way for product design at low cost according to the customer's wishes [19]. Figure 2 shows the robust process design. Taguchi Design of Experiment (TDOE) made up of three stages which are system, process and tolerance designs [15],[20].

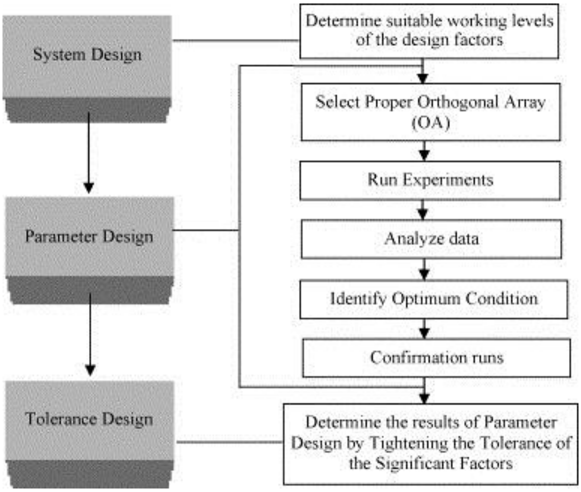

Figure 2. Taguchi design procedure [21].

The Signal to Noise "(S/N) ratio which serves as objective function for optimization" [16] guides the selection of control levels that most compensate for effects of noise factors on response [18]. In this study, since the aim is to maximize the foam hardness as a quality characteristic, the form in Equation (1) is used.

$$S/N = -10 \times log_{10}\,(\frac{1}{n}\sum_{i}^{n}\frac{1}{y_i^2}) \quad (1)$$

n in the formulas represents the number of observations and y_i is the result of the i^{th} experiment.

Some of the chemical studies can be listed as follows. Kumar et al. [22] using Taguchi experimental design technique studied three parameters and three levels that affect the EPC (Evaporative Pattern Casting) process. Since their aim is to maximize slurry density as a quality characteristic, they performed their experiments based on larger the better formula of S/N ratio. They conducted ANOVA to examine effect of parameters on response and concluded that these three parameters had an effect on response. Yang and Hung [19] provided a suitable solution to achieve desired product quality using Taguchi and utility concept to optimize multi-response thermoforming polypropylene foam process. Apparaoa and Kumar [23] aimed to improve casting quality and efficiency of aluminum alloy with Taguchi approach. They found the optimal settings of die casting parameters and managed to reduce porosity formation which is a defect in aluminum casting process. Joshaghani et al. [24] succeeded in optimizing mix design of permeable concrete slab using Taguchi method.

3. MATERIAL AND PROCESS

As shown in Figure 3, during production process of flexible slabstock, mixture of polyol, isocyanate and other raw materials are poured into a moving conveyor with an edge height of 3-4 meters. After reaction takes place, mixture starts to rise within seconds like a cake and become usable products with solidification. It is then allowed to cure for 24 hours to remove carbon dioxide. It can reach up to 220 cm in width and 120 cm in height. If internal temperature of foam exceeds 165 °C due to a heat-giving reaction, it may cause combustion of foam [4], [9],[25].

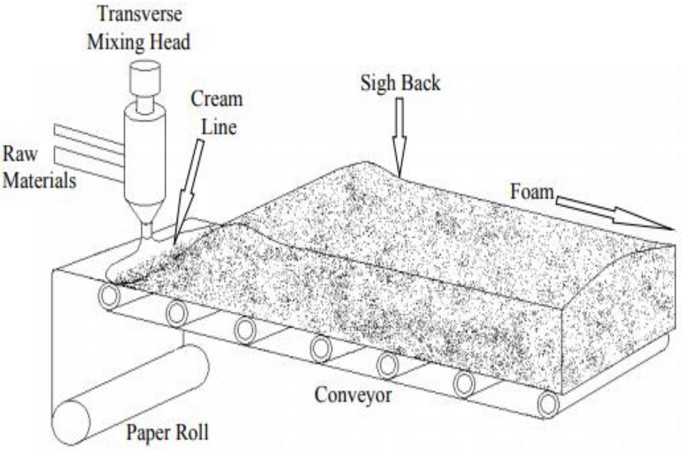

Figure 3. Slabstock process [8].

Work flow of the foam process in the factory is given as Figure 4.

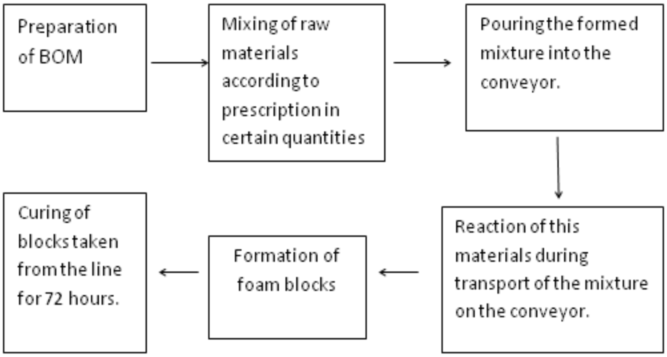

Figure 4. Foam process work flow.

