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FROM SPC TO DOE: A CASE STUDY AT MECO, INC.

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Key Words

Analysis of variance; Confirmation runs; Control charts; Experimental designs.

Background

Meco, Inc. is a manufacturing company located in Greeneville, Tennessee. Meco produces products from one of two production lines: a furniture line and a grill line. The furniture line products include banquet tables, card tables, folding chairs, step ladders, and stepping stools. The grill line products, which are considered in this study, include charcoal grills, electric grills, portable grills, rotisserie grills, and smokers. Meco desired to optimize the process of painting their charcoal grill hoods and bowls, as the paint thickness was above the nominal level and the amount of variation in the paint thickness within a part and between parts was unacceptable.

The paint process involves a series of eight steps as illustrated in Figure 1. The investigation of the process began at automatic paint and ended at quality control (QC) inspection. The line speed through the automatic paint machine will remain at the current setting because the production line is continuous throughout the plant. Plant personnel stated the temperature in the dry-off oven and bake oven cannot be changed. Meco plans to eliminate the manual reinforcement paint position from the process. The manual painter currently paints the area of the grill that the automatic paint guns do not cover. According to product design, this position should not be required when painting grills. The design of the production line allows two parts to be simultaneously painted. One part is hung from the top hook and the other part is hung underneath it on the bottom hook.

At the present time, no written procedures exist for the paint process, although, some studies, mainly one-at-a-time experiments, have been attempted. The one operator on each shift sets up the automatic paint machine according to his knowledge of the machine and of the process. Therefore, the process is never set up the same and is never run the same. As we shall see, *design of experiments* techniques will be used to determine the key variables that affect paint thickness and then determine the optimum settings for these key variables. Optimization of the process should result in reduced variation around the nominal paint thickness, ultimately reducing the cost of painting grill hoods and bowls black.

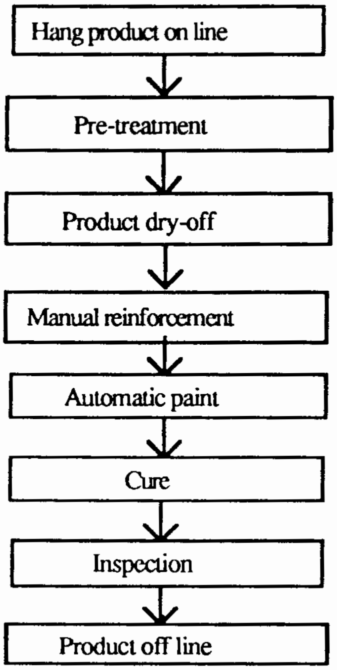

Figure 1. Process flowchart

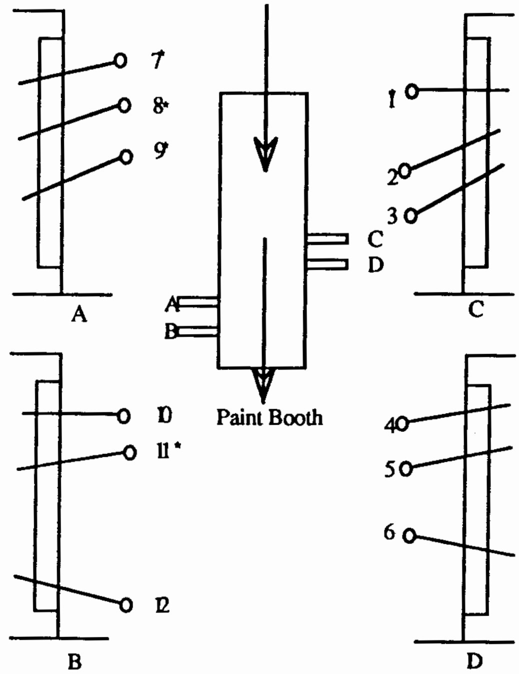

Figure 3. Gun location within the paint booth. An asterisk (*) indicates experimental factors.

The Operation Process

Meco uses a powder paint that is first sprayed, then baked onto the product. The optimal paint thickness for the outside of the grills is 1.5 mils, and for the inside of the grills, it is 1.0 mil. There are four measurements taken on the inside and the outside top of the hoods and bowls. There are also two measurements taken on the outside side where the hinge is attached. Figure 2 displays the locations of these measurements. The location of each measurement position is the same for every part. However, due to the line configuration, these measurements are not taken until 30–40 min after the painting of the parts. A sole operator makes the measurements using the one instrument. The instrument has proven to be a very reliable digital measurement device that is calibrated daily and beeps if not used properly, so that measurement error is generally negligible.

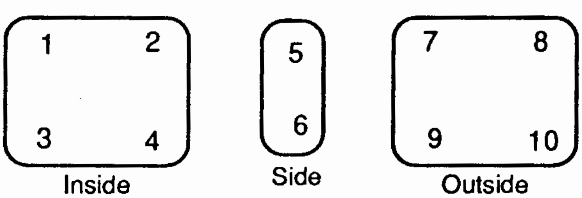

Figure 2. Measurement locations.

The automatic paint machine consists of 12 individual paint guns, as illustrated in Figure 3. Guns 7, 8, 9, and 11 oscillate. Guns 1 through 6, 10, and 12 remain at a fixed position. Each paint gun has four controls: gun position, forward air pressure, dilution air pressure, and powder pressure. The machine operator sets up and adjusts the four controls for each gun according to QC's paint thickness report.

