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Keywords

Mouldability, Optimization techniques, Design management

Abstract

This paper presents a study on implementing design of experiments for optimizing the extrusion blow molding process. The effect of screw speed, melting temperature, cooling time, pressure, mold temperature, and ambient temperatures on the outcome of the process is investigated. The significant factors affecting the volume and mass of the blow molded bottles are identified. The results show that melting temperature, pressure, and ambient temperature have a significant impact on the variation of produced bottle quality. An optimization technique is implemented to identify the best operating conditions to meet the required product output.

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Practical implications

Optimization of manufacturing processes and parameters control are known to have direct impact on the production line maintenance and operations. In this paper the extrusion blow molding process is optimized taking into consideration the effect of process parameters. This paper's results shed light onto the process that, if taken into consideration, is expected to increase the molding process efficiency and productivity. The major parameters affecting the process are melting temperature, pressure, and ambient temperature. These factors have a direct effect on the condition of the components of the extruder that influence its life and maintenance requirements. For example, excessive rise in temperature would result in extruder screw deformation and affects the life of the equipment. Lower temperatures would increase the viscosity of the melt and cause pressure build up which could also affect the life and performance of the equipment. Operating at optimum conditions will have both technological and economical benefits.

1. Introduction

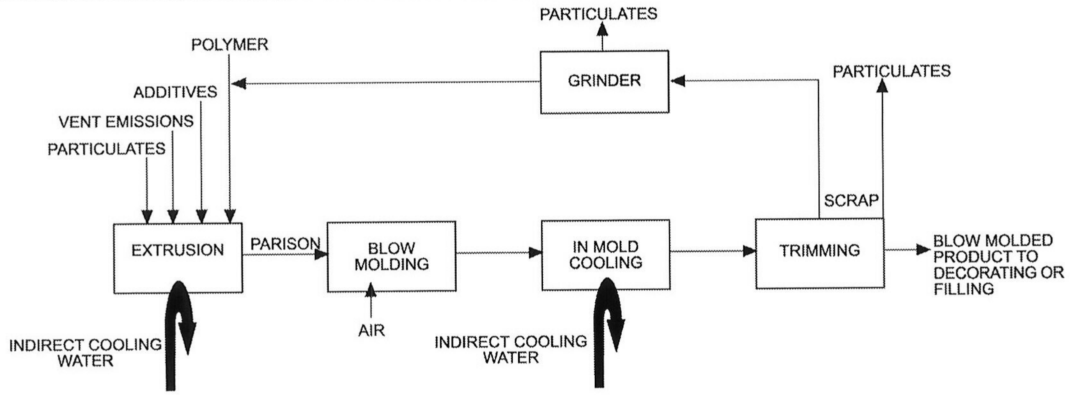
Blow molding is the wold's third largest plastics processing technique. Blow molding is used to produce hollow, thin wall objects from thermoplastic materials. In the last 20 years blow molding have seen a rapid growth due to the development of new application areas in the automotive, sports and leisure, electronics, transportation and packaging industries (Gao *et al.*, 1998). The complexity of these new molding techniques calls for a much better understanding of the process, machine and material behavior and its effect on the performance of the final part.

Blow molding processes can be divided into two main categories:

(1) Extrusion blow molding.
(2) Injection blow molding.

Extrusion blow molding is a continuous blow molding process capable of high production rates. The extrusion blow molding process involves three main stages, i.e. parison formation, parison inflation, and part solidification (see Figure 1). Polymer powder or pellets, colorants and other additives are fed to a rotating screw extruder where they are mixed and heated into a homogenous melt. The plastic melt is forced through a die, which forms the plastic into a parison shaped as a cylindrical tube. Compressed air is introduced into the parison by a blow pin at the top. The air pressure forces the parison to conform to the inner

Figure 1 Extrusion blow molding process chart



shape of the mold. The mold halves are cooled by indirect cooling water thereby solidifying the blown melt into its final product shape. When the part has sufficiently cooled to hold the desired shape, the mold halves open and the part is stripped from the mold.

