MULTI-RESPONSE EVOLUTIONARY OPERATIONS WITH TAGUCHI PARAMETER DESIGNS FOR AUTOMATIC ELECTROSTATIC PAINTING SYSTEM

P. LUANGPAIBOON*
W. WANKAEW

Department of Industrial Engineering, Faculty of Engineering,
Thammasat University, 12120 Thailand

ABSTRACT

Evolutionary Operations (EVOP) or Response Surface Methodology (RSM) is a method for finding the optimal conditions of industrial processes. In general, this approach will search for the proper conditions under a consideration of a uni-response system. This work determines the efficiency of a proposed sequential algorithm in the context of RSM for automatic optimisation of metallic painting parameters for aluminium alloy wheels via Taguchi parameter design. The study categories the area on wheel into four zones and there are then four responses. The metallic painting system in this work uses an automatic electrostatic painting (AEP) spray gun and there are seven parameters (controllable predictor variables) that affect the metallic paint thickness including colour shade. To improve metallic painting parameters via Taguchi design we do study the interaction of each parameter to create linear graph of interaction for all parameters. This brings an orthogonal array of the specific experiments. By referred past records we can design lower and upper levels of each parameter. The purpose of experimental designs is to find the relationship among parameters to paint thickness and colour shade on the wheel. All experimental data will be used to fit a multiple regression model for paint thickness in each zone. A sequence of runs is then carried out by moving in the direction of steepest ascent to approach the better responses. Optimisation strategy in this work will be applied on each significant path in each zone. The results suggest that the proposed levels of predictor variables from the method of steepest ascent seems to be more efficient on the AEP surface when compared with the same preset levels. The EVOP based on Taguchi design works well on both the average and the standard deviation of the thickness when the responses are determined in areas zoned Z1, Z2 and Z4. Although the average and the standard deviation of the responses in zone Z3 after the EVOP are not satisfied, it is at the same level, on average, when compared. Under a consideration of customer's requirement on paint thickness and colour shade of the wheel, experimental analyses on metallic painting parameters also bring the reduction of metallic paint consumption in each wheel during the manufacturing process.

KEYWORDS: evolutionary operations, response surface, Taguchi parameter design, multiple regression, steepest ascent
hailand

1. INTRODUCTION

The objective of Response Surface Methodology is to describe how the response of a process varies with changes in k predictor variables. The predictor variables determined will depend on the specific field of the application. Most industrial processes have some predictor variables. These predictor variables can be adjusted by plant operators or by automatic control mechanisms to enhance the efficiency of the machine.

* Corresponding author. Tel: (662)-5643001-9 ext. 3081 Fax: (662)-5643017

E-mail: lpongch@engr.tu.ac.th

Response surface methodology (RSM), first proposed by Box and Wilson [1], is designed to explore an experimental region for finding the optimal settings of a set of variables that maximize the response. Usually the functional relationship between variables and the yield is unknown. In this situation the proper choices to optimize the response are search techniques. In RSM, it is convenient to transform these variables to corresponding coded predictor variables x_1, x_2, ..., x_k, referred as process variables. The coding is chosen so that changes of one unit are practical when searching for optimum conditions. The process is normally extended to quadratic functions near optima.

Box [2] suggested a sequence of 2^k factorial experiments; each displaced in the direction of steepest ascent from the preceding experiment. He described this as evolutionary operation, and stated that the objective of evolutionary operation is to move a full scale process towards optimum efficiency as quickly as possible. Many textbooks, for example [3, 4, 5] offer advice on this strategy. Brooks and Mickey [6] gave a theoretical argument that the minimal number of trials to estimate the direction of steepest ascent, from noisy observations, is just one more than the number of influential variables, that is a simplex design. For a planar surface, the best design in terms of expected improvement per unit effort is a triangular design.

However, these papers investigated the applications of first order designs through computer simulation models. Montgomery and Evans [7] later considered and discussed the use of various second order approximating polynomials on six response surfaces with the presence of noises. Myers and Carter [8] proposed an algorithm associated with the exploration of a surface with dual responses. The approach is to search variable settings which optimise a primary response function of average responses subject to the condition that a constraint response function, the variance of responses, takes on some specified or preferable value. Vining and Myers [9] presented how the dual-response approach of optimising a primary (mean) response function while simultaneously satisfying conditions on a secondary response (variance) function can be applied to achieve the goal. Its significance is the use of statistical methods to achieve both criteria.

Castillo and Montgomery [10] expressed how the goals of a dual response optimisation approach can be achieved using standard Non-Linear Programming (NLP) technique, the generalised reduced gradient (GRG) algorithm. It has been claimed that the proposed method leads to be more flexible and easier to use than the original dual response approach. The dual response problem is nonlinear programming since the primary and secondary responses are quadratic (second order) function). Lin and Tu [11] proposed a more satisfying and substantially simpler optimisation procedure on a dual-response approach.

