ST 516 Final Project

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Executive Summary:

A manufacturer that makes precision plastic parts needed our project team's help to optimize the transfer molding process to minimize the variability in the parts. The objectives were to identify any significant main effects of process parameters and interactions on the variability of the final part, build a model to predict variability from the significant factors, and generate a list of optimal settings/characteristics based on that model. Six different data requests were sent, totaling 74 runs and $74,000. Initially, the team had mixed thoughts about the inclusion of the Dwell Time as one of the main effects as when we analyze data as a whole, but it was cleared after analysis of the fifth run. The first request was an initial screening design, which after analysis yielded significant factors as **Cure Temperature, Cure Time, and Material Percent Resin**. The second request was to gather more data on the factors having more. The third one, revolved around center point runs of the three of the significant factors while the fourth run was made up of four center runs of then believed four significant factors. The fifth was a composite design run which included the axial runs for four factors of interest which finally reinforced our belief that the active factors did not include Dwell Time. The final run consisted of the axial runs of Cure Temperature, Cure Time and Material Percent Resin. The list of optimal settings to minimize variability is 10 cc/sec for Material Flow Rate, 200°C for Mold Temperature, and 150 MPa for Mold Pressure. Finally, we ran one large model with all run requests to confirm the results.

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1. Introduction

Our project team was working for a manufacturer that makes a high volume of precision plastic parts using a transfer molding process. As precision parts are manufactured at the plates the manufacturer would be seriously considerate about the variability of geometrical features. The process starts with the mixing of a specific percentage of resin into glass fiber and then preheating it. Next, the mixture is injected into a mold cavity kept under a given temperature and pressure. After a specific dwell time, the parts are removed from the cavity and transferred to a low-temperature curing oven for a prolonged time to stabilize geometry.

Our project team wanted to run a process experiment to determine the best combination of settings for the molding process to minimize the geometrical variability. The following factors were put to the investigation: Material flow rate (ranges from 3-10 cc/sec); Mold temperature (ranges from 200-300 °C); Mold pressure (ranges from 50 to 150 MPa); Dwell time (ranges from 5 to 20 sec); Cure temperature (ranges from 30 to 60 °C); Cure time (ranges from 5 to 15 hours); Material percent resin (ranges from 10% to 50%); Raw material supplier (Dexter or Polymax). The objectives were to identify any significant main effects and interactions on variability, build a model to predict variability from the significant factors, and generate a list of optimal settings/characteristics based on that model. The team had $100,000 for the experimental runs, with each run costing $1000.

For reference, A = Material Flow Rate; B = Mold Temperature; C = Mold Pressure; D = Dwell Time; E = Cure Temperature; F = Cure Time; G = Material Percent Resin; H = Raw Material Supplier.

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2. Experimental Design

2.1. Data Request 1: Initial Screening Design

The initial screening design has 2^{8-4} fractional factorial designs with resolution IV. This model includes all the main factors and some two-factor interactions. Figure 1 shows the initial screening design with all values.

	Pattern	flow rate	mold temp	mold pressure	dwell time	cure temp	cure time	material percent resin	raw meterial supplier	Variability
1	−−−−−−...	3	200	50	5	30	5	10	Dexter	528.2473524
2	−−−+++...	3	200	50	20	60	15	10	Polymax	455.8830768
3	−−+−++...	3	200	150	5	60	15	50	Dexter	546.664367
4	−−++−−...	3	200	150	20	30	5	50	Polymax	582.8485821
5	−+−−+−...	3	300	50	5	60	5	50	Polymax	565.6341698
6	−+−+−+...	3	300	50	20	30	15	50	Dexter	472.6607491
7	−++−−+...	3	300	150	5	30	15	10	Polymax	422.0845729
8	−++++−...	3	300	150	20	60	5	10	Dexter	465.6704233
9	+−−−−+...	10	200	50	5	30	15	50	Polymax	490.2102774
10	+−−++−...	10	200	50	20	60	5	50	Dexter	541.1396677
11	+−+−+−...	10	200	150	5	60	5	10	Polymax	488.5082085
12	+−++−+...	10	200	150	20	30	15	10	Dexter	341.3880405
13	++−−++...	10	300	50	5	60	15	10	Dexter	583.0994478
14	++−+−−...	10	300	50	20	30	5	10	Polymax	489.1839789
15	+++−−−...	10	300	150	5	30	5	50	Dexter	583.4421075
16	++++++...	10	300	150	20	60	15	50	Polymax	534.9683156

Figure 1: Initial screening design including all factors with low and high values

2.2. Data Request 2: Fold-over Experiment Design

The single factor fold over design has 16 experimental runs. This is a follow-on experiment to de-alias interactions. All main factors and some two-factor interactions are included. Figure 2 shows the follow-on experiment design.