The investigation of this process began with the historical data. Due to the historical data collection plan, little knowledge was gained about the process. The use of control-charting techniques clearly indicated the need for improvement. Current data were collected, using a new data collection plan, and analyzed to determine key variables affecting the paint thickness. Knowledge gained from the current data allowed the construction of a designed experiment. The results of the designed experiment then led to confirmation runs. Based on the results of the confirmation runs, the best setting for the painting process was determined and led to significantly reduced paint costs for Meco.

Historical Data

The available historical data are the daily paint thickness measurements from one part hung on the top hook and one on the bottom hook. The two parts are collected for paint thickness measurements about 1 hr after the grill painting process begins. Four measurements are made on the inside of the bowl/hood; four measurements are made on the outside top of the bowl/hood; and two measurements are made on the outside side where the hinge is attached to the bowl/hood (see Fig. 2).

Initially, two $\overline{X}/R$ control charts, one for inside paint measurements and one for outside paint measurements, were constructed using the historical data gathered from 9/1/94 through 12/15/94. The first control chart displays the parts' inside measurements (locations 1 through 4, which form a sample size of 4 for each part measured). The second control chart displays the parts' outside measurements (locations 5 through 10, which form a sample of size $n = 6$ for each part measured). Both of the $\overline{X}$ charts demonstrated a sawtooth pattern, indicating a possible "mixture" problem which can be seen in Figures 4 and 5.

Separate control charts were constructed for the parts hung on the top and the bottom hooks to eliminate the "mixture" problem. Figure 6 illustrates the manner in

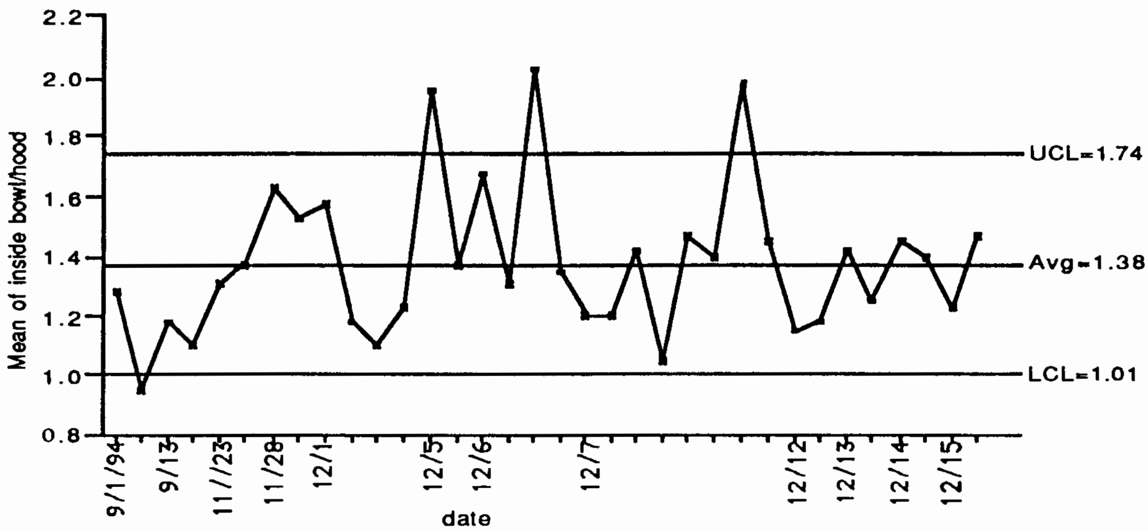

Figure 4. $\overline{X}$ control chart for inside paint thickness for bowls and hoods; historical data.

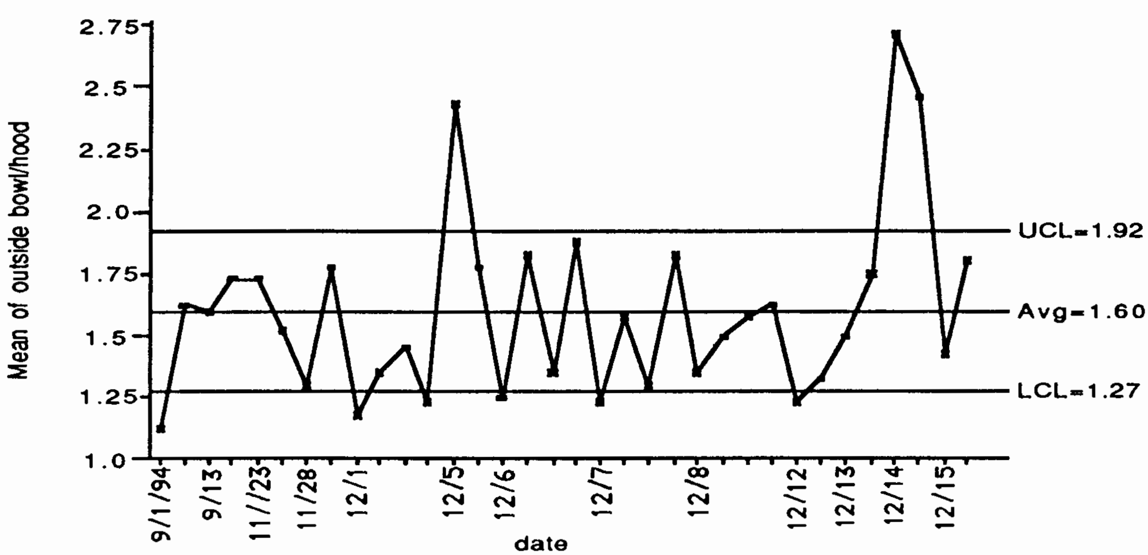

Figure 5. $\overline{X}$ control chart for outside paint thickness for bowls and hoods; historical data.