Verbeek investigated the improvement of polymer strength via Young's modulus of compression [12]. Taguchi parameter design was applied to analyse effects on all factors to strength or a process response. The results suggested that the size of particle and a combination of polymer affect Young's modulus. Sequential design of experiments combined with Taguchi robust parameter design as an efficient process improvement methodology was presented by Hartjoy [13]. On the experimental results he claimed that Taguchi seems to be better than a full factorial design on both average responses and speed of convergence.

Zeng introduced an application of robust designs to an electromagnetic study [14]. This work determined the non-destructive experimental results by a finite element method. However, to enhance the reliability the Taguchi parameter design of experiments could be applied. In development of hydroxyapatite scaffolds for artificial bone grafts [15], Ajaal expressed the Taguchi parameter design to improve the process of manufacturing artificial bone grafts. The results suggested that time and resources to achieve the proper levels of factors are reduced and it would be proper to be applied as evolutionary operations. It also leads to higher level of the strength of artificial bone grafts. Application of Taguchi method in the optimisation of laser micro-engraving of photomasks was expressed by Chen, et al. [16]. Taguchi L16 designs brought the better line-width of 18 μm of engraving with the process parameters: 5x, 50 mm, 0.4 w, 5 kHz and 5000 mm/min. for beam expansion ratio, focal length, laser average power, pulse repetition and engraving speed respectively. Otto and Antonsson introduced extensions to the Taguchi method of product design [17] in various kinds of problems. The application of proper levels from Taguchi parameter design is determined to meet designer's requirement and it could be practical to apply to systems. Factorial design and Taguchi method in improving process quality [18] by Ansuj, et al. compared two designs to inspect the performance of raw materials, work in process to finally achieve products with the proper level of quality and manufacturing expenses.

Nowadays products and processes need the flexibility and low expenses. Effective total quality control is not the right choice. Evolutionary operations and product and process design via experimental design are used to achieve the proper level of system operation. Taguchi parameter design is the one of various kinds of designed experiments could be introduced to industries. Because of its performance in Japan, now it is well-known in all over countries. This paper undertakes further investigation with a sequential movement, the method of steepest ascent. Specifically, we determine the performance of the proposed optimisation strategy on the automatic electrostatic painting system. Conclusions are drawn, and recommendations are made.

2. METHODS

2.1 Method of Steepest Ascent

The procedure of steepest ascent is that a hyperplane is fitted to the results from the initial 2^k designs. The direction of steepest ascent on the hyperplane is then determined by using principles of least squares and experimental designs. The next run is carried out at a point, which is some fixed distance in this direction, and further runs are carried out by continuing in this direction until no further increase in yield is noted. When the response first decreases another 2^k design is carried out, centered on the preceding design point. A new direction of steepest ascent is estimated from this latest experiment. Provided at least one of the coefficients of the hyperplane is statistically significantly different from zero, the search continues in this direction. Once the first order model is determined to be inadequate, the area of optimum is identified via a second order model or a finishing strategy.

2.2 Taguchi Design

Taguchi design is an engineering strategy for robust process or product parameter design that focuses on minimising variation or signal noise over various conditions. The aim is to search for factor settings that minimise response variation, while attaining the process or product on its target. The strategy does try to find settings for controllable predictor variables that will reduce the variation. This also makes the product insensitive to changes in environmental variation during the product's usage, manufacturing variation, and component deterioration called as uncontrollable predictor variables or noise factors. Noise factors for the outer array should selected and require preliminary experimentation. The noise factor levels selected should reflect the range of conditions under which the response should remain robust.

Taguchi design is used to classify the predictor variables associated with the product or process into noise, control (specified by the designer), signal (input), and response (output) factors selected from related Linear Graph. Orthogonal Arrays (OA) are then used for gathering dependable information about control factors (design parameters) with a small number of experiments. OA consists of Inner Array for Controllable Factors and Outer Array for Uncontrollable Factors or Noise Factors. The combination of both arrays is called a Crossed Array as shown in Figure 1 for 2^2 (Inner) x 2^2 (Outer) Crossed Array.