	Pattern	flow rate	mold temp	mold pressure	dwell time	cure temp	cure time	material percent resin	raw meterial supplier	Variability
1	−−−−−+...	3	200	50	5	30	15	50	Polymax	455.8314769
2	−−−++−...	3	200	50	20	60	5	50	Dexter	540.6427799
3	−−+−+−...	3	200	150	5	60	5	10	Polymax	494.2309663
4	−−++−+...	3	200	150	20	30	15	10	Dexter	329.3380541
5	−+−−++...	3	300	50	5	60	15	10	Dexter	504.8449839
6	−+−+−−...	3	300	50	20	30	5	10	Polymax	510.8073217
7	−++−−−...	3	300	150	5	30	5	50	Dexter	601.7493308
8	−+++++...	3	300	150	20	60	15	50	Polymax	569.689743
9	+−−−−−...	10	200	50	5	30	5	10	Dexter	543.7839089
10	+−−+++...	10	200	50	20	60	15	10	Polymax	411.9569056
11	+−+−++...	10	200	150	5	60	15	50	Dexter	556.2384939
12	+−++−−...	10	200	150	20	30	5	50	Polymax	555.0368491
13	++−−+−...	10	300	50	5	60	5	50	Polymax	536.798706
14	++−+−+...	10	300	50	20	30	15	50	Dexter	485.3665147
15	+++−−+...	10	300	150	5	30	15	10	Polymax	412.5891453
16	+++++−...	10	300	150	20	60	5	10	Dexter	448.031089

Figure 2: Follow-on fold over experiment design including all factors with low and high values

2.3. Data Request 3 and 4: Center-Runs for most active factors

From the previous two runs, we narrowed down only four factors that had main effects on the variability and requested for their center runs. In data we tried to find the effect of cure temperature with cure time, material resin and dwell time, hence we centered runs around cure time and material percent resin. Figure 3 shows center runs and figure 4 shows four-factor central runs to add to data.

	Pattern	cure temp	cure time	material percent resin	flow rate	mold temp	mold pressure	dwell time	material supplier	Y
1	--------	30	5	10	3	200	50	5	Dexter	523.5859076
2	--+-----	30	5	50	3	200	50	5	Dexter	519.5633601
3	-+------	30	15	10	3	200	50	5	Dexter	405.1904384
4	-++-----	30	15	50	3	200	50	5	Dexter	469.6354181
5	-00-----	30	10	30	3	200	50	5	Dexter	72.55210537
6	-00-----	30	10	30	3	200	50	5	Dexter	81.51035681
7	-00-----	30	10	30	3	200	50	5	Dexter	45.08369283
8	-00-----	30	10	30	3	200	50	5	Dexter	35.76495731
9	+00-----	60	10	30	3	200	50	5	Dexter	92.55739215
10	+00-----	60	10	30	3	200	50	5	Dexter	107.2420377
11	+00-----	60	10	30	3	200	50	5	Dexter	70.9071019
12	+00-----	60	10	30	3	200	50	5	Dexter	55.33214762
13	+-------	60	5	10	3	200	50	5	Dexter	434.6831063
14	+-+-----	60	5	50	3	200	50	5	Dexter	604.8539473
15	++------	60	15	10	3	200	50	5	Dexter	464.5250412
16	+++-----	60	15	50	3	200	50	5	Dexter	585.2434352

Figure 3: Center Runs for most active factors

	Pattern	mold pressure	Mold temperature	Material flow rate	Dwell time	Cure temp	cure time	material percent resin	Raw material supplier	variability
1	---0000-	50	200	3	12.5	45	10	30	Dexter	42.40982349
2	---0000-	50	200	3	12.5	45	10	30	Dexter	36.78094704
3	---0000-	50	200	3	12.5	45	10	30	Dexter	54.89839821
4	---0000-	50	200	3	12.5	45	10	30	Dexter	5.617659034

Figure 4: Center Runs

2.4. Data Request 5 and 6: The fifth request was a central composite design.

Data request 5 run included runs of the best values for flow rate, mold temperature, mold pressure, and material obtained from previous requests. Additionally, axial points for each continuous factor were calculated using the range of the factor and $\pm\sqrt{k}$. These axial points were run with the center points of active factors. This data request totaled 16 runs. Data request 6 had six runs with axial runs for three active factors that are required to validate the active three factors.