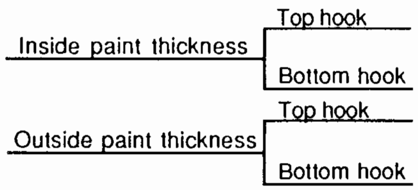

Figure 6. Historical data control-chart stratification.

which the data were stratified for control-chart construction. These control charts are available upon request.

The four $\overline{X}/R$ control charts revealed variations in the average paint thickness across the part:

- Inside Paint Thickness: The average paint thickness was greater if the parts were on the top hook ($\overline{\overline{X}}$ = 1.47, $\overline{R}$ = 0.50) instead of the bottom hook ($\overline{\overline{X}}$ = 1.28, $\overline{R}$ = 0.50). The control chart for inside paint thickness–top hook had four points out of control. The control chart for inside paint thickness–bottom hook was in statistical control.
- Outside Paint Thickness: The average paint thickness was greater if the parts were on the bottom hook ($\overline{\overline{X}}$ = 1.68, $\overline{R}$ = 0.45) instead of the top hook ($\overline{\overline{X}}$ = 1.51, $\overline{R}$ = 0.43), which are opposite of the results for the inside paint thickness. On the control chart for outside paint thickness–top hook, there were two points out of control and a run of seven points below the average. On the control chart for outside paint thickness–bottom hook, there was one point out of control and a run of seven points above the average.

Thus, it can be concluded from the control charts that part location, top or bottom hook, has an effect on the average paint thickness. Inside paint thickness is greater for parts hung on the top hook, whereas outside paint thickness is greater for parts hung on the bottom hook. Hook design is thought to be the cause of this. The variation in paint thickness was consistent regardless of the hook from which the part was hung. The causes for the out-of-control points and the runs were undetermined. Because these were historical data, nobody could remember what happened during the time period in question.

With one data point being recorded per day, no information was obtainable on how the process behaves during the production run. To obtain this knowledge, parts need to be collected throughout the production run for measurement. Paint thickness for one part hung on each hook will be recorded every 15 min for the length of the production run, usually 2 or 3 hrs, for approximately 2 weeks. Also, any changes made to the process will be recorded to determine their effect on the process.

Hoods and bowls differ in the application of touch-up paint. They both receive touch-up paint on the side (locations 5 and 6) but with a different technique. To be able to determine the effects of touch-up paint, separate control charts for hoods and for bowls are set up to stratify further the data. Figure 7 illustrates the stratification of data for each control chart.

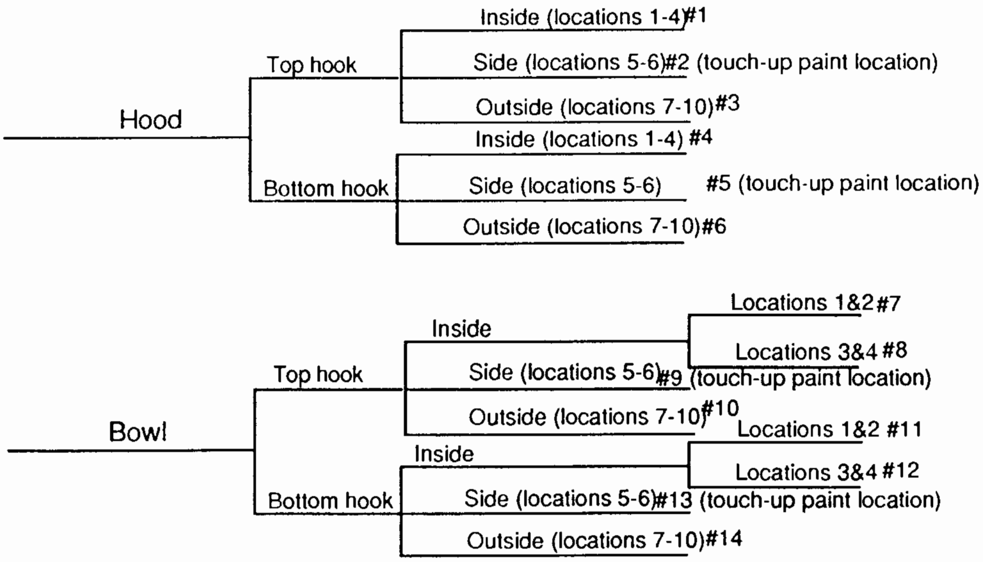

Figure 7. Stratification of data for control charts.

As Figure 7 illustrates, 14 $\overline{X}/R$ control charts will be required when data are collected in the future. Six control charts will be constructed from data pertaining to the hoods and eight control charts will be constructed from the data pertaining to the bowls.

Current Data

Current data will be described as data collected from 2/16/95 through 2/22/95. During this time period, data were collected throughout the following three painting processes:

- Routine painting process
- Automatic gun powder pressure changed from routine setting
- Touch-up paint position eliminated

Grill bowls and hoods were painted by the routine paint process. Only bowls were painted during the other two process changes; the automatic gun powder pressure was changed and the touch-up paint position was eliminated. Hoods were not painted under these last two conditions due to the production schedule.

Data collected from the routine paint process were used for control-chart construction. The control charts were constructed in the manner recommended from the historical data. All 14 $\overline{X}/R$ charts demonstrated statistical control. A couple of the control charts had one point out of control. These control charts are available upon request.