Figure 5. Foam production process.

The foam chosen to realize this study is 22 density hard foam which is considered as harder than other flexible foams in the flexible polyurethane foam class. This foam corresponds to 10% of the total production volume in the company. Foam production capacity of the company is 185.000 m3 per year. Flexible Polyurethane Foam in Turkey is generally produced between 14 and 100 kg per m3 as a density. The company produces foam with automated system as shown in Figure 5. The process for producing foams is explained by using TDI, polyol, water, amine and tin catalysts. The polyurethane raw materials are brought together with the help of pipes from gallons seen in image number 1 of Figure 5. The resulting mixture is poured into the conveyor line which moves at a certain speed, as shown in image number 2 of Figure 5. As shown in image number 3 of Figure 5, by reacting the reagents during course of the line, the foamy mixture solidifies and rises as a cake. This method is the slabstock production method as mentioned in the previous sections (with the developing technology, slabstock foam with a width of 240 cm and height of 130 cm can be produced in the company). When the exothermic reaction is completed, the formed 20 m foam blocks are left to rest for another 72 hours in order to remove all of the CO2. The process is called curing. Image number 4 of Figure 5 shows the equipment used in the production of foams.

Foam was tested at Zwick hardness testing machine according to ISO 2439 (method B) Indentation Force Deflection (IFD) testing method for evaluation of hardness. In order to analyze the measurement system, a total of 12 samples were taken from 4 pieces of 22 density hard foam blocks and 3 pieces of 38 cm x 38 cm x 5 cm dimensions from each block. It was firstly tuned in the tester machine up to 25% compression as in Figure 6 and the response of foam against this compression in newtons was measured. The same procedure was then used for 40% and 65%, respectively. Response of the foam to this application is called its hardness value. Hardness measurement tests were performed under standard atmospheric conditions (per cent 50±5 relative humidity and 23±2°C temperature) and the samples were conditioned and tested later than 72 hours after manufacture. Measurement System Analysis and TDOE analysis were run with Minitab Version 16.0 software package that is a computer program designed to perform basic and advanced statistical functions.

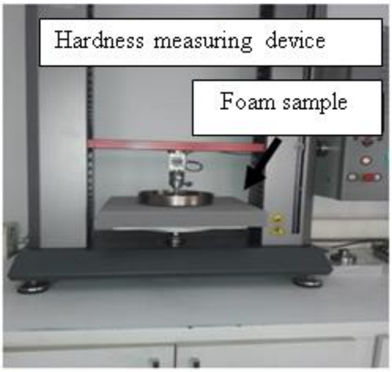

Figure 6. Hardness measurement test device.

4. MEASUREMENT SYSTEM ANALYSIS

In quality improvement studies, the second phase of DMAIC is measure which is a standard practice to be needed in validation of reliability of measurements before doing any analyses. The significant aspect of quality of a measurement procedure is its precision, or measurement variation. In order for an improvement study to be meaningful, measurement system used should be sufficient and capable. if variance in the process is caused by parts produced and not measurement system, process improvement by DOE should be performed. The same operator for measurement carried out 2 replications for each sample and test results are shown in Table 2.

Firstly, suitability of data to normal distribution was tested with the obtained measurement data. Figure 7 shows that data are suitable for normal distribution as p value is greater than 0.01.

Table 2. Test results for measurement system analysis.

Parts (C1)	Test1 40% IFD (N)	Test 2 40% IFD (N)
1.block-1.piece	211	211
1.block-2.piece	207	208
1.block-3.piece	210	211
2.block-1.piece	208	210
2.block-2.piece	213	213
2.block-3.piece	210	209
3.block-1.piece	210	210
3.block-2.piece	209	211
3.block-3.piece	212	211
4.block-1.piece	208	208
4.block-2.piece	211	209
4.block-3.piece	207	209

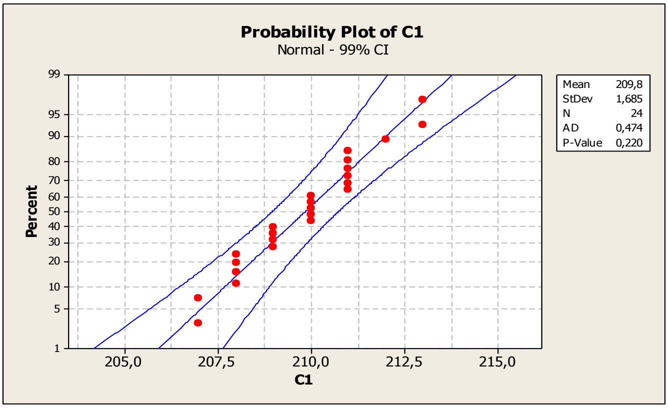

Figure 7. Normal Probability Plot.