Operating parameter optimization is considered the main challenge for the extrusion blow molding process. This is due to the high sensitivity of the process to the smallest variations in the settings and/or the surrounding environment. Several different techniques have been utilized in the literature for the study and evaluation of the blow molding process. These techniques include, search algorithms (Wang and Makinouchi, 2000), digitized video techniques (Kumaravel and Jabarin, 1996), optical techniques (Swan *et al.*, 1996), statistical response surface method (Martins and De Paoli, 2001), artificial neural networks (Woll *et al.*, 1996; and Huang and Liao, 2002), and Finite element and numerical simulation (Tanoue *et al.*, 1996; Marckmann *et al.*, 2001; Debbaut *et al.*, 1999; Laroche *et al.*, 1999; Liu, 1999; Schmidt *et al.*, 1998; McEvoy *et al.*, 1998; and Tanifuji *et al.*, 2000).

Statistical quality control and the use of design of experiments techniques have been used where variation in machine and process parameters are used to indicate variation in product quality. Design of experiments (DOE) is an efficient problem solving quality improvement technique that can be used for various experimental investigations. The application of DOE is a powerful methodology which if properly used leads to a great deal of insight about experimental processes. Prasad (1997) presented the key factors that need to be considered in PVC compounding or bottle blow molding set-up in a generic format to show the merit and applicability to other manufacturing industries. Lu and Khim (2001) implemented statistical methods in the injection molding of plastic optical lenses, the processing conditions have critical effects on the quality of the molded lenses. Statistical methods were employed in the experimental studies in order to systematically analyze the effects of various process parameters on the lens contour errors. Barbosa and Kenny (1999) presented a statistical analysis of the relationship between processing conditions and final properties applying modern experimental design concepts. Tseng (1998) implemented a statistical two-level, 16-run factorial experiment to evaluate the influence of various process parameters on the dimensional variation of injection-molded ceramics. Skourlis *et al.* (1997) presented the effect of processing conditions on the performance of advanced styrenic resins (ASR). Loh and German (1996) conducted a 2(4) factorial design to establish the effects of powder injection molding (PIM) parameters on the shrinkage properties of the widely used Fe-Ni powder system. An analysis of variance, together with the *F*-test, was used to determine the statistical significance of each of the parameters on the length, width and thickness shrinkages.

In this paper, the optimization of operating process parameters of an extrusion blow molding process is investigated using DOE techniques. The process under investigation here is an existing industry in Jordan that was plagued by high variation in product output, namely volume and mass of produced bottles. The objective here is to determine the optimal process parameter settings that yield the required volume and mass of the produced bottles by utilizing analysis of variance (ANOVA), regression analysis, and optimization.

2. The DOE implementation

After a thorough investigation of the existing process, the factors that affect the volume and mass of the produced bottles were identified as:

- cooling time;
- screw speed;
- melting temperature;
- blow pressure;
- blowing time; and
- mold temperature.

Other factors that are related to the mold behavior, but were not considered significant in this work, include:

- opening-mold time;
- time before closing the mold;
- closing speed; and
- mold positioning.

Furthermore, it has been determined that the acceptable specification on the volume of produced bottles should fall within $407 \leq V \leq 415$ml.

As a first step in analyzing this problem and in order to estimate the current operating conditions of the blow molding machine under investigation, $\bar{X}$ and R control charts were established with a sample size of five bottles. A sample was taken every 30 minutes for a total of 20 samples. The resulting charts are shown in Figure 2. The charts show that the process is in statistical control and is centered around 414ml with an average range of 1.6. Accordingly, setting 3σ natural limits implies that volume will vary between 416ml and 412ml. It is hence clear that a study to improve the performance of the machine is needed. It is noted here that, although the process is producing bottles that fall nearly within specification limits, this setting does note produce the specified target for the volume. The following objectives are hence set for the study: First, to center the process as close as possible to 411ml volume. This can be done by determining the significant factors affecting the volume and setting these factors at the levels that produce the target volume. Second, to identify possible sources of variation (factors) in volume, and to eliminate or reduce their effect. Since the variations in bottle volume will have an affect on the mass of the produced bottles, mass is also investigated in this study.