Table 1 records the average paint thickness ($\overline{X}$) and the range of the paint thickness (R) for each measurement location. The results are separated by parts hung on the top hook and parts hung on the bottom hook. The entries with a slash indicate locations with an outlying paint thickness reading. The first number includes the outlying point, and the second number eliminates the outlying value.

The automatic paint machine operator revealed, in an interview, that the powder pressure setting is used to adjust paint thickness. To determine the effect of powder pressure, the 12 automatic gun powder pressure settings were changed from their routine settings. The routine and special settings for powder pressure were as follows:

Routine gun settings
39 lbs = guns 8, 9, 12
40 lbs = guns 1, 2, 3, 4, 5, 6, 10
50 lbs = guns 7, 11
Special gun settings
30 lbs = guns 1, 2, 3, 4, 5, 6, 8, 9, 10, 12
40 lbs = guns 7, 11

The settings for forward air pressure and dilution air pressure remained at their regular settings. Table 2 records the average paint thickness and the range of the paint thickness for each measurement location. The results are separated by parts hung on the top hook and parts hung on the bottom hook. At the special powder pressure settings, the paint thickness was thinner than at the routine powder pressure settings for all locations. The variation in paint thickness was the same for the special and routine powder pressure settings.

The paint process was set up according to routine procedure, except for the elimination of the manual touch-up paint position prior to automatic paint. Table 2 records the average paint thickness and the range of the paint thickness for each measurement location. The results are separated by parts hung on the top hook and parts hung on the bottom hook. Even though touch-up paint is at side locations

Table 1. Paint Thickness by Location and Hook, Current Data; Routine Paint Process Settings

	BOWLS				HOODS			
LOC.	TOP $\overline{X}$	BOT $\overline{X}$	TOP R	BOT R	TOP $\overline{X}$	BOT $\overline{X}$	TOP R	BOT R
1	1.72	1.33	0.9	0.8	1.0	1.01	0.7	1.5/0.9
2	1.80	1.39	0.5	1.0/0.4	1.27	0.98	0.7	0.7
3	1.43	1.36	0.6	0.6	0.82	1.03	0.3	0.9
4	1.63	1.36	1.3/0.7	0.7	0.86	0.91	0.5	0.4
5	2.42	2.19	1.1	1.8/0.9	2.10	2.12	0.9	0.8
6	2.31	2.39	1.4	1.4	2.44	2.20	0.8	0.8
7	1.95	2.14	0.8	0.9	1.67	1.92	1.0	0.9
8	2.18	2.26	1.1	1.1	1.79	2.12	1.5/0.9	0.7
9	2.13	2.55	0.7	1.4	2.04	2.26	0.8	1.2/0.8
10	2.24	2.44	1.3	1.4	2.15	2.49	1.2/0.8	1.6/1.2

Table 2. Paint Thickness by Location and Hook; Current Data

LOC.	BOWLS SPECIAL POWDER PRESSURE SETTING				BOWLS ROUTINE SETTING WITHOUT MANUAL REINFORCEMENT			
	TOP $\bar{X}$	BOT $\bar{X}$	TOP R	BOT R	TOP $\bar{X}$	BOT $\bar{X}$	TOP R	BOT R
1	1.59	1.2	0.7	0.6	1.35	1.3/1.03	0.4	1/0.1
2	1.575	1.12	0.7	0.5	1.45	1.075	0.8/0.4	0.7
3	1.14	1.26	0.6	0.6	0.925	0.9	0.3	0.4
4	1.21	1.28	1.0	0.9	1.00	1.05	0.2	0.3
5	1.86	2.08	0.6	0.6	2.05	2.425	0.4	0.7
6	1.89	2.19	0.8	0.9	2.35	2.175	0.4	0.4
7	1.59	2.1	0.6	1.1	1.925/1.7	2.3	1.2/0.8	0.4
8	1.56	2.32	0.6	0.6	1.55	2.625	0.6	0.5
9	1.99	2.15	0.8	1.4	2.525	2.8	0.4	0.3
10	1.73	2.375	0.7	0.8	2.05	2.975	0.6	1.3

5 and 6, the average paint thickness on the side was not reduced. Instead, the average paint thickness at the inside locations, 1 through 4, was reduced. The elimination of the touch-up paint position reduced the variation at the inside and the side locations.

Three findings were consistent across the three different painting processes:

- The paint thickness at locations 1 and 2 on the top hook is significantly thicker than the other inside locations.
- The paint thickness at outside locations 7 through 10 is significantly thicker on the bottom hook.
- The range of the paint thickness is greater at the side and the outside locations.

These findings will assist in determining the variables to be included in the designed experiment.

Design of Experiment

Design of experiments (DOE) techniques were applied to the grill painting process to reduce variability in paint thickness, ensure closer conformance to nominal paint thickness, and reduce overall painting cost. The objectives of the designed experiment are to determine four points:

- Which variables influence the response, paint thickness
- Where to set the influential variables so that the paint thickness is always near the nominal value
- Where to set the influential variables so that the variation in paint thickness is small
- Where to set the influential variables so that the effects of uncontrollable variables are minimized

The steps for the designing of this experiment were as follows:

1. Select the response variable.
   - Make sure this variable provides useful information about the process under study.
2. Choose variables, controlled and uncontrolled, and their levels.
   - Choose the factors to be varied.
   - Choose range over which these factors will be varied.
   - Choose factor levels at which runs will be made.
3. Choose the experimental design.
4. Perform the experiment.
5. Analyze the resulting data and draw conclusions (see the next section).