	Pattern	flow rate	mold temp	mold pressure	dwell time	cure temp	cure time	material percent resin	raw meterial supplier	Variability
1	+-+0000-	10	200	150	12.5	45	10	30	Dexter	54.89258373
2	+-+0000-	10	200	150	12.5	45	10	30	Dexter	51.08619844
3	+-+0000-	10	200	150	12.5	45	10	30	Dexter	10.52733743
4	+-+0000-	10	200	150	12.5	45	10	30	Dexter	10.98068124
5	+-++-+--	10	200	150	20	30	15	10	Dexter	351.145441
6	+-++-+--	10	200	150	20	30	15	10	Dexter	390.6214254
7	+-++-+--	10	200	150	20	30	15	10	Dexter	372.4964946
8	+-++-+--	10	200	150	20	30	15	10	Dexter	399.2352338
9	+-+00<0-	10	200	150	12.5	45	0	30	Dexter	225.4252027
10	+-+00>0-	10	200	150	12.5	45	20	30	Dexter	72.25804156
11	+-+000<-	10	200	150	12.5	45	10	0	Dexter	834.4996594
12	+-+000>-	10	200	150	12.5	45	10	70	Dexter	1732.285082
13	+-+<000-	10	200	150	0	45	10	30	Dexter	22.81685041
14	+-+>000-	10	200	150	27.5	45	10	30	Dexter	4.656257886
15	+-+0<00-	10	200	150	12.5	15	10	30	Dexter	109.8549481
16	+-+0>00-	10	200	150	12.5	75	10	30	Dexter	224.7061971

Figure 5: Composite Runs with axial design

	Pattern	flow rate	mold temp	mold pressure	dwell time	cure temp	cure time	material percent resin	raw meterial supplier	Variability
1	+-++0<0-	10	200	150	20	45	6.3	30	Dexter	225.4252027
2	+-++0>0-	10	200	150	20	45	23.7	30	Dexter	72.25804156
3	+-++00<-	10	200	150	20	45	10	0	Dexter	834.4996594
4	+-++00>-	10	200	150	20	45	10	64.6	Dexter	1732.285082
5	+-++<00-	10	200	150	20	19	10	30	Dexter	109.8549481
6	+-++>00-	10	200	150	20	70	10	30	Dexter	224.7061971

Figure 6: Axial Design composite runs with the main factors

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3. Results and analysis

3.1. Data Request 1 and 2: When considering all the factors, the effect summary (shown in Figure 7) displayed the following main factors as affecting: material percent resin, cure time, dwell time, and cure temp. Another model was run considering only the main effects and their interactions, and this normal plot is shown in Figure 8. The following main factors affect: **dwell time, material percent resin**, **cure time**, **cure temp**, which also can be confirmed by the effect summary in Figure 9. This analysis tells us about the main factors which influence variability. Now, we can move forward with the center runs to further analyze a model of main effects with center runs to generate a model to predict variability.

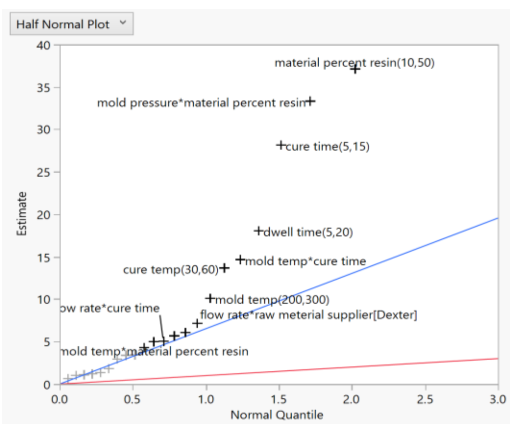


Figure 7: Half Normal plot of whole data

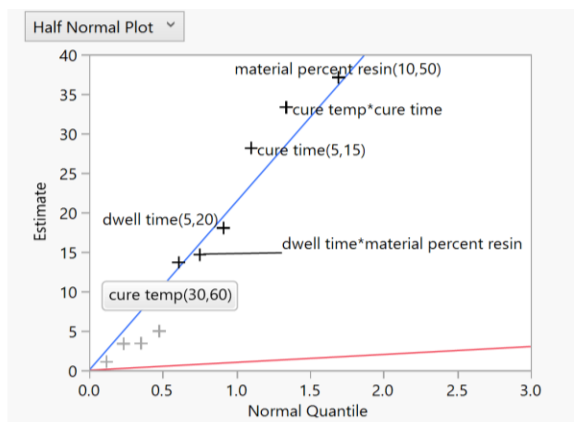


Figure 8: Half Normal Plots main effects

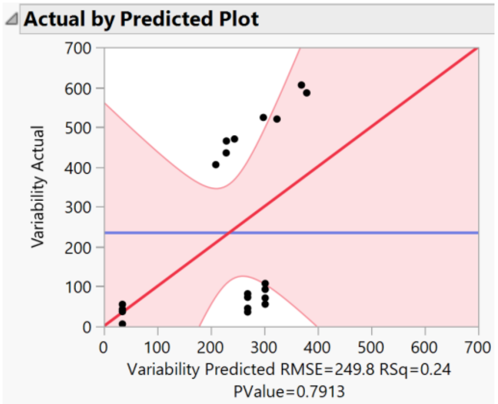
Source	LogWorth	PValue
material percent resin(10,50)	8.669	0.00000
cure temp*cure time	7.788	0.00000
cure time(5,15)	6.504	0.00000 ^
dwell time(5,20)	3.782	0.00017
dwell time*material percent resin	2.860	0.00138
cure temp(30,60)	2.598	0.00252 ^

