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Optimal Performance of Caps' Pressing Process Using Taguchi-Grey Method

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Abstract

This paper aims at improving the performance of caps' pressing process using Taguchi-grey relational analysis. Five main quality characteristics were considered, involving cap's height, inner diameter, outer diameter, angle, and plastic weight. The individual and moving range control charts were constructed for each quality characteristic. Then, process capability analysis was then carried out to assess process performance at initial process factor settings, at which the process was found incapable in producing conforming caps for some quality characteristics. Thus, the Taguchi's designed experiments were employed to provide experimental layout followed by the grey relational analysis to determine the combination of optimal factor settings. Results showed significant in almost all the five quality responses and thereby resulted in huge production and quality cost savings.

Keywords: grey relational analysis, taguchi method, caps, control charts

1. Introduction

Because caps can withstand corrosive chemicals, plastic caps find extensive use for bottles used in packaging cosmetics, carbonated drinks, drugs, chemicals, and adhesives. The metal cap under study is depicted in Figure1. The caps' production line starts by cutting the rolls into sheet metals using big slitters. The metal sheet is covered with white licker (stick varnish). The production rate of this process is 5300 sheets per hour. The sheet metals are then turned over (white face) using a turnover machine to be ready for the next stage. Next, the printed sheets are moved to the pressing machine to form the caps, the pressing machine carries out twenty seven pressed crown caps. Caps are finally transferred to plastic injection and packaged. Five quality characteristics are of main importance to produce quality caps, including height, inner diameter, outer diameter, angle, and plastic weight, where nonconforming caps result in considerable manufacturing and quality losses. This research, therefore, aims at improving the performance of production process of bottle caps with five quality characteristics.

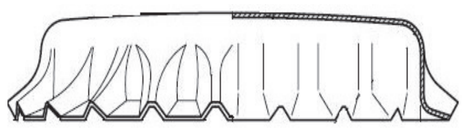


Figure 1. Crown cap diagram

The Taguchi method is widely applied because of its proven success in improving the quality of manufactured products for a single quality characteristic (Al-Refaie, 2014a,b,c). In reality, products are manufactured with multiple built in quality characteristics of main customer interest (Al-Refaie *et al*., 2009; Al-Refaie, 2012). Several optimization techniques were employed in previous studies to optimize process performance (Al-Refaie, 2015; Al-Refaie *et al*., 2016; Al-Refaie, 2017). Among them, the grey relational analysis based on the grey system theory (Deng, 1982; Tsao, 2009) can be utilized for solving complicated interrelationships among multiple quality responses (Deng, 1989; Al-Refaie, 2010). This method has been employed to optimize performance in a wide range of business applications. For example, Jiang *et al*. (2002) applied machine vision-based grey relational theory to IC marking inspection. Lin *et al*. (2002) optimized the EDM process based on the orthogonal array with fuzzy logic and grey relation analysis method. Fung (2003) optimized manufacturing process for wear property of fiber-reinforced polybutylene terephthalate composites with grey relational analysis. Huang & Liao (2003) optimized machining parameters of Wire-EDM bases on grey relation and statistical analysis. Tosun (2006). Determination of optimum parameters for multi-performance characteristics in drilling by using grey relational analysis. Nalbant *et al*. (2007) applied Taguchi method in the optimization of cutting parameters for surface roughness in turning. Pan *et al*. (2007) optimized multiple quality characteristics via Taguchi method-based grey analysis. Kuo *et al*. (2008) used grey relational analysis in solving multiple attribute decision-making problems. Somashekhar *et al*. (2011) conducted multi-objective optimization of micro wire electric discharge machining parameters using grey relational analysis with Taguchi method. Kacal & Yıldırım (2013) applied grey relational analysis in high-speed machining of hardened AISI D6 steel.

This research, therefore, utilizes the grey relational analysis for optimizing the performance of the manufacturing process of bottle caps for multiple quality characteristics. The research results are valuable to process engineering by determining the combination of optimal process factors settings that result in quality as well productivity improvement. The remaining of this paper is outlined in the following sequence. Section 2 present the method. Section 3 implements the grey relational analysis for process improvement. Section 4 summarizes research results. Finally, Section 5 summarizes research conclusions.