The DOE team brainstormed the uncontrolled and controlled variables based on findings from the historical and the current data. The following uncontrolled variables were identified:

- Line speed
- Ambient temperature
- Humidity
- Ground
- Forward/dilution air pressure
- Fluidizing

The levels for these variables will not be deliberately changed during the experiment but will be recorded throughout the experiment. The following controlled variables were chosen for the experiment:

- Gun 1 position
- Gun 8 position
- Gun 9 position
- Powder pressure
- Gun 7 position
- Gun 11 position

Gun position 1 was chosen because of the thick paint at locations 1 and 2 of parts hung on the top hook. Gun positions for guns 7, 8, 9, and 11 were chosen because they are oscillating guns that will be held stationary during the experiment to reduce the variation in paint thickness at the outside and side locations (see Fig. 3). Powder pressure was chosen because the automatic paint machine operator routinely changes this setting to adjust the paint thickness.

During the experiment, guns 1, 8, and 9 were studied at two levels, and powder pressure, gun 7, and gun 11 were studied at three levels. Powder pressure, gun 7, and gun 11 were studied at three levels because they are more important variables. Powder pressure directly affects paint thickness. Guns 7 and 11 paint the parts underneath the hook on which they are hung.

The experimental design run was a $2^{3-1} * 3^{3-1}$ design. This experimental design allows 6 variables to be studied in 36 experimental runs, as shown in Table 3. Three variables are studied at two levels (coded -1 and 1) and the other three variables are studied at three levels (coded -1, 0, and 1). Due to process confidentiality, the actual level values for each variable are not reported. The 36 experimental runs were run in random order.

The experiment provided the estimated effects of all six controlled variables (main effects) and some two-way interactions. The two-way interactions estimated were as follows:

- Gun 1 position * powder pressure
- Gun 1 position * gun 7 position
- Gun 1 position * gun 11 position
- Gun 8 position * powder pressure
- Gun 8 position * gun 7 position
- Gun 8 position * gun 11 position
- Gun 9 position * powder pressure
- Gun 9 position * gun 7 position
- Gun 9 position * gun 11 position

The two-way interactions that could not be estimated due to confounding with the main effects were as follows:

- Gun 1 position * gun 8 position
- Gun 1 position * gun 9 position
- Gun 8 position * gun 9 position
- Powder pressure * gun 7 position
- Powder pressure * gun 11 position
- Gun 7 position * Gun 11 position

Due to the production schedule, grill bowls were the only parts painted during the experiment. Sixteen parts were painted on each of the 36 experimental runs. Eight parts were hung on both the top and bottom hooks. The hoods hung on the fourth, fifth, and sixth top and bottom hooks were measured for comparison. Only parts hung on the fifth top and bottom hooks were used for the analysis because the parts at this location were surrounded by other parts being painted and the paint booth had enough time to settle at the adjusted levels.

Data Analysis

To optimize the grill painting process, three responses required investigation: the paint thickness, the variation in paint thickness, and the amount of paint used to paint the part. The average paint thickness and the variation in paint thickness for the inside, side, and outside locations were recorded for analysis. Parts hung on the top and the bottom hooks were weighed before and after the parts were painted. The difference between these two readings, the weight of the paint used, was recorded for analysis. Table 4 lists the 13 response variables analyzed.

The routine locations for measuring paint thickness are given in Figure 2. An eleventh measurement was also taken between measurement locations 7 and 8 because parts have failed QC inspection due to this area's paint being too thin. The same operator made all measurements using the same digital measurement device. The average paint thickness for the inside, the side, and the outside area of the bowls were calculated. The optimal average paint thickness for the inside of the part is 1.0 mil. The optimal average paint thickness for the side and the outside of the part is 1.5 mils.

The range provided a method of measuring the variation in paint thickness. The range of the paint thickness for the inside, the side, and the outside area of the parts was calculated. The range has an optimal value of zero. A

Table 3. Experimental Design

EXPT. NO.	RUN ORDER	GUN 1	GUN 8	GUN 9	PRESSURE	GUN 7	GUN 11
1	20	-1	-1	1	-1	-1	0
2	19	1	-1	-1	-1	-1	0
3	17	-1	1	-1	-1	-1	0
4	36	1	1	1	-1	-1	0
5	34	-1	-1	1	0	-1	1
6	2	1	-1	-1	0	-1	1
7	23	-1	1	-1	0	-1	1
8	6	1	1	1	0	-1	1
9	22	-1	-1	1	1	-1	-1
10	26	1	-1	-1	1	-1	-1
11	28	-1	1	-1	1	-1	-1
12	10	1	1	1	1	-1	-1
13	27	-1	-1	1	-1	0	1
14	12	1	-1	-1	-1	0	1
15	31	-1	1	-1	-1	0	1
16	8	1	1	1	-1	0	1
17	9	-1	-1	1	0	0	-1
18	33	1	-1	-1	0	0	-1
19	14	-1	1	-1	0	0	-1
20	1	1	1	1	0	0	-1
21	18	-1	-1	1	1	0	0
22	21	1	-1	-1	1	0	0
23	24	-1	1	-1	1	0	0
24	35	1	1	1	1	0	0
25	29	-1	-1	1	-1	1	-1
26	15	1	-1	-1	-1	1	-1
27	32	-1	1	-1	-1	1	-1
28	16	1	1	1	-1	1	-1
29	13	-1	-1	1	0	1	0
30	30	1	-1	-1	0	1	0
31	3	-1	1	-1	0	1	0
32	11	1	1	1	0	1	0
33	5	-1	-1	1	1	1	1
34	25	1	-1	-1	1	1	1
35	7	-1	1	-1	1	1	1
36	4	1	1	1	1	1	1

Table 4. Experimental Responses

HOOK	LOCATION	RESPONSE
Top hook	Inside (1–4)	Average and range of paint thickness
	Side (5,6)	Average and range of paint thickness
	Outside (7–10)	Average and range of paint thickness
Bottom hook	Inside (1–4)	Average and range of paint thickness
	Side (5,6)	Average and range of paint thickness
	Outside (7–10)	Average and range of paint thickness
Weight	Top and bottom hook	Weight of paint covering parts

range equal to zero indicates a part with a consistent paint thickness.