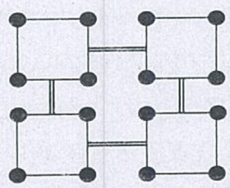


Figure 1. 2^2 x 2^2 Crossed Array

Signal-to-Noise (SN) Ratio, a measure of robustness, is used for predicting the product or process response (y_i) through experimental data of the crossed array. This is the step of variance reduction. SN can be categorised into 3 classes:

- Smaller the Best, SN_S: Maximise $SN_S = -10 \log\left(\frac{1}{n}\sum_{i=1}^{n} y_i^2\right)$
- Larger the Best, SN_L : Maximise $SN_L = -10 \log\left(\frac{1}{n}\sum_{i=1}^{n} \frac{1}{y_i^2}\right)$
- Nominal is the Best, SN_T : Maximise $SN_{T1} = -10 \log S^2$; $S^2 = \frac{\sum_{i=1}^{n}(y_i - \bar{y})^2}{n-1}$

Maximise SN_{T2}= 10 log $\frac{\bar{y}^2}{S^2}$; where n is the number of experimental runs, $\bar{y}$ is the mean responses and S^2 is the sample variance.

The designer then adjusts the level of controllable factors to achieve the goal of the experimentation based on main effect s and interaction graph.

3. ELECTROSTATIC PAINTING SYSTEM

Automatic electrostatic painting (AEP) or powder coating creates a durable finish on metal and some plastics without the runs, drips and bubbles which can occur with traditional liquid paints via the principal of the opposites attract. It's used on two main classes of plastics and every kind of metal. Concept and operation of electrostatic painting system is simple. Dry powder with the combination of pigments and resins is pneumatically fed from a supply reservoir to a spray gun where the high voltage charge is imparted to the powder. To be finished the part is electrically grounded. When the charged powder articles are sprayed, they are firmly attracted to the grounded part's surface. They are held there until melted and fused into a smooth coating in the curing ovens.

Electronic painting is a process utilising the property high states that opposite magnetic poles attract. This means that an electrical charge between a metal object being painted and the painting device (sprayer) causes the paint to be directly applied without overspray. The electrostatic painting process is perfect for on-site painting of metal items. Due to the unique application process, adjacent surfaces are safe from overspray. Because the paint is magnetically drawn to the surface to be painted, items such as railings can be painted from one side, and the paint will wrap around to the other side.

It is an environmentally friendly process because there are no solvents to evaporate into the air or go down the drain. At the same time it is also much more durable than liquid paint. Different formulations e.g. epoxy, urethane, polyester or a hybrid, are determined by the intended use of the item. For example, epoxy is best for corrosion protection and chemical and solvent resistance while urethane and polyester offer the best exterior durability. Because the surface of parts must be free of oil, dirt and rust prior to powder-coating, sandblasting, chemical and acid pre-treatments are needed on this system.

The AEP system in this work have 7 predictor variables effect to quality of metallic painting and for all predictor variables can be separated into two categories as follows. For metallic paint material there are 3 predictor variables and for 2 stations of the electrostatic painting system there are 4 predictor variables that show in Figure 2 and Table 1. In each cycle the low and high levels of factors will be designed for experiments. All uncontrollable variables are experimented in the early phase to preset the proper ranges.

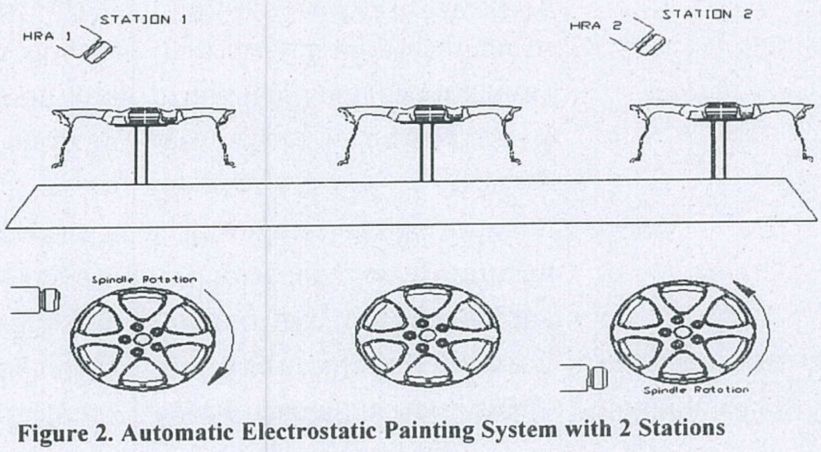


Figure 2. Automatic Electrostatic Painting System with 2 Stations

Table1. Predictor Variables of Painting System

No.	Ref.	Predictor Variables
1	A	Paint Resistance
2	B	Electrostatic Charging
3	C	Paint Viscosity
4	D	Paint Flow Rate for HRA1 (Painting Station 1)
5	E	Ring Air Pressure for HRA 1 (Painting Station 1)
6	F	Paint Flow Rate for HRA 2 (Painting Station 2)
7	G	Ring Air Pressure for HRA 2 (Painting Station 2)

The 7 predictor variables of electrostatic painting system also have 8 interactions predictor variables for each other then there are total 15 predictor variables effect to the quality of metallic painting shown in Table 2.