C With the help of Minitab 16, Gage R&R statistical analysis was performed with data obtained from these tests. The analysis results are shown in Table 3, Table 4 and Table 5. In Table 3, since p (=0.002) value is less than 0.01, it can be said that there is no measurement error. The main reason of process variability is due to parts.

Table 3. One-way ANOVA.

Source	DF	SS	MS	F	P
C1	11	55.33	5,03	6.03	0,002
Repeatability	12	10	0.83		
Total	23	65.33			
α to remove interaction term = 0.05					
S = 0.9129 *R-Sq* = 84.69% *R-Sq(adj)* = 70.66%					

Minitab output of Table 4 indicates that most of the variability results in parts as Part-to-Part Contribution value (71.58%) is greater than Total Gage R&R (28.42%).

Table 4. Variance components (varcomp).

Source	VarComp	%Contribution(of VarComp)
Total Gage R&R	0.83	28.42
Repeatability	0.83	28.42
Part-To-Part	2.09	71.58
Total Variation	2.93	100
Lower process tolerance limit = 199.5		

In Table 5, total gage R&R %Tolerance (SV/Toler) value (26.50%) below 30% indicates the adequacy of the measurement system.

Table 5. Evaluation of measurement system.

Source	StdDev (SD)	Study Var (6 × SD)	%Study Var (%SV)	%Tolerance (SV/Toler)
Total Gage R&R	0.91	5.47	53.31	26.5
Repeatability	0.91	5.47	53.31	26.5
Part-To-Part	1.44	8.69	84.6	42.06
Total Variation	1.71	10.27	100	49.71
Number of Distinct Categories = 2				

Number of distinct categories indicates how many parts can be separated in the system. If this value is less than 2, measurement system is not valid since one part cannot be distinguished from another. It is suggested that the number of categories should be more than 2 by AIAG [10]. Components of variation of Figure 8 shows where source of variation stems from.

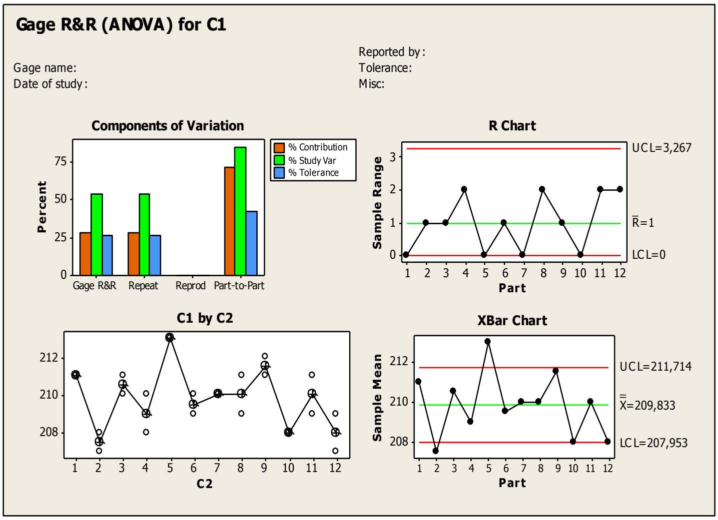

Figure 8. Gage R&R graphics.

We checked only repeatability (consistency of measurements) as measurements was performed by one operator. This indicates that it may be a good enough measurement system as the largest component of variation is part-to-part variation. Otherwise, the measurement system should be corrected. The *R* chart graphically expresses operator consistency. When parts are not consistently measured, any points on the R-chart are above upper control limit (UCL). It is seen that there is no error due to measurement since values are within the specified control limits. The Xbar chart compares the part-to-part variation to repeatability component. As points falling inside the limits is more than the points that is out of limits, which is not good for our system, measuring error seems to be also considered. Individual points -C1(parts) by C2(measurement)- spreads out from the sample 4, 8, 11, 12. As a result of the analysis, it is seen that the variation caused by the measurement system is too small to be taken into consideration and the most important variability in the total variation is due to the part variation. This result demonstrates the need to reduce variation in the process. Experimental design method was chosen for this purpose. In the last stage, we should make residual analyses for model validation as shown in Figure 9(a). The dots in a residual plot of Figure 9(b) are randomly dispersed around the horizontal axis, thus, we can say that linear regression model is appropriate for the data; otherwise, a non-linear model would be more appropriate.