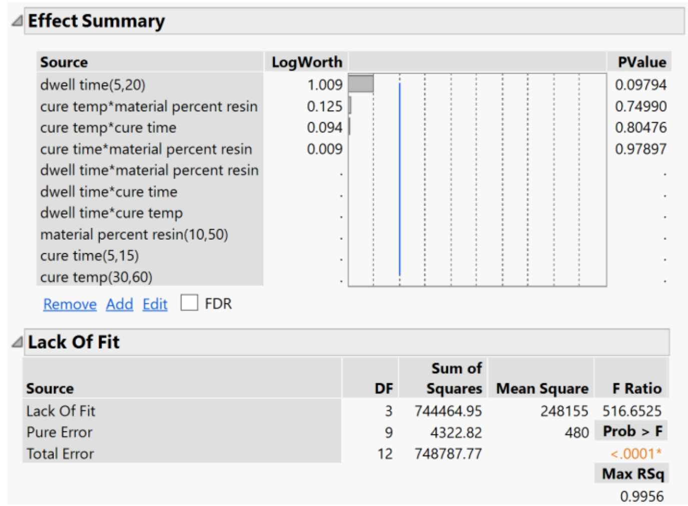
Remove Add Edit Undo ☐ FDR ('^' denotes effects with containing effects above them)

Figure 9: Effects Summary of the main effects

3.2. Data Request 3: Center Runs

After running the data from the first and second sets of runs using the main factors of material percent resin, cure temperature, cure time, dwell time, and their interactions, the lack of fit was significant. This is shown in Figure 10 by the variability in the actual by predicted plot, the lack of significance in the factors, and the significant f-value for lack of fit. The conclusion drawn from this data request was that the data had curvature that was not being accounted for by the model.





Effect Summary

Source	LogWorth	PValue
dwell time(5,20)	1.009	0.09794
cure temp*material percent resin	0.125	0.74990
cure temp*cure time	0.094	0.80476
cure time*material percent resin	0.009	0.97897
dwell time*material percent resin	.	.
dwell time*cure time	.	.
dwell time*cure temp	.	.
material percent resin(10,50)	.	.
cure time(5,15)	.	.
cure temp(30,60)	.	.

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Lack Of Fit

Source	DF	Sum of Squares	Mean Square	F Ratio
Lack Of Fit	3	744464.95	248155	516.6525
Pure Error	9	4322.82	480	Prob > F
Total Error	12	748787.77		<.0001*
				Max RSq
				0.9956

Figure 10: Effect Summary and lack of fit

Now we know that a curvature exists in the data we can describe analysis by observing the desirability and cube plots to determine the minimum variability at different factors. It is observed that the variability is negative, which is not possible in this case, so it can be deduced that still there are non-significant interaction terms. Hence, it was decided that we would go for central composite axial runs to find the parameter estimates of the variability. And still, at this point, we had split opinions about involving dwell time as our main effect, which was cleared when we analyzed Run 5.