2.1 Selection of factors

The following factors (controllable) are determined to have significant effect on the volume of bottles produced:

- blow pressure;
- screw speed;
- cooling time; and
- melting temperature.

The mold temperature depends on ambient temperature (uncontrollable). This dependency exposes the mold temperature to large variation. Ambient temperature is believed to have two effects; the first one is on the product after production (expansion or shrinkage) while the other effect is on the process during manufacturing. The effect of ambient temperature on products after production can be estimated by heating the bottles to 40° and cooling them to 7°, respectively. This treatment of ambient temperature enables the mold temperature and the effect of ambient temperature on products after production to be included in the experiment as two separate factors.

2.2 Selecting the levels of the factors

Two levels for each factor are considered to minimize the number of runs. The ranges of these levels are set around the current operating conditions as shown in Table I.

2.3 Constructing the fractional factorial design

Interest here is in the main effects and to get information about the two-factor interactions. Hence, higher order interactions are assumed to be negligible and are not considered in the analysis of the data. Since there are six factors to consider, then a 2^{6-1} full factorial design with 32 runs and 31 degrees of freedom (dof) is needed to estimate the effects. In order to reduce the number of runs, a 2^{6-2} fractional factorial design is chosen with $n = 3$ as a replicate number; three readings for volume and three readings for mass at each factors combination. This design contains 16 runs and 15 dof. The resulting fraction is shown in Table II, and the complete defining relation for the design is given by: $I = ABCE = BCDF = ADEF$. This defining relation has been used to find the aliases of the factors considered in the experiment.

2.4 Experimental data analysis

A completely randomized experiment was carried out. The data obtained from the experiment and the calculated total volume (TV), total mass (TM), and standard deviation (sd) at each factors combination is presented in Table III. For every main effect and interaction the contrast, effect, and sum of squares were calculated as shown in Table IV.

ANOVA tables are then presented in Table V for volume and Table VI for mass. Table V shows that A (screw speed), B (melting temperature), C (cooling time), and F (ambient temperature) main effects are significant in their contribution to volume. The two factor interactions, AB+CE, AC+BE, and CF+BD are also significant. Since the factors A, B, C, and F are the largest, the interaction CF is recorded in the ES column in the row of BD effect. Table VI shows that A, C, and E (mold temperature) main effects are significant in their contribution to mass. The two factor interaction AC+BE is also significant.