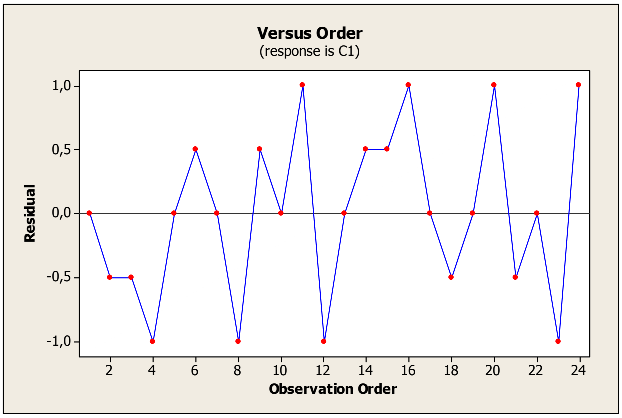

Figure 9 (a). Residual versus order.

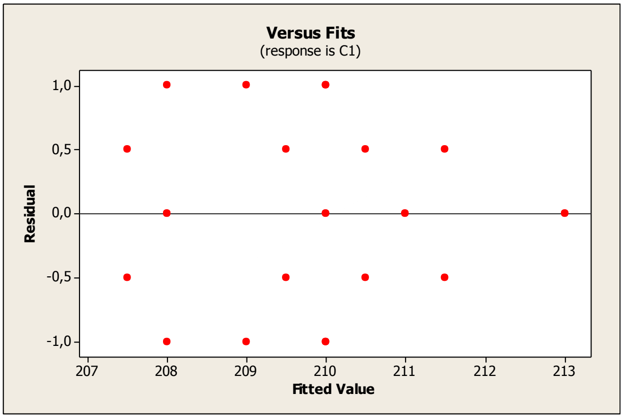

Figure 9 (b). Residual versus fits.

At the 99% confidence level, the residual analysis in Figure 10 showed that the residues were suitable for normal distribution.

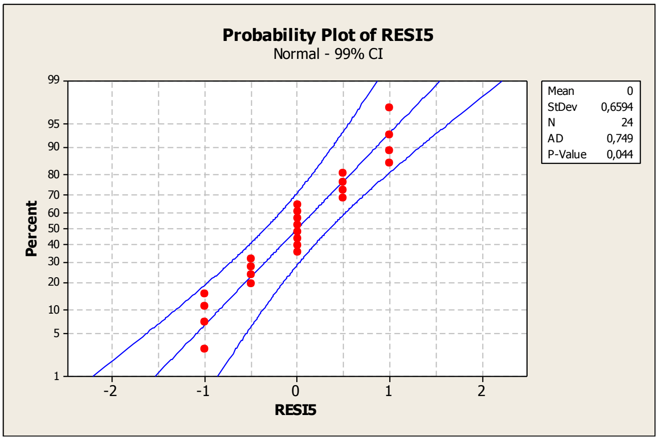

Figure 10. Plobabilty plot of residuals.

5. TAGUCHI DOE

The Taguchi approach is a technique that accomplishes its purpose by following a series of procedures. These procedures are presented as follows:

5.1. Determination of factors and levels

Factors that can be controlled during the foam production process are polyol, water, silicon, amine catalysts, tin catalyst, TDI index, mixer pressure, air amount, polyol temperature and TDI temperature. Uncontrolled factors are ambient temperature and humidity. However, TDI index, polyol, air amount and water factors which are thought to have more effect on foam hardness were selected with the help of brainstorming and the experience of process engineers as significant factors. The number of levels was decided to be three to better understand nonlinear system behaviours according to the selected four factors and level values were kept close to avoid exceeding the values required in the foam formulation. Four process parameters with three levels, 34 = 81 experiments have to be conducted. So, the number of tests in terms of time and cost constraint have been reduced using DOE. The experiments were designed based on L9. The appropriate factors and levels identified in Table 6 are shown together. Our main aim is to maximize foam hardness value as a quality characteristic in the process since the customers want to have as much hardness as possible of 22 density hard foam.

Table 6. Factors and their levels.

Code	Factors	Level-1	Level-2	Level-3
A	TDI index	113	111	109
B	Polyol (kg)	98	100	102
C	Water (kg)	3.67	3.64	3.61
D	Air Amount (lt/min)	2.65	2.7	2.75

5.2. Selection of orthogonal matrix and experiment application

The total degree of freedom (df) for four factors, each having three levels, is 8 [23]. The total value of the orthogonal array selected by this method should be greater than or equal to 8 required for the experiment [22]. Therefore, it has been found appropriate to select an L_9 orthogonal sequence having a degree of freedom at least 8 to carry out the experiments. For experiments, level values according to OA are written in the matrix for four factor-three level combinations assigned using Minitab Statistical Package Program. Then, the other controllable factors in the process were kept constant and experiments were started, and 9 sets of tests were repeated three times at different times in order to make statistical evaluation of the results. The hardness measurements of the produced foams were made after each experiment carried out in random order by taking Taguchi principles into consideration and the results were noted. The hardness results that were measured in experimental sets 1, 2 and 3 are expressed in terms of newton (N) as Y1, Y2 and Y3, respectively. The mean hardness ($\overline{Y}$) and S/N ratios determined as larger the better was calculated for each of the 9 trial conditions and are shown in Table 7.