2. Method

2.1 Control Charts

The control chart contains a center line (*CL*), upper control limit (*UCL*), and lower control limit (*LCL*). Two rows of caps are produced by a single presser stroke; row A includes fourteen caps, while row B contains thirteen caps. Twenty samples; each of which contains two rows, are randomly selected then the five quality characteristics; height (mm), inner diameter (mm), outer diameter (mm), angle (degrees), and plastic weight (grams), are measured on each cap as shown in Figure 2. The height of cap is measured using the Deal Gauge comparator. According to the specification the height shall fall between 5.93 mm and 6.07 mm. The inner and outer diameters of the crown cap are measured using the Digital Vernier caliper. According to design, specifications of the inner diameter are limited between 26.7 and 26.9 mm, while the outer diameters of cap are limited between 31.9 and 32.3 mm. The angle of crown cap is limited between 12 and 18 degrees. Finally, the plastic weight is measured using the balance. The specification limits for the plastic weight is between 0.18 and 0.20 grams. The individual and moving range (I-MR) control chart**s** are the constructed for each quality characteristic because of the repeated measurements on the samples differ due to laboratory or analysis error, and multiple measurements are taken at distinct locations on the same unit of product. For example, the I-MR control charts of cap's height for sample of rows A and B are shown in Figure 3. It is noticed that no point falls outside the *LCL* and *UCL* for both charts. In addition, no significant pattern or run is observed in these charts. Consequently, the process is concluded to be in statistical control for height. Similar conclusions are obtained from I-MR control charts of the inner diameter, outer diameter, angle, and plastic weight.

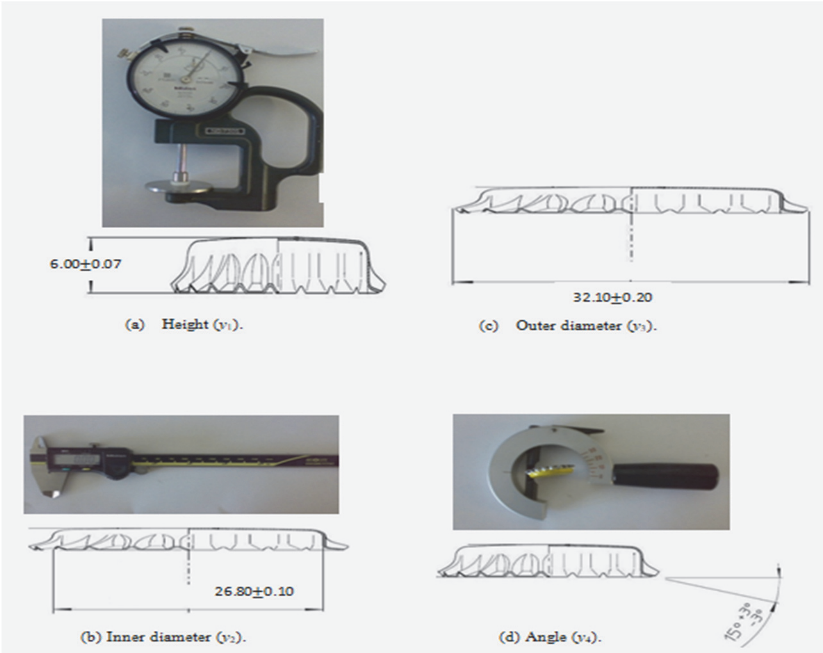
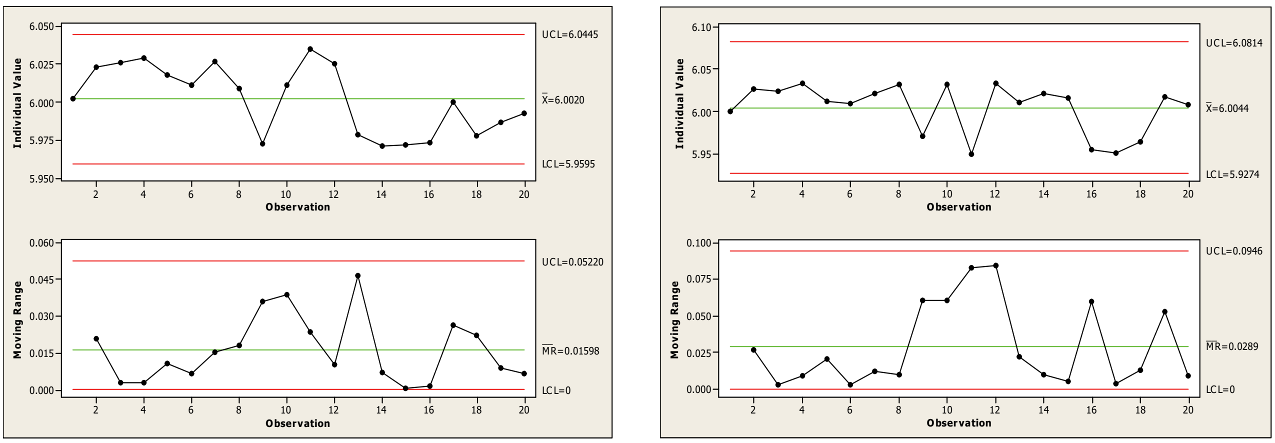