Figure 2 $\bar{X}$ and R charts for the blow molding process

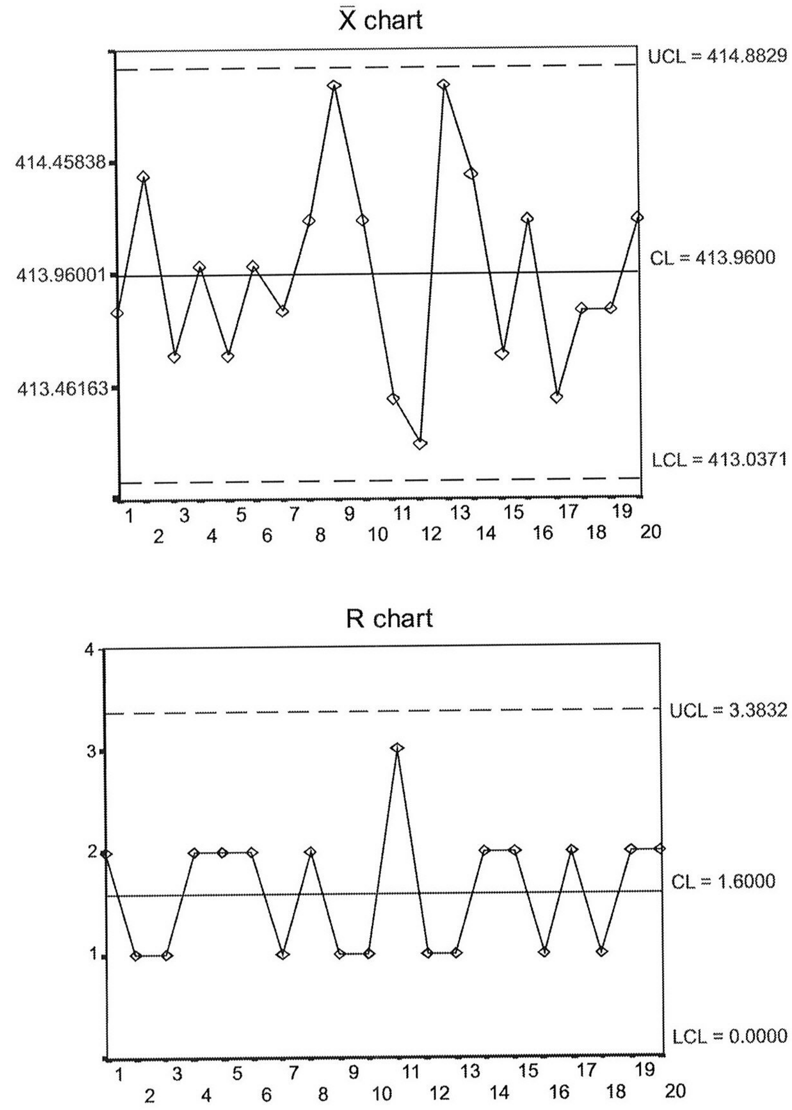


Table I Selected levels for the factors

	Variable name		Low value (−)	High value (+)
X_1	A: Screw speed (rpm)	Controllable	425	455
X_2	B: Melting temp (°C)	Controllable	165	175
X_3	C: Cooling time (sec)	Controllable	20	23
X_4	D: Pressure (bar)	Controllable	4.5	6
X_5	E: Mold temp. (°C)	Uncontrollable	17	20
X_6	F: Ambient temp. (°C)	Uncontrollable	7	40

2.5 Model building

In order to quantify the relationship between the input variables and the output responses, and utilizing the linearity assumption the volume and mass equations can be calculated using the regression analysis. After repetitive model building and checking, the best-fit model was selected to have the following formula for the volume (equation (1)) below:

$$V = \beta_o + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_3 + \beta_6 X_6 + \beta_{12} X_1 X_2 + \beta_{13} X_1 X_3 + \beta_{36} X_3 X_6 \ldots \quad (1)$$

where:

- β_o = grand average of all observations;
- β_i = Effect $(X_i)/2$;

Table II Design of the experiment

Run	A	B	C	D	E	F	ΣYi
1	−1	−1	−1	−1	−1	−1	1
2	+1	−1	−1	−1	+1	−1	ae
3	−1	+1	−1	−1	+1	+1	bef
4	+1	+1	−1	−1	−1	+1	abf
5	−1	−1	+1	−1	+1	+1	cef
6	+1	−1	+1	−1	−1	+1	acf
7	−1	+1	+1	−1	−1	−1	bc
8	+1	+1	+1	−1	+1	−1	abce
9	−1	−1	−1	+1	−1	+1	df
10	+1	−1	−1	+1	+1	+1	adef
11	−1	+1	−1	+1	+1	−1	bde
12	+1	+1	−1	+1	−1	−1	abd
13	−1	−1	+1	+1	+1	−1	cde
14	+1	−1	+1	+1	−1	−1	acd
15	−1	+1	+1	+1	−1	+1	bcdf
16	+1	+1	+1	+1	+1	+1	abcdf

- β_{ij} = Effect (X_i X_j)/2; and
- X_i: take values between the low and high values given in Table I.