Table 2. Predictor Variables and Their Interactions

Predictor Variables	A , B , C , D , E , F , G
Interaction	AxB , BxC , BxD , BxE , DxE , BxF , BxG , FxG

Actually there are six types on L16 Taguchi linear graph [19]. In this work, there are two levels of each predictor variables then this could match a standard Taguchi linear graph with L16 (2^{15}) of type II. According to the predictor variables and their interactions of electrostatic painting system can be shown in Figure 3.

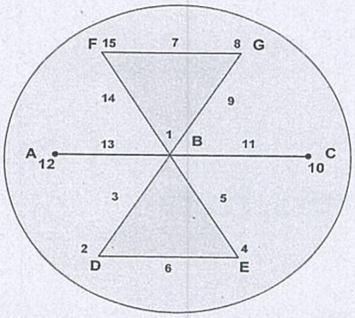


Figure 3. Standard Linear Graph L16 (2^{15}) Type II

The orthogonal array of L16 (2^{15}), a factorial design with two levels of low (1) and high (2), type II are shown in Table 3 and on the design experiment table we can not set the experiment for interaction of variables then the experiment table will concentrate on column of variables.

Table 3. The Orthogonal Array of L16 (2^{15}) Type II

	Predictor Variables and Their Interactions														
No.	B	D	BxD	E	BxE	DxE	FxG	G	BxG	C	BxC	A	AxB	BxF	F
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
2	1	1	1	1	1	1	1	2	2	2	2	2	2	2	2
3	1	1	1	2	2	2	2	1	1	1	1	2	2	2	2
4	1	1	1	2	2	2	2	2	2	2	2	1	1	1	1
5	1	2	2	1	1	2	2	1	1	2	2	1	1	2	2
6	1	2	2	1	1	2	2	2	2	1	1	2	2	1	1
7	1	2	2	2	2	2	1	1	1	2	2	2	2	1	1
8	1	2	2	2	2	2	1	2	2	1	1	1	1	2	2
9	2	1	2	1	2	1	2	1	2	1	2	1	2	1	2
10	2	1	2	1	2	1	2	2	1	2	1	2	1	2	1
11	2	1	2	2	1	2	1	1	2	1	2	2	1	2	1
12	2	1	2	2	1	2	1	2	1	2	1	1	2	1	2
13	2	2	1	1	2	2	1	1	2	2	1	1	2	2	1
14	2	2	1	1	2	2	1	2	1	1	2	2	1	1	2
15	2	2	1	2	1	1	2	1	2	2	1	2	1	1	2
16	2	2	1	2	1	1	2	2	1	1	2	1	2	2	1

The metallic paint thickness in each zone of the wheel are the response that use to evaluate the effect of each variables and in this work categories into four zones (zone Z1 to zone Z4) are shown in

Figure 4. In each zone there is also the controlled specification of metallic paint thickness from customers as shown in Table 4.

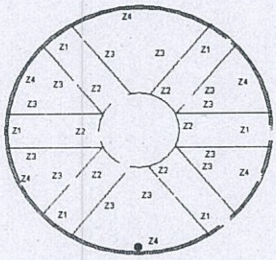


Figure 4. Reference Zone on the Wheel

Table 4. Customer Specification for Metallic Paint Thickness in Each Zone

Zone	Reference Area	Metallic Paint Thickness
Z1	Outboard spoke area	15 – 30 microns
Z2	Inboard spoke area	15 – 30 microns
Z3	Window between spoke area	10 – 25 microns
Z4	Window outboard	10 – 25 microns

4. DETAILS OF THE PROPOSED METHOD

Step 1: Perform Taguchi designs centred at the current operating condition.
Step 2: Fit a regression plane to the data, i.e.

$$\hat{y} = \hat{\beta}_0 + \hat{\beta}_1 x_1 + \hat{\beta}_2 x_2 + \hat{\beta}_3 x_3 + \hat{\beta}_4 x_4 + \hat{\beta}_5 x_5 + \hat{\beta}_6 x_6 + \hat{\beta}_7 x_7$$

Step 3: Test whether there is evidence that either β_i is different from zero at the 5% level of significance.
Step 4: If the result is significant, move one step along the path of steepest ascent. If the result is not significant then replicate the design and return to *Step 2*.
Step 5: Carry out two replicates of a factorial design, and return to *Step 2*.
Step 6: If there is evidence of a curvature effect, stop the algorithm.