Table 7. Mean of foam hardness as a response and S/N ratios.

Trial Number	Random Order	A	B	C	D	Y1	Y2	Y3	$\overline{Y}$	S/N Ratio
1	1	113	98	3.67	2.65	203	201	204	202.66	46.13
2	4	113	100	3.64	2,7	205	203	205	204.33	46.20
3	9	113	102	3.61	2.75	208	208	209	208.33	46.37
4	8	111	98	3.64	2.75	195	198	194	195.66	45.82
5	6	111	100	3.61	2.65	199	200	199	199.33	45.99
6	2	111	102	3.67	2.7	202	200	201	201	46.06
7	5	109	98	3.61	2.7	190	192	191	191	45.62
8	3	109	100	3.67	2.75	193	194	192	193	45.71
9	7	109	102	3.64	2.65	195	195	197	195.66	45.83

Figure 11 shows that the data collected for the experimental design at 99% confidence level have normal distribution.

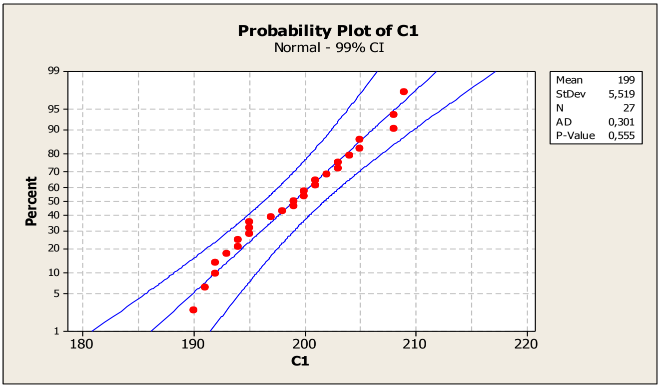

Figure 11. Probabilty plot of DOE process tests.

Main effects plot for S/N ratios and means of the factors used in the experiment were analyzed at different levels, respectively, and are shown in Figure 12(a) and 12(b).

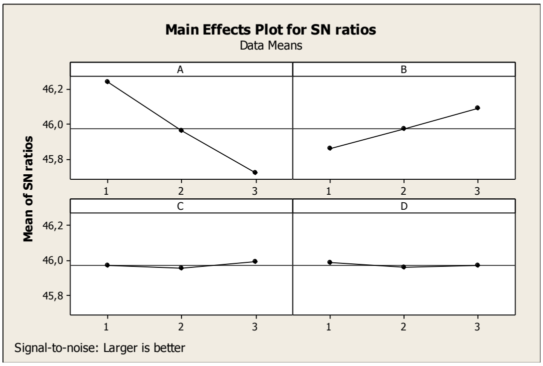

Figure 12 (a). Main effects plot for S/N ratios.

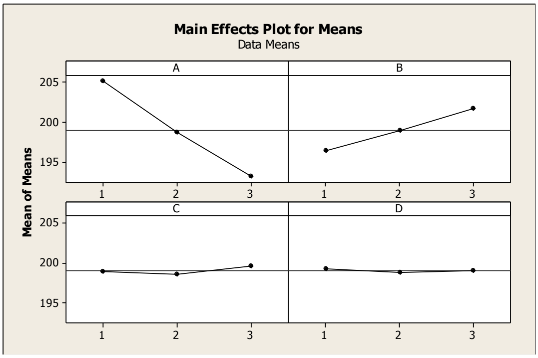

Figure 12 (b). Main effects plot for means.

The optimum level of factors are 1 for A, 3 for B, 3 for C and 1 for D, respectively. The line of A factor (TDI index) comes in the most perpendicular to the horizontal position, whereas B factor (polyol) is slightly less perpendicular than A. It can be concluded that both factors may have a significant effect on hardness. Since the line for C (water) and D (air amount) is close to the horizontal position, the effect of these factors on the hardness can be considered insignificant. Variance Analysis was performed to confirm whether the main effects exist or not between variables and given in Table 8. For ANOVA, the following hypotheses are established:

H_0: The parameters have no effect on the hardness values of the produced foams.
H_1: The parameters have an effect on the hardness values of the produced foams.

Table 8. ANOVA for DOE.