It should be noted here that the regression coefficient is one-half the effect estimate since the regression coefficients measure the effect of a unit change in the main effect while the effect estimates are based on a two-unit change from −1 to +1.

Solving the regression coefficients in equation (1) using least squares yields:

$$V = 2858.198 - 5.827X_1 - 12.921X_2 - 13.468X_3 + 1.061X_6 + 0.0297X_1X_2 + 0.04X_1X_3 - 0.0465X_3X_6 \quad (2)$$

Using the symbols A, B, C, and F instead of the X_I's, equation (2) becomes:

$$V = 2858.198 - 5.827A - 12.921B - 13.468C + 1.061F + 0.0297AB + 0.04AC - 0.0465CF \quad (2.1)$$

In a similar manner the regression equation for mass can be obtained as:

$$M = -186.183 + 0.574X_1 + 11.674X_3 - 0.431X_5 - 0.0287X_1X_3 \quad (3)$$

Or using A, C, and E:

$$M = -186.183 + 0.574A + 11.674C - 0.431E - 0.0287AC \quad (3.1)$$

Table III Measured weight, volume, and standard deviation for bottles

CN	M	V	TV	TM	sd
	42	404			
1	40	407			
	40	409	1220	122	2.516
	39	401			
2	40	403			
	40	401	1205	119	1.153
	38	409			
3	39	407			
	40	404	1220	117	2.516
	41	407			
4	37	414			
	38	413	1234	116	3.785
	40	410			
5	36	417			
	37	415	1242	113	3.6056
	36	417			
6	38	413			
	38	415	1245	112	2
	38	413			
7	38	414			
	39	413	1240	115	0.5745
	34	421			
8	33	422			
	33	422	1265	100	0.5745
	39	412			
9	39	412			
	38	413	1237	116	0.5745
	39	409			
10	39	408			
	40	407	1224	118	1
	38	404			
11	40	399			
	39	404	1207	117	2.8862
	39	411			
12	39	411			
	41	409	1231	119	1.1533
	37	415			
13	36	418			
	38	413	1246	111	2.5159
	37	416			
14	37	417			
	37	416	1249	111	0.5745
	38	415			
15	38	414			
	38	415	1244	114	0.5745
	33	422			
16	33	421			
	33	423	1266	99	1

Notes: CN: coded number for factors combination: M: mass of empty bottle; V: volume

2.6 Optimization

The standard deviations for every three volume readings at each factors combination that are included in the fractional factorial experiment were calculated in Table III. Using regression

Table IV Calculated effects, contrasts, and sum of squares

	Volume			Mass		
	Effect	Contrast	SS	Effect	Contrast	SS
ABD	0.2083	5	0.5208	−0.125	−3	0.1875
ACD	−0.625	−15	4.6875	−0.292	−7	1.0208
BF	−0.292	−7	1.0208	−0.042	−1	0.0208
BD	−2.292	−55	63.021	0.4583	11	2.5208
AF	−0.458	−11	2.5208	0.0417	1	0.0208
AE	1.125	27	15.188	−0.542	−13	3.5208
AD	0.375	9	1.6875	0.375	9	1.6875
AC	1.7917	43	38.521	−1.292	−31	20.021
AB	4.4583	107	238.52	−1.125	−27	15.188
F	2.0417	49	50.021	−0.375	−9	1.6875
E	−1.042	−25	13.021	−1.292	−31	20.021
D	1.375	33	22.688	−0.375	−9	1.6875
C	9.125	219	999.19	−2.875	−69	99.188
B	1.625	39	31.688	−1.042	−25	13.021
A	2.625	63	82.688	−1.292	−31	20.021
$SS_T(V)$			1,695		$SS_T(M)$	234.8
$SS_E(V)$			130		$SS_E(M)$	34.67