5. EXPERIMENTAL RESULTS

In the experiment for the proposed method, the responses for all design points are measured from the process with the same controllable predictor variables. Constant levels for all uncontrollable variables; room temperature, room humidity, air room flow rate, speed of conveyor, wheel, direction of station 1 and 2 are set at 25 – 30 Celsius, 65 – 85%, 26550 – 29500 m^3/hr, 4.1 m/min, 40 rpm, clockwise, counter-clockwise, respectively. The actual data of responses will not be given. Taguchi experimental design for all controllable variables is on Table 5.

Table 5. Taguchi Experimental Design

No.	Predictor Variables of Metallic Painting Parameters							No. of Wheels
	B	D	E	G	C	A	F	
1	35	50	2.0	2.5	9.00-9.49	75	60	5
2	35	50	2.0	3.0	9.50-10.00	100	70	5
3	35	50	2.5	2.5	9.00-9.49	100	70	4
4	35	50	2.5	3.0	9.50-10.00	75	60	4
5	35	60	2.0	2.5	9.50-10.00	75	70	3
6	35	60	2.0	3.0	9.00-9.49	100	60	3
7	35	60	2.5	2.5	9.50-10.00	100	60	3
8	35	60	2.5	3.0	9.00-9.49	75	70	2
9	65	50	2.0	2.5	9.00-9.49	75	70	2
10	65	50	2.0	3.0	9.50-10.00	100	60	2
11	65	50	2.5	2.5	9.00-9.49	100	60	2
12	65	50	2.5	3.0	9.50-10.00	75	70	2
13	65	60	2.0	2.5	9.50-10.00	75	60	2
14	65	60	2.0	3.0	9.00-9.49	100	70	2
15	65	60	2.5	2.5	9.50-10.00	100	70	2
16	65	60	2.5	3.0	9.00-9.49	75	60	2

Sample means and standard deviations (Stdev) categorised on a zone from the pilot experiments are shown in Table 6 including the normal probability plot of effects on the response, Zone Z2 (Figure 5). On the Pareto chart, the significant effects consists of A, C and G including BC interaction.

Table 6. Process Multi-Responses from the Pilot Experiments

No.	Metallic Paint Thickness							
	Zone Z1 (Spec.15-30 micron)		Zone Z2 (Spec.15-30 micron)		Zone Z3 (Spec.10-25 micron)		Zone Z4 (Spec.10-25 micron)	
	Mean	Stdev	Mean	Stdev	Mean	Stdev	Mean	Stdev
1	10.2000	3.4880	10.2670	2.8520	4.5760	1.5280	5.4000	1.5670
2	9.6000	2.8840	10.9330	3.1290	5.8480	1.4610	5.6000	2.0610
3	9.7920	1.5320	13.6250	1.2450	6.6880	2.6190	8.7500	2.2510
4	11.5000	3.3620	12.2080	4.1180	5.9380	1.4200	6.0420	1.7320
5	10.4440	3.1480	11.8330	2.1490	5.8890	1.8170	6.2220	1.7340
6	9.2780	1.9650	9.5000	3.0530	5.4720	1.2980	7.8330	3.4000
7	10.5000	1.7240	11.0560	1.9840	6.0000	2.0280	6.8330	2.4070
8	11.1670	2.6570	11.1670	2.3680	4.8750	1.2960	6.4170	2.3530
9	13.0000	2.8920	12.7500	1.7650	5.4580	1.7190	7.2500	1.3570
10	10.7500	1.8150	12.0000	1.3480	4.9170	1.6400	8.1670	1.7490
11	13.3330	2.9340	13.8330	4.2180	6.8750	3.5420	5.5000	1.5080
12	9.9170	1.3790	14.0000	3.0750	6.5420	2.0640	5.9170	1.5050
13	12.6670	2.0150	12.6670	2.0150	5.2500	1.6480	5.6670	1.9230
14	12.0000	2.2160	13.9170	2.3530	5.7080	2.3310	6.7500	1.9130
15	11.0000	2.0450	14.6670	1.2310	5.7500	1.6480	7.9170	1.6210
16	12.0000	5.0450	13.0000	3.1330	5.6250	1.2790	6.5000	3.5290