The weight of the parts hung from the top and the bottom hooks was recorded prior to painting, then again after the parts were painted to determine the actual amount of paint used. The amount of paint required should be reduced once the parts are painted at a consistently nominal paint thickness. The parts were weighed on the same digital scale. See the Appendix for data.

Analysis of variance (ANOVA) techniques determined significant main effects and two-way interactions for each of the 13 responses. For each response variable, the main effects and two-way interactions significant at the 1%, 5%, and 10% levels are displayed in Table 5.

The information in Table 5 assisted in evaluating the effect of changing the variables' levels. Two interactions (gun 1 * gun 7 and gun 9 * gun 11) greatly affect the process outcome. Several setting combinations of these interactions would optimize the process.

The readings of the uncontrolled variables were recorded after each experimental run. The values of the uncontrolled variables remained constant throughout the experiment. The residuals were checked with the uncontrolled variables. No correlations or special patterns were noted. Meco was interested in learning the power of designed experimentation. Thus, the basic ideas were illustrated to them in a simple manner.

Preliminary Conclusion

The goals of the experiment consisted of the following:

- Lowering the guns' powder pressure setting
- Determining fixed positions for guns 1, 7, 8, 9, and 11
- Eliminating the manual reinforcement paint position
- Optimizing the paint thickness at the nominal levels
- Reducing the amount of variation in paint thickness

The experiment showed that the above goals are obtainable. Several of the experimental runs met all the goals, with the parts also passing inspection.

Examination of the significant main effects and interactions led to eight combinations of variable settings that would optimize the painting process. These combinations resulted from gun 8 being set at its low level (-1) and powder pressure being set at its middle level (0). Levels for guns 1, 7, 9, and 11 were determined by the possible combinations of the gun 1 * gun 7 and the gun 9 * gun 11 interactions that would produce favorable results. Table 6 lists the possible combinations of variable settings.

The values of the 13 response variables were predicted, using their respective model equations, for each setting combination in Table 6. The predicted response values assisted in ordering the eight combinations such that the combination with the best predicted values came first and

Table 5. Significant Variables for Each Response Variable

RESPONSE			1% SIGNIFICANCE	5% SIGNIFICANCE	10% SIGNIFICANCE
Top Hook					
	Inside:	Avg.	*P* 9 * 7 7		1 * 7 8 * 11 8 * 7 1 * *P*
		Range		8 * 11 9 * P 1 * 7	
	Side:	Avg.	*P* 9 * 11	8 * 7	1 * 7 9
		Range	8**P*		7
	Outside:	Avg.	*P*		1 * 7
		Range		11	7
Bottom Hook					
	Inside:	Avg.	*P*		9 * 11 9 9 * *P* 8 * *P*
		Range		1 * 11	9 1 * 7
	Side:	Avg.	*P*	1	9 * *P* 9
		Range	9		
	Outside:	Avg.	*P* 11	9 8	8 * 7 1 * 11 8 * *P* 1 * *P*
		Range		*P*	9 * 11
Weight			*P*	1 9 * *P* 1 * 7 7	9 * 7

Table 6. Eight Possible Optimizing Variable Combinations

VARIABLE	1	2	3	4	5	6	7	8
Gun 1	-1	+1	+1	-1	-1	+1	+1	-1
Gun 8	-1	-1	-1	-1	-1	-1	-1	-1
Gun 9	-1	+1	-1	-1	+1	-1	-1	-1
Pressure	0	0	0	0	0	0	0	0
Gun 7	0	-1	-1	0	0	-1	-1	0
Gun 11	-1	0	-1	+1	0	0	+1	0

the combination with the worst predicted values came last. Further investigation is required to determine which combination contains the optimal variable settings.

Recommendations

Confirmation runs are required to identify the optimal combination of variable settings. The confirmation runs would consist of the eight possible optimal combinations and the setting combination of the one run from the experiment that had the best results. Table 7 lists the order in which the confirmation would be run. The confirmation should be run in the given order, which was determined using best predicted results, because there is a possibility that all of the confirmation runs might not be run due to the production schedule. Run 1 is identical to the original experimental run 5 in Table 3, chosen by the "pick the winner" strategy; runs 2 through 9 are the selected setting combinations, beginning with the combination exhibiting the best predicted results. Even when no (new) confirmation run yields acceptable results, run 1 will ensure one favorable combination.

The confirmation runs should be run in the same manner as the 36 experimental runs. Sixteen parts are to be painted at each of the nine confirmation runs. Eight parts are hung on both the top and bottom hooks. Bowls hung on the fourth, fifth, and sixth top and bottom hooks should be measured at the 11 measurement locations. The parts should be labeled whether or not they pass inspection. The next step is to calculate the average and range of the paint thickness for the inside, side, and outside locations of the three parts (bowls 4, 5, and 6) from the top and bottom hooks. Finally, compare the results from each confirmation run. The selection of the "best" confirmation run is based on the following criteria:

- Nominal inside, side, and outside paint thickness for parts painted on the top and the bottom hooks
- Smallest paint thickness range values for inside, side, and outside locations for top and bottom hooks

The confirmation run selected would be implemented throughout a production run. The process should be monitored for conforming and nonconforming parts. If the selected confirmation run performs acceptably during production, implement it as the new paint process. If the selected confirmation run does not produce acceptable results, select the next best confirmation run and test it throughout a production run. Continue in this manner until a confirmation run yields acceptable results during production.