Figure 2. Measurement of cap's quality characteristics



(a) Height (row A). (b) Height (row B).

Figure 3. I-MR control charts for cap's height

2.1 Process Capability Analysis

Tables 1 and 2 display the quality characteristics' summary of control charts' parameters for row A and B, respectively. The process capability analysis is an engineering study to estimate process capability. The estimated process capability ratio, C_p, first introduced as:

$$\hat{C}_p = \frac{USL - LSL}{6\hat{\sigma}} \tag{1}$$

where USL and LSL denote the upper and lower specification limits, respectively and $\hat{\sigma}$ is sample standard deviation for process. The process has both upper and lower specification limits. For one sided specifications, the one-sided capability index is defined as:

$$\hat{C}_{pu} = \frac{USL - \hat{\mu}}{3\hat{\sigma}} \tag{2}$$

$$\hat{C}_{pl} = \frac{\hat{\mu} - LSL}{3\hat{\sigma}} \quad (3)$$

Process capability ratio for an off-centered process, $\hat{C}_{pk}$, is defined as:

$$\hat{C}_{pk} = \min\left\{\hat{C}_{pl}, \hat{C}_{pu}\right\} \quad (4)$$

The $\hat{C}_{pk}$ estimates the process capability when the estimated process mean, $\hat{\mu}$, is not centered between the specifications limits. To calculate the process capability ratio, the quality characteristic should be normally distributed. Tables 3 and 4 display the quality characteristics' summary of process capability indices for row A and B, respectively.

Table 1. Summary of control charts calculations for row A.

Response	Individual values			Moving Range		
	LCL	*CL*	*UCL*	*LCL*	*CL*	*UCL*
y_1: Height	5.9595	6.0020	6.0445	0.00000	0.01598	0.05220
y_2: Inner Diameter	26.7491	26.7916	26.8342	0.00000	0.01602	0.05233
y_3: Outer Diameter	31.8836	31.9816	32.0796	0.00000	0.03680	0.12040
y_4: Angle	14.8815	15.2241	15.5614	0.00000	0.12780	0.41760
y_5: Plastic Weight	0.1941	0.1965	0.1989	0.00000	0.00090	0.00295

Table 2. Summary of control charts calculations for row B.

Quality	Individual values			Moving Range		
Characteristic	*LCL*	*CL*	*UCL*	*LCL*	*CL*	*UCL*
y_1	5.9274	6.0044	6.0814	0.00000	0.02890	0.09460
y_2	26.7557	26.7958	26.8358	0.00000	0.01506	0.04921
y_3	31.9372	31.9717	32.0061	0.00000	0.01296	0.04233
y_4	13.8220	15.0380	16.2550	0.00000	0.45700	1.49500
y_5	0.1936	0.1963	0.1990	0.00000	0.00101	0.00331

Table 3. Summary of process capability ratios for row A (Critical value =1.6).

Response	$\hat{\mu}$	$\hat{\sigma}$	C_p	C_{pl}	C_{pu}	C_{pk}	Decision
y_1	6.0020	0.014167	1.647	1.694	1.600	1.600	Critically Capable
y_2	26.7920	0.014202	2.347	2.159	2.535	2.159	Capable
y_3	31.9820	0.032624	2.043	0.838	3.249	0.838	Incapable
y_4	15.2210	0.113298	8.826	9.476	8.176	8.176	Capable
y_5	0.1965	0.000798	4.177	6.876	1.479	1.479	Incapable

Table 4. Summary of process capability ratios for row B (Critical value =1.6).