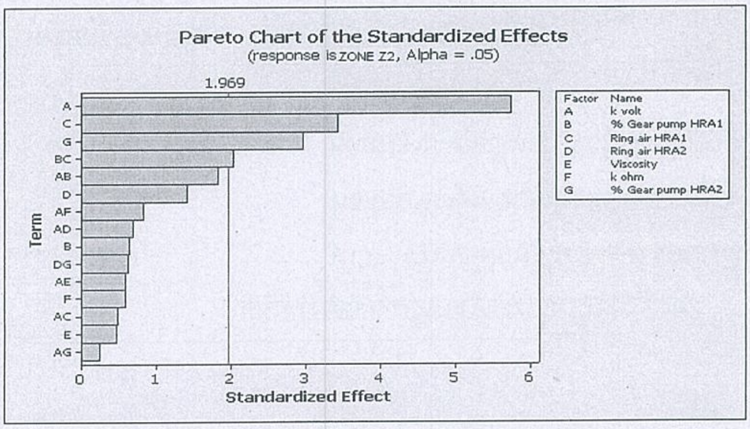


Figure 5. Significant Effects for the Pilot Experiment on Zone Z2

On the pilot experiments, the metallic paint thickness in all zones is under customer's specification. After the first cycle, the new level of Electrostatic Charging, B, is then reset at 50–70 kv and the remaining predictor variables are fixed. The number of replicates in each treatment combination is at two wheels throughout. As expected the metallic paint thickness in all zones, except zone Z3, are in specification. Zone Z3, the window between spoke area, is the most difficult area to spray all over that region followed the concept and operation of electrostatic painting system. However, it could be enhanced by increasing the combination of pigments and resins, though this brings higher level of expense. All the experimental runs on the second cycle are used to analyse the regression model in each zones (Minitab 14). Each effect estimate is measured to compare with the approximate 95% confidence interval (or its p-value). The estimate of σ^2 is the mean square of error (*MSE*) of the model and the statistic for testing H_0: $\beta_i = 0$ against H_1: $\beta_i \neq 0$ is $t_0 = \dfrac{\hat{\beta}_i}{\sqrt{C_{ii}MSE}}$ which has Student's *t*-distribution with $v = 2^k\text{-}k\text{-}1$ degrees of freedom. H_0 is rejected at significance level α if $|t_0| > t_{v,\alpha/2}$, where $t_{v,\alpha/2}$ is the upper $\alpha/2$ percentage point of the *t*-distribution with *v* degrees of freedom and C_{ii} is the diagonal element of the inversed matrix of the products between the level of the predictor variable matrix and its transposed matrix, $(X^TX)^{-1}$. The results of predictor variables and its significance and the adequacy of the first order model on zone Z1 was investigated from the analysis of variance (ANOVA) are shown in Tables 7 and 8.

Table 7. The Results of Predictor Variables and its Significance on Zone Z1.

Ref.	Predictor Variable	Coefficient	T	p-Value	Previous Level	New Level
A	**Paint Resistance**	**-0.0738**	**-4.99**	**0.000**	**87.5**	**90**
B	**Electrostatic Charging**	**0.0912**	**4.94**	**0.000**	**60**	**55**
C	Paint Viscosity	0.1354	0.37	0.714	9.00-9.49	9.00-9.49
D	**Paint Flow Rate for HRA1 (Painting Station 1)**	**0.1302**	**3.53**	**0.001**	**55**	**50**
E	**Ring Air Pressure for HRA 1 (Painting Station**	**-2.6875**	**-3.64**	**0.000**	**2.25**	**2.5**
F	**Paint Flow Rate for HRA 2 (Painting Station 2)**	**0.101**	**2.74**	**0.007**	**65**	**60**
G	Ring Air Pressure for HRA 2 (Painting Station 2)	0.8958	1.21	0.227	2.75	3

Table 8. The Analysis of Variance (ANOVA) on Zone Z1.

Source of Variation	Sum of Squares	Degree of Freedom	Mean Square	F	p-Value
Regression	550.245	7	78.606	12.01	0
Error	1204.25	184	6.545		
Total	1754.495	191			

On the first experimental results via the linear regression equation the metallic paint thickness in all zones is out of customer's specification because of the gear pump leak. The new low and high levels, [low, high], of all predictor variables is then reset at [75, 100], [50, 60], [9.00-9.49, 9.50-10.00], [70, 80], [2.0, 2.5], [70, 80], and [2.5, 3.0] for A, B, C, D, E, F and G, respectively. Similarly, all the experimental runs are used to analyse the regression model in each zones as above. The final regression models for all zones on the second cycle then did fit with these data as followed:

YzoneZ1 = 13.9 - 0.109A + 0.176B + 0.906C - 0.0344D - 0.77E + 0.118F + 0.40G
YzoneZ2 = 15.3 - 0.0396A + 0.0969B + 0.177C + 0.128D - 0.688E – 0.0052F - 1.56G
YzoneZ3 = 2.56 + 0.0006A + 0.0276B + 0.922C + 0.0276D - 0.135E + 0.0245F - 0.073G
YzoneZ4 = -0.91 - 0.0325A + 0.0208B + 1.00C + 0.0729D + 0.167E + 0.0750F + 0.625G

The estimate of coefficient was significant from the table of testing individual regression of coefficients. The results of new levels of predictor variables via those models are then adjusted and shown in Table 9.