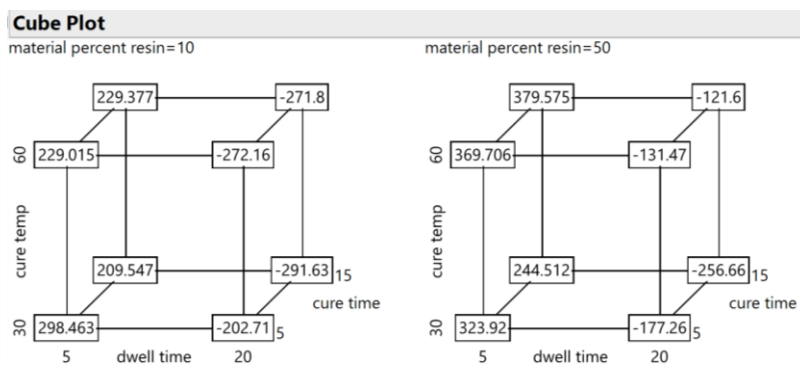


Figure 11: Cube Plots

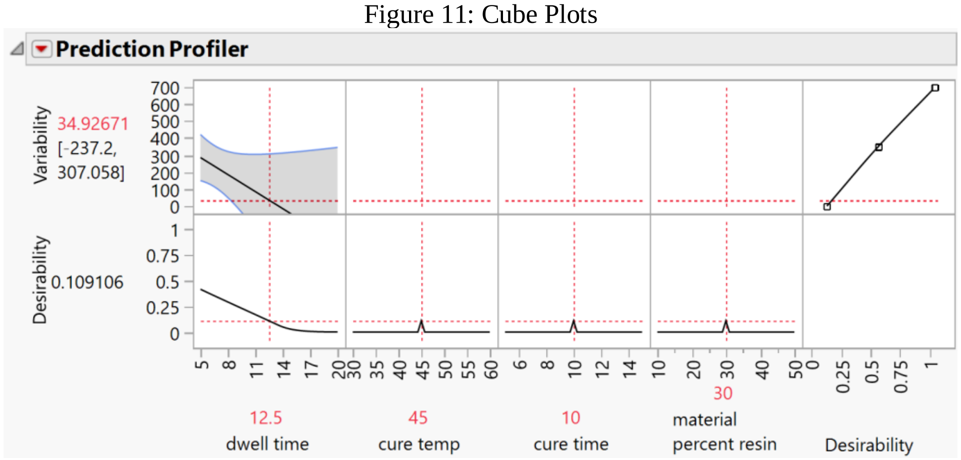


Figure 12: Prediction Profiler

3.3. Data Request 5: Central Composite Axial Runs

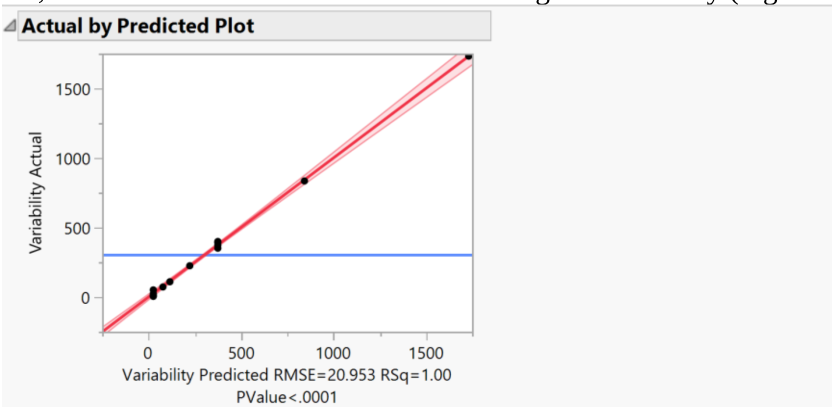
After running a response surface analysis on the four-factor composite axial runs we determined that dwell time is not a significant factor (Figure 13).

Effect Summary

Source	LogWorth	PValue
material percent resin*material percent resin	10.295	0.00000
cure temp*cure temp	3.760	0.00017
cure time*cure time	3.379	0.00042
material percent resin(10,50)	3.378	0.00042 ^
cure time(5,15)	2.682	0.00208 ^
cure temp(30,60)	1.987	0.01030 ^
dwell time*dwell time	0.324	0.47378
dwell time(5,20)	0.022	0.95085 ^

Figure 13: Insignificant Dwell Time

After eliminating dwell time, the analysis of the data from run 5 yielded that the square of material percent resin square of cure time and cure temperature, material percent resin, cure time, and cure temperature are significant terms (Figure 14). The absence of interaction terms was a little dubious, so the team decided to run an analysis on the combined data from data requests 3, 4 and 5 to see the factors that are affecting the variability (Figure 15).



Effect Summary

Source	LogWorth	PValue
material percent resin*material percent resin	13.178	0.00000
cure temp*cure temp	4.862	0.00001
cure time*cure time	4.385	0.00004
material percent resin(10,50)	4.216	0.00006 ^
cure time(5,15)	3.309	0.00049 ^
cure temp(30,60)	2.448	0.00357 ^

Figure 14: Actual by the predicted plot and effect summary after the removal of the dwell time

After combining data from runs 3, 4, and 5 we analyzed the summary of the fit and effects of the factors as shown in figure 15. As we are now analyzing the data, we look at the residual plots and q-q plots, which in this case seems pretty good (Figure 16 and 17 respectively). The desirability for variability was set to minimize using the prediction profiler, producing an optimal design with variability as 11.95 at 37.8°C cure temperature, Cure time 13.2 hours, and 28.7% material percent resin. This optimal design shows relative desirability of 0.85 which is relatively high (Figure 18). Contour profiles for all the interactions are shown in figure 19.