Response	$\hat{\mu}$	$\hat{\sigma}$	C_p	C_{pl}	C_{pu}	C_{pk}	Decision
y_1	6.0044	0.025621	0.911	0.880	0.968	0.853	Incapable
y_2	26.7960	0.013351	2.497	1.520	2.397	2.397	Capable
y_3	31.9720	0.011489	5.803	1.670	2.089	2.089	Capable
y_4	15.0380	0.405142	2.468	2.120	2.500	2.437	Capable

y_5	0.1963	0.000895	3.724	5.930	6.060	1.389	Incapable

From Table 3, it is noted that the process for row A is only found capable for y_2 and y_4. However, it is incapable for y_3 and y_5, critically capable for y_1. While in Table 4 for row B, the process is judged capable for y_2, y_3, and y_4. But it is found incapable for y_1 and y_5. These results urge to conduct process improvement to enhance caps quality and save significant production and quality losses.

3. Process Improvement

A designed experiment is extremely helpful in discovering the key variables influencing the quality characteristics of interest in the process, it is also an approach to systematically varying the controllable input factors in the process and determining the effect these factors have on the output product parameters. Statistically designed experiments are invaluable in reducing the variability in the quality characteristics and in determining the levels of the controllable variables that optimize process performance. The main factors affecting the crown caps quality characteristics are temperature of the cooling system in the whole machine (x_1), Machine production rate (x_2), extruder speed (x_3) ,and temperature of water to cool the punches (x_4). Four factors each at three levels will be investigated for the crown caps, Taguchi's orthogonal array L_{18} ($2^1 \times 3^7$) is utilized to conduct the designed experiments (Phadke, 1989; Taguchi, 1995). Current settings for the crown caps production machine are: Temperature of the cooling system at 3 C°, production rate of 2200 pc/min, Extruder speed of 30 rpm, and Temperature of water of 3 C°. The factor levels will be listed in Table 5.

Table 5. Physical values of process factor levels.

Factor	Level		
	1	2	3
x_1 (C°)	2	3	4
x_2(pc/min)	1900	2200	2500
x_3(rpm)	25	30	35
x_4(C°)	2	3	4

The experimental work was conducts utilizing the factor level combinations suggested in the L_{18} ($2^1 \times 3^7$) array. The resulted response measurements are summarized in Table 6.

Table 6. The experimental results.

Exp. *i*	**Factors**				**Responses**									
	x_1	x_2	x_3	x_4	y_{1Ai}	y_{1Bi}	y_{2Ai}	y_{2Bi}	y_{3Ai}	y_{3Bi}	y_{4Ai}	y_{4Bi}	y_{5Ai}	y_{5Bi}
1	2	1900	25	2	6.010	6.006	26.804	26.792	31.999	32.010	15.429	14.692	0.224	0.214
2	2	2200	30	3	6.011	6.004	26.803	26.804	31.966	31.995	15.071	15.308	0.217	0.219
3	2	2500	35	4	6.002	6.000	26.791	26.802	31.974	32.008	15.071	15.615	0.252	0.255
4	3	1900	25	3	6.023	6.027	26.761	26.768	31.938	32.002	15.429	15.077	0.226	0.220
5	3	2200	30	4	6.009	6.018	26.800	26.802	31.973	32.032	15.786	15.154	0.215	0.215
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
15	3	2500	25	3	6.026	6.023	26.773	26.775	31.941	31.960	15.429	15.000	0.190	0.194
16	4	1900	35	3	6.016	5.998	26.782	26.796	31.992	31.965	15.462	15.462	0.250	0.249
17	4	2200	25	4	6.012	6.024	26.793	26.819	31.969	31.976	14.929	15.154	0.214	0.219
18	4	2500	30	2	6.018	6.011	26.785	26.792	31.992	31.947	15.429	15.077	0.280	0.248

The proposed procedure for optimizing the crown caps production process is outlined in the following steps:

Step 1: Calculate the signal-to-noise (S/N, η_{ij}) ratio for each quality characteristic. Let η_{i1}, η_{i2}, η_{i3}, η_{i4}, and η_{i5} the

S/N ratio of the height, inner diameter, outer diameter, angle, and plastic weight at experiment i, respectively. The η_{ij} values; i=1,..., 18; j=1,...,5, are expressed using:

$$\eta_{ij}=10\left[\log\frac{\overline{y}_i^2}{s_i^2}\right], \quad j=1, 2, 3...5;\ i=1, 2, 3\ldots18 \tag{5}$$

where $\overline{y}_i^2$ and s_i^2 are the sample mean and variance, respectively at experiment i.