Table V ANOVA table for volume

p_value	f_o	MS	Dof	SS		ES
8E-05	20.354	82.688	1	82.688	A	A
0.0088	7.8	31.688	1	31.688	B	B
0	245.95	999.19	1	999.19	C	C
0.0244	5.5846	22.688	1	22.688	D	
0.0829	3.2051	13.021	1	13.021	E	
0.0014	12.313	50.021	1	50.021	F	F
0	58.713	238.52	1	238.52	AB	AB
0.0004	9.4821	38.521	1	38.521	AC	AC
0.5238	0.4154	1.6875	1	1.6875	AD	
0.0621	3.7385	15.188	1	15.188	AE	
0.4367	0.6205	2.5208	1	2.5208	AF	
0.0004	15.513	63.021	1	63.021	BD	CF
0.6196	0.2513	1.0208	1	1.0208	BF	
0.2908	1.1538	4.6875	1	4.6875	ACD	
0.7227	0.1282	0.5208	1	0.5208	ABD	
		4.0625	32	130	ERROR	
			47	1695	TOTAL	

Note: ES: effective source, reject if *p*_value ($P(f_{1,32} > f_0)$) < 0.01

analysis those factors that significantly affect the variability in volume can be identified. After repetitive model building and checking, the best-fit model was selected to have the following formula for the standard deviation (SD) is obtained:

$$SD = \beta_o + \beta_1 X_1 X_3 + \beta_2 X_3 X_6 + \beta_3 X_4 X_5 + \beta_4 X_4 X_6. \tag{4}$$

The parameters (β_i) can be estimated using the matrix approach to multiple linear regression which gives the least squares estimates β matrix as shown in equation (5).

$$\beta^\wedge = (X^T X)^{-1} X^T SD \tag{5}$$

Table VI ANOVA table for mass

F_0	MS	dof	SS		ES
4.92821	20.0208	1	20.0208	A	A
3.20513	13.0208	1	13.0208	B	
24.4154	99.1875	1	99.1875	C	C
0.41538	1.6875	1	1.6875	D	
4.92821	20.0208	1	20.0208	E	E
0.41538	1.6875	1	1.6875	F	
3.73846	15.1875	1	15.1875	AB	
4.92821	20.0208	1	20.0208	AC	AC
0.41538	1.6875	1	1.6875	AD	
0.86667	3.52083	1	3.52083	AE	
0.00513	0.02083	1	0.02083	AF	
0.62051	2.52083	1	2.52083	BD	
0.00513	0.02083	1	0.02083	BF	
0.25128	1.02083	1	1.02083	ACD	
0.04615	0.1875	1	0.1875	ABD	
	1.08333	32	34.6667	ERROR	
		47	234.479	TOTAL	

Note: Reject if $f_0 > (f_{0.05,1,32} = 4.15)$

Applying equation (5) and substituting the values obtained for β_i in equation (4), the standard deviation equation without coding becomes:

$$SD = 7.933 - 0.00103 X_1 X_3 + 0.0125 X_3 X_6 + 0.0334 X_4 X_5 - 0.0492 X_4 X_6 \tag{6}$$

Or using A, C, D, E, and F we get:

$$SD = 7.933 - 0.00103 AC + 0.0125 CF + 0.0334 DE - 0.0492 DF \tag{6.1}$$

Our main objective is to target the process at producing bottles with 411ml volume mean and minimum variability while taking the physical limitations of the factors and the limitations on mass into consideration. Mathematically, the problem of minimizing variability in volume can be formulated as:

$$\text{Minimize} : SD$$

subject to:

$$410.5 \le v \le 411.5$$
$$35 \le m \le 39$$
$$425 \le A \le 455$$
$$165 \le B \le 175$$
$$20 \le C \le 23$$
$$4.5 \le D \le 6$$

It is noted that the uncontrollable variables are not considered as variables during solving the problem, because it would be meaningless to give the best operating conditions with minimum variability at specific values, obtained by the solution, for the uncontrollable variables. Instead, values for the uncontrollable variables in the equations will be substituted by constants. The goal is to move the operating conditions toward the optimum. The method should not require large or sudden changes that might disrupt production. Controllable variables are set at the levels that minimize variability at different values for the uncontrollable variables.