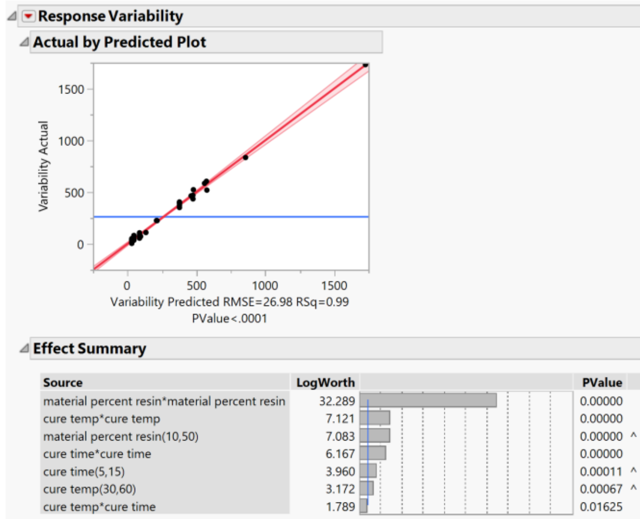


Figure 15: Actual by predicted and Effect Summary

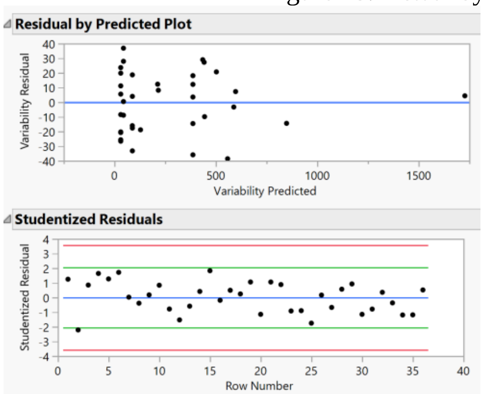


Figure 16: Residual Plots

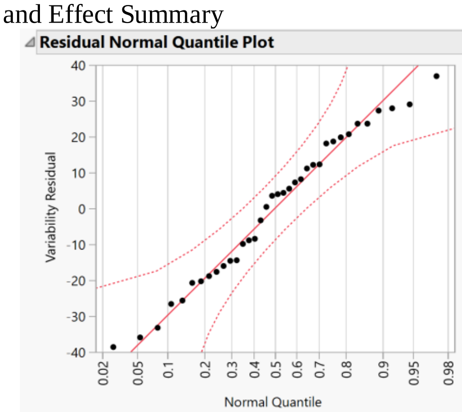


Figure 17: Q-Q plot

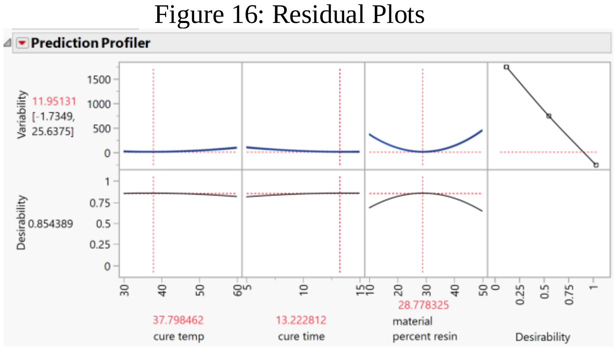


Figure 18: Prediction Profile (Data Analysis 4)

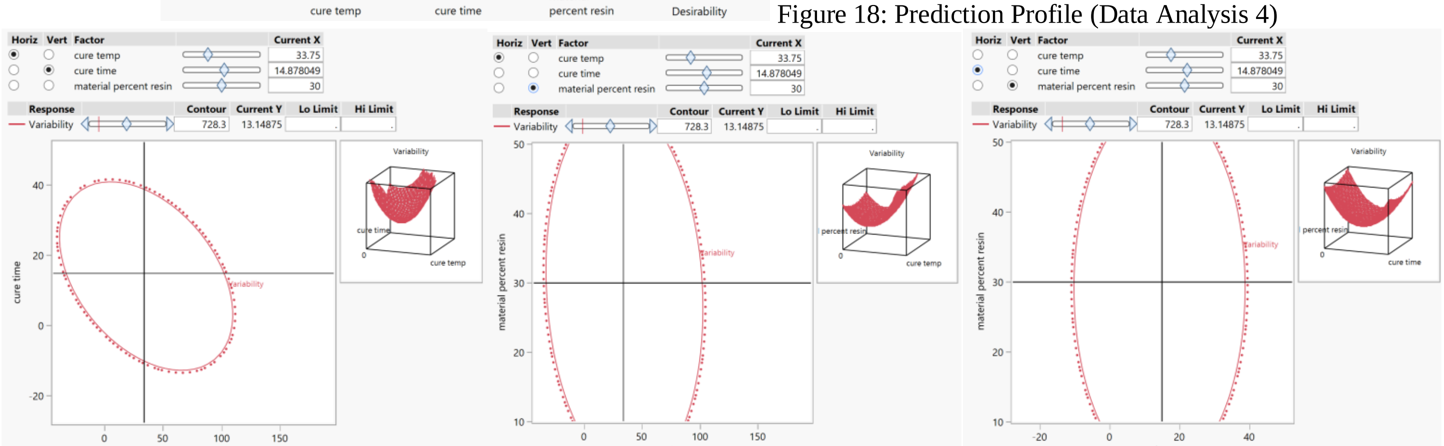
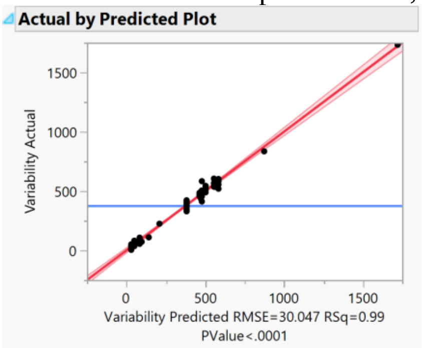