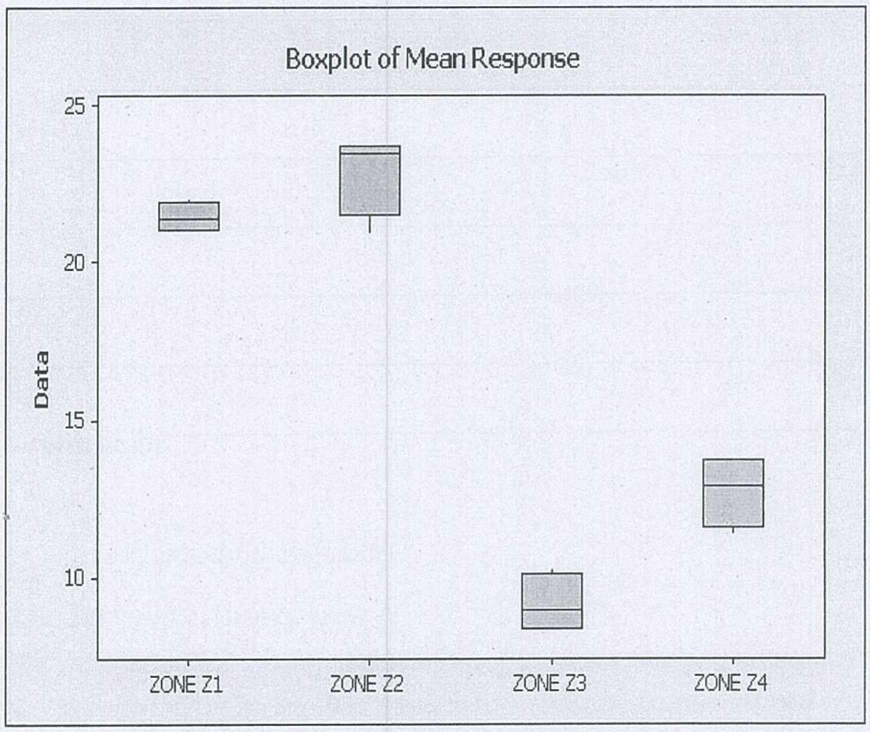
Table 9. New Levels of Predictor Variables

Ref.	Predictor Variable	New Level
A	Paint Resistance	50
B	Electrostatic Charging	70
C	Paint Viscosity	2
D	Paint Flow Rate for HRA1 (Painting Station 1)	70
E	Ring Air Pressure for HRA 1 (Painting Station 1)	2.5
F	Paint Flow Rate for HRA 2 (Painting Station 2)	9.5-10.00
G	Ring Air Pressure for HRA 2 (Painting Station 2)	100

The results on the metallic paint thickness in all zones, except zone Z3, are in specification and seem to be better. The metallic paint thickness on zone Z3 is than 10 microns as appeared on the pilot experiments. However, this happened as well when the previous levels of predictor variables are applied.

6. CONCLUSIONS AND DISCUSSIONS

The process settings for all predictor variables give the performances of the mean responses and the standard deviation of responses which can be explained by the box plots in Figure 6. These results show that the performance of the new settings under the basic linear regression element of the method of steepest ascent seems superior to the previous levels.



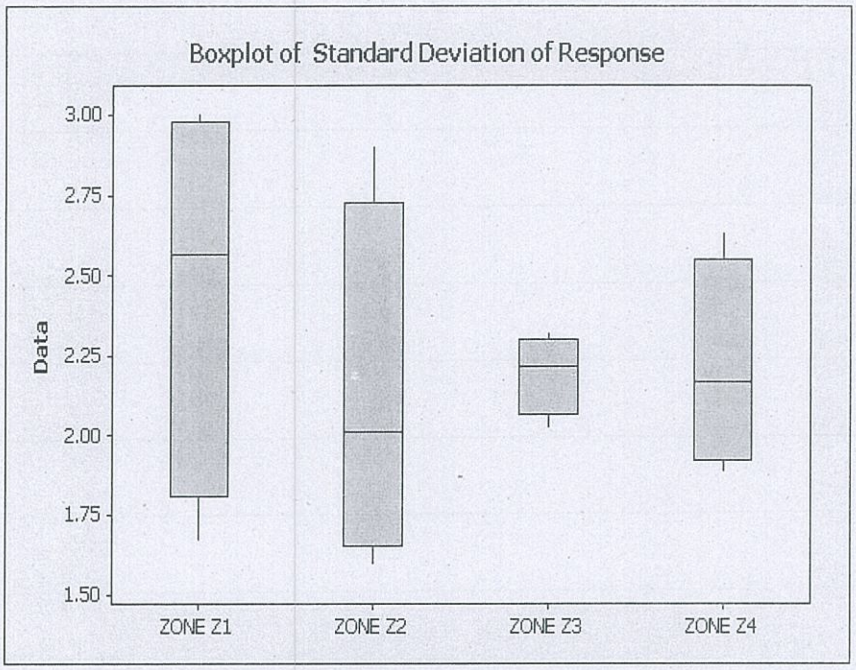


Figure 6. Two Independent Box Plot Comparisons showing the Performance of the Mean Responses and the Standard Deviation of Responses.