Source	df	Seq SS	Adj SS	Adj MS	F	P	%cont
TDI	2	637.5	637.5	318.7	220.6	0.0	80.4
Polyol	2	122.8	122.8	61.4	42.5	0.0	15.5
Water	2	4.6	4.6	2.3	1.6	0.2	0.5
Air amount	2	0.8	0.8	0.4	0.3	0.7	0.0
Error	18	26	26	1.4			3.2
Total	26	792					100

Since p values of A and B are smaller than α = 0.01, H_0 hypothesis is rejected, thus we can conclude that A and B parameters have an effect on foam hardness of 99 % confidence level. It appears that TDI has the highest effect on foam hardness with a share of 80%, followed by Polyol with a share of 15.51%.

According to Figure 13, the progression of the data indicates that there is no contradictory value in the normal distribution table since p value is bigger than 0.01. Versus fits table shows that the residual values have a fixed variance. In histogram graph, the large sample is directly proportional to the correct interpretation of this graph. It is not correct to interpret normality according to histogram graph. In the Versus order graph, residues appear to be independent, but it should be noted that there may be a relationship between very close residues in the template.

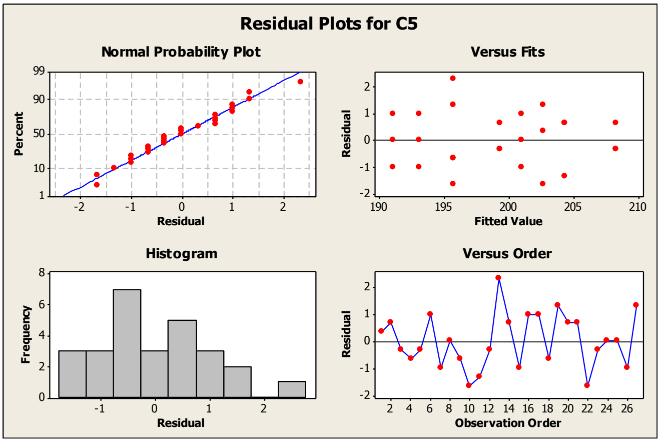

Figure 13. Residual graphics for TDOE.

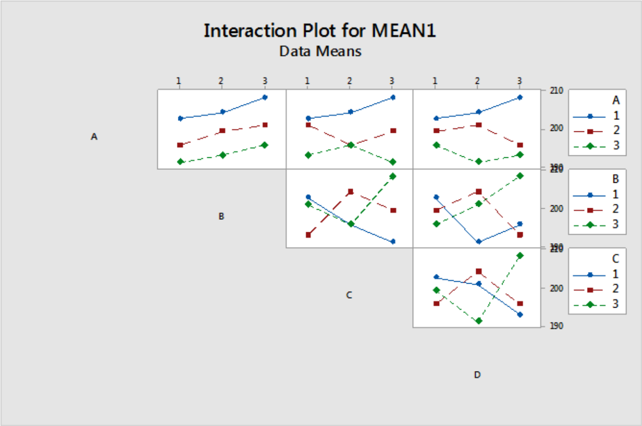

Figure 14. Interaction graphics.

According to interaction graphs in Figure 14, the interaction between A and B, A and C, A and D is insignificant. Whereas there is a stronger interaction between B and C, B and D, C and D. As a result, when the factor-level values TDI index = 113, Polyol = 102, Water = 3.61 and Air amount = 2.65, it was found that the test results could give the optimum value. The optimum configuration is $A_1B_3C_3D_1$.

5.3. Model prediction and confidence interval

The estimated optimum average of foam hardness as response, taking into account the parameters having significant effect on the response (A: TDI index and B: Polyol), is calculated as shown in the formula below;

$\overline{T}$: Average of foam hardness
$\overline{A_1}$ and $\overline{B_3}$ are the means of the responses of A at level 1 and B at level 3, respectively.
$\mu = \overline{T} + (\overline{A_1} - \overline{T}) + (\overline{B_3} - \overline{T}) = \overline{A_1} + \overline{B_3} - \overline{T} = 205.11 + 201.67 - 199 = 207.78$ Newton

The confidence interval to be used in conjunction with the estimation of the mean is the range within which the results of the verification tests should remain.

CI_{CE}: Confidence interval for confirmation experiments. The calculation formula is given in Equation (4).
$F_\alpha\ (1,\ f_e)$: The degree of freedom at the level of confidence from 1 to (1-α). f_e is the degree of freedom of error.
V_e = Error variance.

$$n_{eff} = \frac{N}{1+\begin{pmatrix}\text{Total degree of freedom associated with}\\ \text{estimation of response average}\end{pmatrix}} \tag{2}$$

n_{eff}: The effective sample size
N: The total number of results.
R: The total number of validation experiments.