Figure 19: Contour Profilers

3.4. Final Run: All the runs combined

All runs were combined, and analysis was performed using Cure Temperature, Cure Time, and Material Percent Resin. Figure 20 shows the actual by the predicted plot as a good fit to the data, this is represented by the linear relationship observed. When looking at the parameter estimates, all factors were significant except for the interaction between cure time and material percent resin, therefore it was removed.



Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	30.701592	8.103791	3.79	0.0004*
cure temp(30,60)	16.884863	3.913674	4.31	<.0001*
cure time(5,15)	-28.77763	4.2087	-6.84	<.0001*
material percent resin(10,50)	40.915754	4.301492	9.51	<.0001*
cure temp*cure temp	36.283075	5.40256	6.72	<.0001*
cure temp*cure time	31.520839	4.581796	6.88	<.0001*
cure time*cure time	30.889824	5.084944	6.07	<.0001*
material percent resin*material percent resin	402.08894	5.807422	69.24	<.0001*

Figure 20: Actual by Predicted and Parameter Estimates for coded variables

Figure 21 shows a lack of fit which seems pretty insignificant which implies that the curvature has been resolved. Figure 22 shows residual plots and normal q-q plots which can be deduced with no anomaly.

Lack Of Fit

Source	DF	Sum of Squares	Mean Square	F Ratio
Lack Of Fit	9	7779.941	864.438	0.9504
Pure Error	51	46389.045	909.589	**Prob > F**
Total Error	60	54168.987		0.4911
				Max RSq
				0.9908