Step 2: It is necessary to normalize the S/N ratio before using relational grey analysis. Normalize η_{ij}, to avoid the effect of adopting different units of the five quality characteristics.

$$\eta^*_{ij}=\frac{\eta_{ij}-\min\{\eta_{ij}\}}{\max\{\eta_{ij}\}-\min\{\eta_{ij}\}} \quad j=1, 2, 3...5;\ i=1, 2, 3\ldots18 \tag{6}$$

Table 7. Calculated η_{ij} and η^*_{ij} values.

Exp. i	η_{i1}	η_{i2}	η_{i3}	η_{i4}	η_{i5}	η^*_{i1}	η^*_{i2}	η^*_{i3}	η^*_{i4}	η^*_{i5}
1	66.54370	69.98870	72.28670	29.21770	29.81920	0.76700	0.23727	0.80032	0.00328	0.33033
2	61.68220	91.57410	63.86000	39.14620	43.75880	0.57853	1.00000	0.37077	0.20930	0.77206
3	72.55420	70.74400	62.48130	32.01650	41.54740	1.00000	0.26396	0.30049	0.06136	0.70199
4	66.56820	74.65950	56.98160	35.74660	34.41340	0.76795	0.40232	0.02014	0.13876	0.47592
5	59.50800	85.55270	57.69690	30.78580	35.57810	0.49425	0.78723	0.05660	0.03582	0.51283
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
15	69.06630	85.54400	67.52480	34.00630	36.63510	0.86479	0.78692	0.55758	0.10264	0.54632
16	53.47800	68.64690	64.48020	77.25230	50.95170	0.26049	0.18986	0.40238	1.00000	1.00000
17	57.01570	63.27550	76.20390	39.51250	35.74010	0.39763	0.00006	1.00000	0.21690	0.51796
18	61.69230	74.66730	60.04080	35.74660	21.33940	0.57893	0.40259	0.17608	0.13876	0.06162

Step 3: Calculate the grey relational coefficient,

$$\gamma_{ij}=\frac{\min\{|1-\eta^*_{ij}|\}+\xi\max\{|1-\eta^*_{ij}|\}}{|1-\eta^*_{ij}|-\xi\max\{|1-\eta^*_{ij}|\}}, \quad \forall i, j, \tag{7}$$

where ζ is the distinguishing coefficient, which defined in the range [0, 1] and it is commonly set 0.5. Table 8 displays the values of the deviations and grey relational coefficients of each quality response for all experiments.

Step 4: Generate the grey relational grade, $\overline{\gamma}$, as follows:

$$\overline{\gamma}_i=\sum_{j=1}^{5}\gamma_{ij}, \quad \forall i \tag{8}$$

Table 9 summarizes the values of the grey relational grade for all experiments. Utilizing these values, the grey relation grade mean values are calculated and then displayed in Table 10, where the optimal combination of factor settings is identified as x_{12}, x_{22}, x_{32}, and x_{42}. While the combination of factor settings at initial factor settings is x_{13}, x_{21}, x_{33}, and x_{42}. The sum of grey grades at initial levels was calculated and found to be 1.9871. The anticipated improvement in the mean grey grade by using the combination of optimal factor settings is calculated and found to be 0.1729.

Table 8. Calculated values of the deviations and grey relational coefficients.

Exp. i	Δ_{i1}^*	Δ_{i2}	Δ_{i3}	Δ_{i4}	Δ_{i5}	γ_{i1}	γ_{i2}	γ_{i3}	γ_{i4}	γ_{i5}
1	0.23300	0.76273	0.19968	0.99672	0.66967	0.68212	0.39597	0.71461	0.33406	0.42747
2	0.42147	0.00000	0.62923	0.79070	0.22794	0.54261	1.00000	0.44278	0.38739	0.68687

3	0.00000	0.73604	0.69951	0.93864	0.29801	1.00000	0.40452	0.41684	0.34755	0.62656
4	0.23205	0.59768	0.97986	0.86124	0.52408	0.68301	0.45550	0.33787	0.36731	0.48824
5	0.50575	0.21277	0.94340	0.96418	0.48717	0.49714	0.70149	0.34640	0.34149	0.50650
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
15	0.13521	0.21308	0.44242	0.89736	0.45368	0.78714	0.70119	0.53055	0.35782	0.52429
16	0.73951	0.81014	0.59762	0.00000	0.00000	0.40338	0.38164	0.45553	1.00000	1.00000
17	0.60237	0.99994	0.00000	0.78310	0.48204	0.45357	0.33335	1.00000	0.38968	0.50914
18	0.42107	0.59741	0.82392	0.86124	0.93838	0.54284	0.45562	0.37767	0.36731	0.34761

*$\Delta_i = \left|1 - \eta^*_{ij}\right|$.