Confirmatory tests should always be performed to confirm the accuracy of the predicted results [15]. Total number of experiments are N=27. There are factors A and B that are associated with the estimation of the mean response and have 2 degrees of freedom. This value is 4 because totals are requested in the formula.

$$n_{eff} = \frac{27}{1+(2+2)} = 5.4 \tag{3}$$

R=2

In this study, pooled ANOVA was calculated after the previous ANOVA at 99% confidence level and is shown in Table 9.

Table 9. Pooled ANOVA.

Source	df	Seq SS	Adj SS	Adj MS	F	P
A	2	637.56	637.56	318.78	222.90	0
B	2	122.89	122.89	61.44	42.96	0
Error	22	31.55	31.556	1.43		
Total	26	792				

With the help of these values, f_e = 22 (degree of freedom of error), $F_{0.01}$ (1, 22) = 7.95 is found in the standard F-distribution table. According to Table 9, V_e equals to 1.43. After the value has found, the confidence intervals have been calculated according to the formula as follows;

$$CI_{CE} = \sqrt{F_\alpha\ (1, f_e) \times V_e \times \left[\frac{1}{n_{eff}} + \frac{1}{R}\right]} \tag{4}$$

$$\mathrm{CI}_{CE} = \sqrt{7{,}95 \times 1{,}43 \times \left[\frac{1}{5{,}4} + \frac{1}{2}\right]} = 2.79 \text{ Newton} \tag{5}$$

The estimated 99% confidence interval for confirmation experiments is shown below:

207.78 – 2.79 < foam hardness < 207.78 + 2.79
204.99 Newton < foam hardness < 210.57 Newton

For the purpose of additional control of the study, after verification tests, three more experiments in the highest level of the factors were carried out and the hardness values were obtained as given in Table 10.

Table 10. Additional tests.

Trials	A	B	C	D	Hardness 40% IFD (Newton)
1	115	103	3.61	2.65	220
2	114.5	102.5	3.61	2.65	216
3	114	102	3.61	2.65	213

The hardness values of the 20 foam data belonging to different time period from the company's production are given in Table 11.

Table 11. Real production data.

Production date	Hardness 40% IFD (Newton)	Production date	Hardness 40% IFD (Newton)
07.10.2017	199.07	22.05.17	201.41
09.10.2017	205.68	24.05.17	199.55
11.10.2017	217.56	25.05.17	200.66
13.10.2017	219.56	31.05.17	187.40
17.10.2017	212.06	01.06.17	190.21
18.10.2017	220.55	07.06.17	221.12
19.10.2017	200.99	10.06.17	206.21
25.10.2017	199.03	13.06.17	203.42
27.10.2017	200.74	14.06.17	195.65
30.10.2017	198.56	16.06.17	216.8

The average of these data is 204.81 Newton.

5.4. Confirmation test

The last step in Taguchi DOE is to perform confirmation test which is highly recommended by Taguchi to verify the experimental results. The average of the results from the confirmation test is compared with the predicted average based on the parameters and levels. If the average of the responses obtained remains within the specified confidence interval, it can be inferred that the tests yield a satisfactory result. In the optimum setting of parameters (optimum configuration), Since testing on the process line is very costly, 2 tests could be performed under same conditions as the other tests. In the validation tests, the average foam hardness of confirmation test was found to be 210 Newton ((209+211)/2).

6. CONCLUSIONS

This study indicates that gage R&R measurement systems analysis which have been rarely seemed in the literature of DOE studies must be primarly performed before beginning DOE optimization studies. Also, the study guided manufacturer to make formulation adjustments when a harder foam was requested by customers, due to the presence of parameters and levels that would give the maximum value on foam hardness. Part variance in the foam process is bigger than measurement system. Thus, the study focused on reducing process variance. In order to improve the process, Taguchi DOE approach was used to reach the optimum solution. Since each experiment (trial) and replication are expensive, we could not collect enough data to find intermediate values of factors after DOE study. If the data could have been collected, in the help of Artificial Neural Network, interval values would be achieved. According to variance analysis (ANOVA), the most effective parameters on hardness were found to be TDI index and polyol.

In validation experiments, the average value of the foam hardness of 210 Newton indicates an improvement of about 5 Newton. In addition, when the maximum values of the two most effective factors were taken to the extent allowed by the production conditions of the foam, the foam hardness value was 220 Newton. This value indicates an improvement of 15 Newton. The average of values obtained from the validation tests stays within specified confidence interval. Also, this one confirms the effect of TDI index and polyol which are the most important factors on variability of hardness. This study provided a comprehensive improvement plan for not only one product but also other products. Last but not least, process engineers need to investigate the relationship of interaction between factors of polyol and water, polyol and amount of air, water and amount of air. But, there has not been the effect on hardness of interaction between TDI index and other factors.

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REFERENCES

[1] Lonescu M., *Chemistry and Technology of Polyols for Polyurethanes,* Rapra Technology Limited, Shawbury, England, 2005.