In order to cover all the working range of the uncontrollable variables, i.e, $16 \leq E \leq 22$, and $7 \leq F \leq 40$, three levels for each of the two uncontrollable variables are selected (the two extremes, and the mid point). The optimization problem was then solved for each combination using microsoft Excel and the results are shown in Table VII.

The value of the cooling time at the optimum is not practically attainable, so it was rounded to the nearest 0.5 seconds taking into consideration that the solution does not shift away from the optimum and the feasibility.

It should be pointed out here that the values used in Table VII take into consideration the feasibility of the produced values of V and M in equations (2.1) and (3.1), respectively. That is to say that V should be within the 410.5 and 411.5 range, and M within the 38 and 39 range. Also, a value for B is recorded since it is required for the calculation of V in equation (2.1).

Applying the optimal solution results will not cause any sudden changes in the operating conditions during any production day over the range of mold temperature. The difference between working conditions exists between summer and winter which can be handled easily, and the operators will not find it a complex job to monitor the process using these results.

Table VII Optimum setting for controllable variables

		E		
22	**19**	**16**		
455	455	455	A	
165	165	165	B	
22	22	22	C	
4.5	4.5	4.5	D	F = 10
1.4674	1.0161	0.5648	SD	
411.569	411.569	411.569	V	
35.0586	36.3506	37.6426	M	
455	455	455	A	
165	165	165	B	
21.5	21.5	21.5	C	
6	6	6	D	F = 25
1.6165	1.0148	0.41311	SD	
410.363	410.36289	410.3629	V	
35.7530	37.0451	38.3371	M	
455	455	455	A	
171	171	166	B	
20	20	21	C	
6	6	6	D	F = 40
1.1805	0.5788	0.0092	SD	
410.628	410.628	410.461	V	
37.8363	39.1283	39.0315	M	

2.7 Confirmation experiment

In order to validate the results of Table VII, a confirmation experiment was conducted. On the day of the confirmation experiment mold and ambient temperatures were 22° and 18°, respectively. Solving the optimization problem with these values, the following settings were determined:

- A: Screw speed = 455 rpm;
- B: Melting temperature = 165°;
- C: Cooling time = 22 sec; and
- D: Blow pressure = 6kg/cm.

The volume and mass for ten bottles sampled at the above settings is shown in Table VIII. The experiment shows that the resulting volume mean is equal to 408.6ml and the mass mean is equal to 38.8gm.

It is noted here that although the results for volume are less than the set target but they have less variation and more consistency when compared to the situation in Figure 2.

3. Summary and conclusions

In this paper a DOE approach for optimizing the extrusion blow molding process was investigated. The effect of screw speed, melting temperature, cooling time, pressure, mold temperature, and ambient temperatures on the outcome of the process was studied. The significant factors affecting the volume and mass of the blow molded bottles were identified to be, melting temperature, pressure, and ambient temperature. An optimization technique was then implemented to identify the best operating conditions to meet the

Table VIII Confirmation data

Sample	Volume (ml)	Mass (gm)
1	408	38.8
2	409	38.7
3	408	38.8
4	408	38.9
5	409	38.8
6	409	38.7
7	409	38.7
8	409	38.8
9	408	38.9
10	409	38.9

required product quality. Confirmation experiments with operating settings determined from the optimization table were conducted. The resulting bottle mean volume was 408.6ml which is lower than the required volume of 411ml. The most reasonable explanation for this deviation was attributed to variations in ambient temperature. It is noted here that the results obtained in this study were quite satisfactory for the concerned Jordanian industry since they were able to reduce volume variations in the produced bottles.

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