Figure 21: Lack of fit

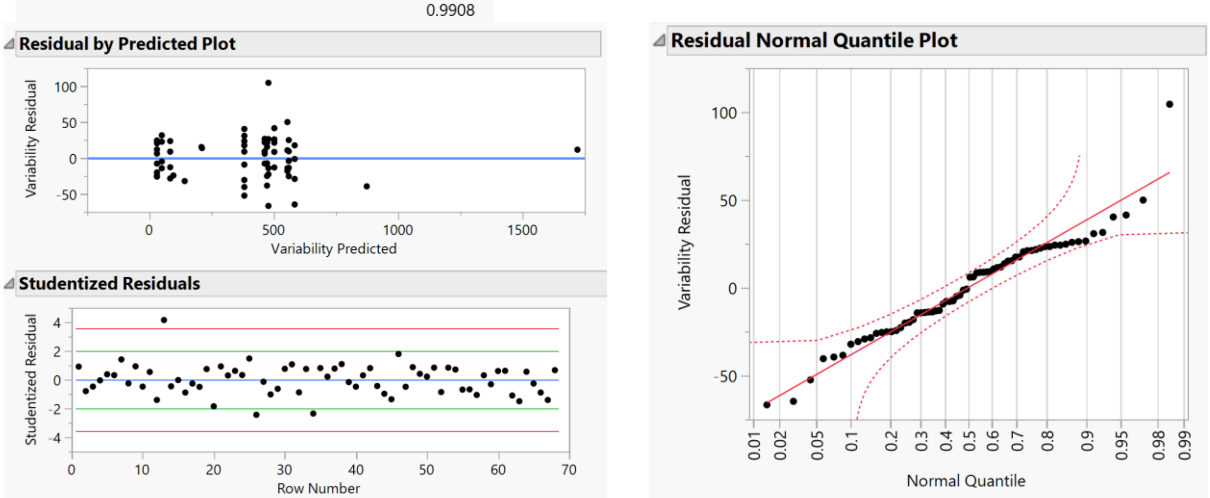


Figure 22: Residual Plots and Normal Q-Q plots

Figure 23 shows the prediction profiler which is set to minimize variability at maximum desirability. After selecting maximum desirability and studying the prediction profiler the following optimal settings were chosen: Cure Temperature of 36.6°C, Cure Time of 13.75 hours, and Material Percent Resin of 29% with the desirability of 0.85. Analysis of variance for this model indicates that the variability under the given conditions cannot be attributed to randomness due to the significant f-value shown in the ANOVA table in Figure 24. The model has a high R-squared value as indicated in the summary of the fit table also in Figure 24. This indicates and supports that the model was accurately predicting variability and was a good fit to the data.

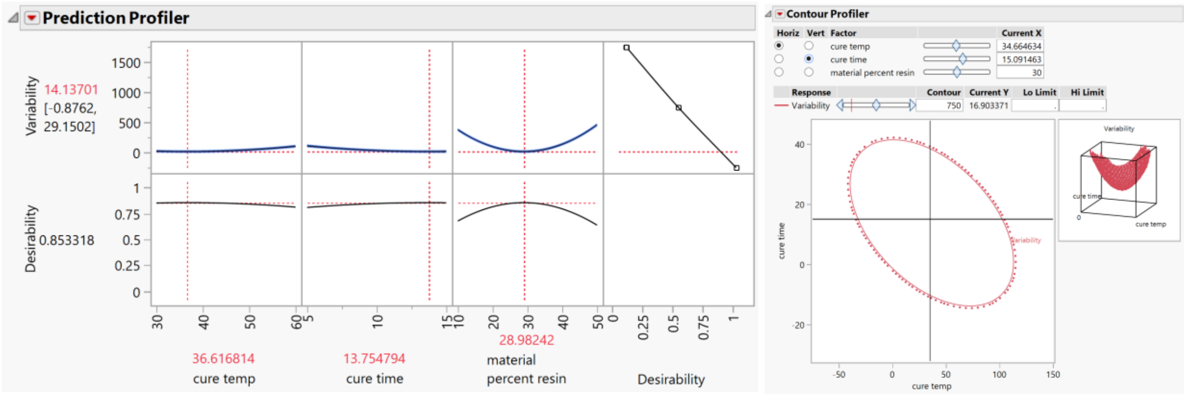


Figure 23: Prediction Profiler and Contour Plot

Summary of Fit

RSquare	0.989215
RSquare Adj	0.987957
Root Mean Square Error	30.0469
Mean of Response	376.8234
Observations (or Sum Wgts)	68

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	7	4968653.3	709808	786.2148
Error	60	54169.0	903	Prob > F
C. Total	67	5022822.2		<.0001*

Figure 24: Summary of Fit and ANOVA Table

4. Recommendations and Conclusions

Talking about the first objective of the project, it was to identify significant factors and interactions which affect the variability of the shape of the plastic part. During initial screening design dwell time, cure temperature, cure time, and material percent resin were identified as main effects, but after careful analysis of further runs, it was ruled out. Finally, quadratic terms of cure temperature, cure time, and material percent resin, the interaction of cure time and cure temperature; and the terms themselves were involved in influencing the variability. The second objective of the project was to formulate an equation to predict variability in the part. The following equation gives an approximation of the variability influenced by the factors mentioned above:

Let,

$$x = \left(\frac{Cure\ Temp - 45}{15}\right);\ y = \left(\frac{Cure\ time - 10}{5}\right);\ and\ z = \left(\frac{Material\ percent\ resin - 30}{20}\right)$$

$$Variability = 62 + 34x - 58y + 82z + 72x^2 + 63xy + 61y^2 + 804z^2$$

Where, x, y, and z are the values for coded variables for the actual value of Cure temperature, Cure Time, and Material Percent Resin respectively.

The optimal setting for minimal Variability in Plastic part is Cure Temperature of 36.6°C, Cure Time of 13.75 hours, and Material Percent Resin of 29%. All the other settings can be chosen as per the economic profitability and cost-effectiveness as they were not significant in the analysis.

While we did not go over our $100,000 budget and saved $26,000 to determine the best possible route to fulfill both the objectives, we could have concluded with a final data set which would have given us a better opportunity for better predictability. Moreover, we could have executed our included 10 runs better while our 64 runs were executed to the point. The desirability could be improved as we only got it around 0.85 due to the involvement of quadratic terms. With a fold-over run, we were able to perform de-aliasing of the factors. In the future, it could be possible to perform a more comprehensive central composite design and gather more information about the optimal settings for other factors as well which might have a little effect on the process.