Table 7. Confirmation Run Order and Settings

VARIABLE	RUN 1	RUN 2	RUN 3	RUN 4	RUN 5	RUN 6	RUN 7	RUN 8	RUN 9
Gun 1	-1	-1	+1	+1	-1	-1	+1	+1	-1
Gun 8	-1	-1	-1	-1	-1	-1	-1	-1	-1
Gun 9	+1	-1	+1	-1	-1	+1	-1	-1	-1
Pressure	0	0	0	0	0	0	0	0	0
Gun 7	-1	0	-1	-1	0	0	-1	-1	0
Gun 11	+1	-1	0	-1	+1	0	0	+1	0

Confirmation Run Results

The confirmation runs, determined from the significant main effects and interactions in the original experiment, verified that all experimental goals are obtainable. The parts from the confirmation runs passed inspection except for those from run 6. The parts hung on the bottom hook of confirmation run 6 questionably passed inspection because the paint was too thin on the bottom side of the part. The reason for the light paint in this area is difficult to determine because no measurements were taken in this area, although, run 6 was the only confirmation run that ran the combination of gun 9 at the high level and gun 7 at the middle level.

The criteria for selecting the best confirmation run were as follows:

- Average paint thickness closest to nominal value
- Smallest range in paint thickness at each measurement location

According to the above criteria, three confirmation runs displayed good results. Confirmation run 2 displayed the best results, followed by run 1 then run 4.

The variable settings for run 2 are as follows:

Gun 1 position	-1
Gun 7 position	0
Gun 8 position	-1
Gun 9 position	-1
Gun 11 position	-1
Powder pressure	0
No manual reinforcement	

These settings should produce quality parts for powder pressure settings between 31 and 35 psi because some of the guns' powder pressure settings were set as low as 31 psi during the running of the confirmation runs. Table 8 displays the average and range of the paint thickness for each measurement location. The average reduction in paint thickness for each area of the bowl is as follows:

- 0.7025 mil for the inside of the bowl (46.76%)
- 0.9700 mil for the side of the bowl (42.68%)
- 0.8663 mil for the outside of the bowl (38.74%)

The range in paint thickness at each measurement location is 0.935 mil on average for the current process and 0.235 mil on average for the new recommended process. Thus, on average, there is a 0.70-mil (74.87%) reduction in the range of paint thickness at each measurement location.

If the selected confirmation run does not produce acceptable results during routine production, then confirmation run 1 should be further investigated. The variable settings for run 1 are as follows:

Gun 1 position	-1
Gun 7 position	-1
Gun 8 position	-1
Gun 9 position	+1
Gun 11 position	+1
Powder pressure	0
No manual reinforcement	

Conclusion

Once the new process has been selected, the implementation of this process should begin. The implementation of

Table 8. Paint Thickness by Location and Hook; Current and New Paint Process Settings

	CURRENT PROCESS				NEW PROCESS			
LOC.	TOP $\bar{X}$	BOT $\bar{X}$	TOP R	BOT R	TOP $\bar{X}$	BOT $\bar{X}$	TOP R	BOT R
1	1.72	1.33	0.9	0.8	0.95	0.8	0.6/0.3	0.2
2	1.80	1.39	0.5	1.0/0.4	0.9/0.7	0.9	0.6/0	0.2
3	1.43	1.36	0.6	0.6	0.83	0.6	0.2	0.2
4	1.63	1.36	1.3/0.7	0.7	0.60	0.87	0.5	0.1
5	2.42	2.19	1.1	1.8/0.9	1.67	1.23	0.1	0.4
6	2.31	2.39	1.4	1.4	1.43	1.1	0.2	0.2
7	1.95	2.14	0.8	0.9	1.43	1.47	0.2	0.2
8	2.18	2.26	1.1	1.1	1.13	1.63	0.1	0.3
9	2.13	2.55	0.7	1.4	1.33	1.07	0.4	0.3
10	2.24	2.44	1.3	1.4	1.47	1.43	0.3	0.3

the new paint process for black grill bowls will involve three steps: training the operators, writing a procedure manual, and monitoring the process performance. The operators will learn how to set up the automatic paint booth and how to make adjustments if the paint becomes too thin. The procedure manual should be written according to a standard format. $\overline{X}/R$ control charts should be used to monitor continued performance of the process.

Future designed experimentation can further optimize the paint process. Investigating the possibility of setting the powder pressure for each gun at different levels could be one such experiment. Other variables that affect the average and the variation of the paint thickness could also be investigated.

The implementation of the new process will result in savings to the company. The new process will accomplish the following:

- Reduce the black paint cost over $7000 per year (only for a single product)
- Decrease the amount of recycled paint in the paint booth
- Eliminate the cost of the touch-up paint operator
- Decrease the time and cost in setting up the process
- Decrease the number of bowls reworked (stripping and repainting)

The amount saved in paint cost only reflects one product painted one color for one year. Optimization of other colors and other products will further increase the amount the company saves in paint cost.