Table 9. The grey relational grade.

Exp. i	$\overline{\gamma}_i$	*Exp. i*	$\overline{\gamma}_i$
1	0.49205	10	0.39935
2	0.50568	11	0.39703
3	0.46365	12	0.55984
4	0.39781	13	0.49762
5	0.39813	14	0.53371
6	0.60959	15	0.47088
7	0.48335	16	0.81851
8	0.49306	17	0.63294
9	0.51539	18	0.36420

Table 10. Grey relation grade mean values.

	*Factor			
Level	x_1	x_2	x_3	x_4
level 1	0.4696	<u>0.5148</u>	0.4844	0.48
level 2	**0.4846**	**0.4934**	**0.4681**	**<u>0.541</u>**
level 3	<u>0.5512</u>	0.4973	<u>0.553</u>	0.4845
Σ optimal	2.16			
Σ initial	1.9871			
Improvement	**0.1729**			

* Initial factor and optimal levels are bolded and underscored, respectively.

4. Results

Table 11 displays the anticipated improvements in the five quality responses. It is found that, by setting the factors at optimal setting identified using the grey relational analysis, the anticipated improvements (dB) in the cap's height, inner diameter, outer diameter, angle, and plastic weight are calculated and found to be 1.06, -18.11, 1.94, 22.22, and 2.67, respectively. Accordingly, the process factors are suggested to be set as follows: temperature of the cooling system (x_1) at 4 degrees, production rate (x_2) of 1900 piece/minute, extruder speed (x_3) at 35 rpm, and temperature of water (x_4) of 3 C^o. Such improvements will result in significant savings in production and quality losses.

Table 11. The anticipated improvements in quality characteristics using grey grade analysis.

*Factor	Height				Inner diameter				Outer diameter			
	x_1	x_2	x_3	x_4	x_1	x_2	x_3	x_4	x_1	x_2	x_3	x_4
level 1	59.89	60.80	59.03	55.54	75.51	71.11	73.72	74.46	64.36	63.74	65.43	65.43
level 2	**60.27**	**56.86**	**57.80**	**60.21**	**76.52**	**81.25**	**76.20**	**78.26**	**63.81**	**65.53**	**60.25**	**61.67**
level 3	55.93	58.43	59.26	60.34	71.32	70.98	73.43	70.62	62.65	61.55	65.14	63.73
Σ optimal	236.2				294.12				253.2			
Σ initial	235.14				312.23				251.26			
Improvement	**1.06**				**-18.11**				**1.94**			

*Factor	Angle (dB)				Plastic weight (dB)			
	x_1	x_2	x_3	x_4	x_1	x_2	x_3	x_4
level 1	37.24	42.66	34.97	36.83	31.84	37.09	34.97	31.26
level 2	**37.36**	**39.65**	**38.57**	**49.84**	**37.44**	**35.36**	**38.27**	**40.56**
level 3	47.04	39.34	48.1	34.96	39.74	37.01	36.91	37.66
Σ optimal	187.64				154.3			
Σ initial	165.42				151.63			
Improvement	**22.22**				**2.67**			

*Note: Initial factor and optimal levels are identified by a bold type and underscore, respectively.

5. Conclusions

In this research, the grey relational analysis is employed to optimize caps' manufacturing process for multiple quality characteristics; height, inner diameter, outer diameter, angle, and plastic weight. Four process factors are studied utilizing the Taguchi's orthogonal L_{18} array. Optimization results showed that the optimal setting of temperature of the cooling system, production rate, and extruder speed. At these settings, the anticipated improvements (dB) in the cap's height, inner diameter, outer diameter, angle, and plastic weight are estimated 1.06, -18.11, 1.94, 22.22, and 2.67, respectively. The results of this research provide valuable assistance to production engineers on how to enhance the capability of cap's process and improve its quality.

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