[2] Melo J.A., Cavaco L.I., 2012. "Polyurethane : Properties, Structure and Applications". http://search.ebscohost.com/login.aspx?direct=true&db=e000xww&AN=540929&lang=tr&site=ehost-live (19.06.2019).

[3] Fan H., Polyurethane Foams Made from Bio-based Polyols, PhD thesis, The University of Missouri, Missouri, USA, 2011.

[4] Defonseka C., 2013. "Practical Guide to Flexible Polyurethane Foams". http://search.ebscohost.com/login.aspx?direct=true&db=e000xww&AN=591457&lang=tr&site=ehost-live (19.06.2019).

[5] Moon J., Kwak S.B., Lee JY, et.al., Synthesis of polyurethane foam from ultrasonically decrosslinked automotive seat cushions, *Waste Management,* 85, 557-562, 2019.

[6] Zhang X.D., Macosko C.W., Davis HT., et.al., Role of silicone surfactant in flexible polyurethane foam, *Journal of Colloid and Interface Science,* 215, 270-279, 1999.

[7] Kraitape N., Thongpin C., Influence of recycled polyurethane polyol on the properties of flexible polyurethane foams, *Energy Procedia,* 89, 186-197, 2016.

[8] Aneja A., Structure-Property Relationships of Flexible Polyurethane Foams. PhD thesis, Virginia Polytechnic Institute and State University, Virginia, USA, 2002.

[9] Daga R., Synthesis of Poly (3-Hydroxybutyrate) Based Crosslinker for Flexible Polyurethane Foams and Its Applications. PhD thesis, Biomedical Engineering and Biotechnology University of Massachusetts Lowell, Massachusetts, United States, 2014.

[10] Chrysler Group LLC, Ford Motor Company, General Motors Corporation. *Measurement systems analysis reference manual*. 4th edn. Michigan, AIAG, 2010.

[11] Henderson G.R., *Six Sigma Quality Improvement with Minitab*. 2nd ed. John Wiley & Sons Ltd. Published, 2011.

[12] http://reliawiki.org/index.php/Measurement_System_Analysis (30.12.2019).

[13] Yang K., El-Haik B., Design for Six Sigma : Roadmap to Product Development. 2nd ed., McGraw-Hill, 2008.

[14] Madhavi S.K., Sreeramulu D., Venkatesh M., Evaluation of optimum turning process of process parameters using DOE and PCA Taguchi method, *Materials Today: Proceedings,* 4, 1937–1946, 2017.

[15] Taguchi G., Crowdhury S., Wu Y., *Taguchi's Quality Engineering Handbook* John Wiley & Sons, Inc., New Jersey, USA, 2005.

[16] Hadi M.N.S., Farhan N.A., Sheikh M.N., Design of geopolymer concrete with GGBFS at ambient curing condition using Taguchi method, *Construction and Building Materials,* 140, 424–431, 2017.

[17] Zhang F., Dear R., Application of Taguchi method in optimising thermal comfort and cognitive performance during direct load control events, *Building and Enviroment,* 111, 160-168, 2017.

[18] Anirban C.M., Mukul J., Tanushri S., et.al., Implementation of Taguchi method for robust suspension design, *Procedia Engineering*, 144, 77 – 84, 2016.

[19] Yang C., Hung S.W., Optimising the thermoforming process of polymeric foams: an approach by using the Taguchi method and the utility concept, *International Journal of Advanced Manufacturing Technology*, 24, 353-360, 2004.

[20] Wang Y., Kim J., Song J., Optimization of plastic injection molding process parameters for manufacturing a brake booster valve body, *Materials and Design,* 56, 313–317, 2014.

[21] Zhang J.Z., Chen J.C., Kirby E.D., Surface roughness optimization in an end-milling operation using the Taguchi design method, *Journal of Materials Processing Technology,* 184, 233-239, 2007.

[22] Kumar S., Kumar P., Shan H.S., Density optimization of slurry of coating material used in the EPC process through Taguchi's parameter design approach, *Materials and Manufacturing Processes,* 23, 719–725, 2008.

[23] Apparao K.C., Birru A.K., Optimization of die casting process based on Taguchi approach, *Materials Today: Proceedings,* 4, 1852–1859, 2017.

[24] Joshaghani A., Ramazanianpour A.A., Ataei O., Golroo A., Optimizing pervious concrete pavement mixture design by using the Taguchi method, *Construction and Building Materials*, 101, 317–325, 2015.

[25] Oosten T van., B ringuer O., Lorne A., 2011. "PUR Facts : Conservation of Polyurethane Foam in Art and Design". http://search.ebscohost.com/login.aspx?direct=true&db=e000xww&AN= 766153&lang=tr&site=ehost-live (19.06.2019).