The techniques used in the case study given here can be applied to most manufacturing processes. By using SPC techniques prior to design of experiments techniques, one is able to select the key process variables to be included in the experiment. If the correct variables are included in the experiment, results that significantly improve the process under study may be obtained.

Design of experiments techniques have been used in industry for many years. Unfortunately, many companies do not realize the power of designed experiments; thus they do not benefit from process improvements and savings that result from these experiments.

Appendix: Data

RUN	INSIDE				OUTSIDE				SIDE				
	TOP		BOTTOM		TOP		BOTTOM		TOP		BOTTOM		
NO.	$\overline{X}$	RANGE	$\overline{X}$	RANGE	$\overline{X}$	RANGE	$\overline{X}$	RANGE	$\overline{X}$	RANGE	$\overline{X}$	RANGE	WEIGHT
1	0.775	0.3	0.725	0.2	0.85	0.4	1.075	0.4	1.15	0.1	0.95	0.1	0.118
2	0.55	0.4	0.675	0.6	0.875	0.4	0.85	0.1	1.05	0.1	0.95	0.1	0.1
3	0.55	0.6	0.575	0.3	0.825	0.7	0.95	0.5	0.95	0.1	1.4	0.2	0.108
4	0.6	0.4	0.675	0.2	0.9	0.4	1.025	0.4	0.9	0	0.95	0.1	0.102
5	0.9	0.2	1.025	0.3	1.425	0.4	1.375	0.7	1.65	0.1	1.9	0.2	0.166
6	0.875	0.1	0.95	0.7	1.95	1.8	1.375	0.9	1.95	0.1	1.85	0.1	0.145
7	1	0.3	0.875	0.5	1.25	0.2	1.55	0.4	1.75	0.1	1.65	0.1	0.182
8	1	0.7	0.95	0.3	1.3	0.2	1.575	0.7	1.8	0.2	1.8	0.2	0.166
9	1.4	0.2	1.25	0.2	1.525	0.4	1.85	0.4	1.95	0.1	2.6	0.6	0.242
10	1.225	0.5	1.1	0.4	1.5	0.6	1.775	0.8	1.6	0.4	1.45	0.1	0.205
11	1.225	0.3	1.225	0.2	1.525	0.2	1.625	0.4	1.8	0	2.45	0.1	0.209
12	1.475	0.4	1.15	0.4	1.75	0.3	2.2	0.6	2.65	0.1	2.35	0.1	0.22
13	0.6	0.3	0.575	0.1	0.975	0.4	1.075	0.4	1.1	0.4	1.1	0.2	0.126
14	0.6	0.3	0.7	0.3	1.125	0.7	1.025	0.3	1.3	0.2	1.35	0.1	0.112
15	0.625	0.7	0.6	0.4	0.975	0.4	0.85	0.7	1.2	0.2	1.25	0.1	0.124
16	0.5	0.2	0.6	0.5	1.025	0.5	0.9	0.8	1.3	0	1.2	0.4	0.122
17	0.925	0.3	0.925	0.2	1.6	0.6	1.5	0.7	2.1	0	1.75	0.1	0.166
18	1.025	0.1	1	0.5	1.525	0.2	1.425	1	1.5	0.1	1.3	0	0.176
19	0.875	0.2	1.025	0.1	1.2	0.2	1.475	0.4	1.45	0.1	1.55	0.1	0.186
20	0.85	0.3	0.85	0.5	1.375	0.7	2.075	0.7	2	0.2	2.05	0.1	0.15
21	1.2	0.4	1.175	0.2	1.875	0.7	2.175	0.6	2.5	0.4	2.85	0.5	0.236
22	1.25	0.3	0.2	0.2	1.525	0.1	2.175	1	2.05	0.3	2.2	0	0.23
23	1.15	0.4	0.925	0.3	1.675	0.3	1.75	1.2	1.9	0	2.2	0	0.224
24	1.15	0.2	1.3	0.2	1.625	0.3	2.05	0.4	1.6	0	1.95	0.3	0.22
25	0.5	0.4	0.575	0.3	1.075	0.3	0.9	0.3	1.25	0.3	1.1	0.2	0.11
26	0.55	0.4	0.525	0.3	0.875	0.4	0.875	0.2	0.85	0.1	1.1	0	0.104
27	0.575	0.2	0.65	0.3	1	0.2	0.95	0.3	0.95	0.3	1.1	0	0.105
28	0.6	0.4	0.625	0.4	0.925	0.4	1.15	0.6	1.15	0.1	1.1	0.2	0.12
29	0.9	0.7	1.05	0.6	1.4	0.8	1.775	0.2	2.1	0.2	1.95	0.3	0.184
30	1.025	0.6	1	0.3	1.225	0.4	1.45	0.3	1.25	0.1	1.4	0	0.184
31	0.85	0.4	0.75	0.8	1.375	1.1	2.325	1.1	2.3	0.8	2.35	0.5	0.18
32	0.975	0.4	0.875	0.2	1.4	0.7	1.75	0.4	2.05	0.3	2.15	0.1	0.176
33	1.1	0.2	1.15	0.4	1.85	1.6	1.475	1.6	2	0.4	2.35	0.1	0.22
34	1.2	0.4	1.15	0.7	1.6	0.7	1.7	0.6	1.9	0.2	2.15	0.1	0.224
35	1.15	0.5	1.15	0.3	1.725	1.7	1.675	0.7	2.8	0	2.2	0.2	0.21
36	1.3	0.5	1.35	0.3	1.55	0.8	2.075	0.7	2	0.2	2.35	0.3	0.226

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