The new levels of predictor variables also bring the 70 % reduction on the metallic paint usage. Though the response on zone Z3 is still apart from the customer's specification, the confirmed experimental results under the previous levels of predictor variables also lead to the unsatisfactory level of responses on zone Z3. As stated earlier, the experiments in this research was restricted to two cycles. Consequently conclusions may not be optimal. Other stochastic approaches could be extended to the method based on conventional factorial designs to compare its performance, especially in terms of speed of convergence, and when the error standard deviation is at higher levels.

7. ACKNOWLEDGEMENT

The authors wish to thank the Faculty of Engineering, Thammasat University, THAILAND for the financial support.

REFERENCES

[1] Box, G.E.P. and Wilson, K.B. **1951** On the Experimental Attainment of Optimum Conditions, *Journal of the Royal Statistical Society, Series. B, 13*, 1-45.
[2] Box, G.E.P. **1957** Evolutionary Operation: a Method for Increasing Industrial Productivity, *Applied Statistics, 6*, 81-101.
[3] Box, G.E.P. and Draper, N.R. **1969** *Evolutionary Operation A Statistical Method for Process Improvement*, John Wiley, New York.
[4] Montgomery, D.C. **2001** *Design and Analysis of Experiment* . 5 th , John Wiley, New York.
[5] Brooks, S.H. **1959** A Comparison of Maximum-Seeking Methods, *Operations Research, 7*, 430-457.
[6] Brooks, S.H. and Mickey, M.R. **1961** Optimum Estimation of Gradient Direction in Steepest Ascent Experiments, *Biometrics, 46*, 48-56.
[7] Montgomery, D.C. and Evans, D.M. **1975** Second-order Response Surface Designs in Computer Simulation, *Simulation, 25*, 169-178.

[8] Myers, R.H. and Carter, W.H. **1973** Response Surface Techniques for Dual Response Systems, *Technometrics, 15*, 301-317.
[9] Vining, G.G. and Myers, R. H. **1990** Combining Taguchi and Response Surface Philosophies: A Dual Response Approach, *Journal of Quality Technology, 22*, 38-45.
[10] Del Castillo, E. and Montgomery, D.C. **1993** A Nonlinear Programming Solution to the Dual Response Problem, *Journal of Quality Technology, 25*, 199-204.
[11] Lin, D.K.J. and Tu, W. **1995** Dual Response Surface Optimisation, *Journal of Quality Technology, 27*, 34-39.
[12] Verbeek, C. J. R. **2002** *The Young's Modulus of Compression-Moulded LLDPE Phlogopite Composites*, Published Doctor of Philosophy Thesis, University of Pretoria, South Africa.
[13] Hartjoy, L.D. **2002** *Sequential Design of Experiments Combined with Taguchi Robust Parameter Design as an Efficient Process Improvement Methodology*. Published Master Thesis, International Society of Robust Engineering Professional.
[14] Zeng, Z. **2003** Applications of POD Studies and Robust Design to Electromagnetic NDE Published Doctor of Philosophy Dissertation, Iowa State University, U.S.A.
[15] Ajaal, T.T. **2002** *Development of Hydroxyapatite Scaffold for Artificial Bone Grafts*. Published Doctor of Philosophy Thesis, Queen's University Kingston, Canada.
[16] Chen, Y.H., Tam, S.C., Chen, W.L. and Zheng, H.Y. **1996** Application of Taguchi Method in the Optimisation of Laser Micro-Engraving of Photomasks, *International Journal of Materials and Product Technology, 11, (3/4)*, 333 – 344.
[17] Otto, K.N. and Antonsson, F.K. **1993** Extensions to the Taguchi Method of Product Design, ASME *Journal of Mechanical Design, 115 (1)* , 5-13.
[18] Ansuj A. P., Dos Santos, C.R. and Radharamanan, R. **2002**. Improving Process Quality Using of Factorial Design and Taguchi, *Technical Report*, Center of Mathematical Sciences, University of Santa Maria, Brazil.
[19] Peace, G. S. **1993** *Taguchi Methods: A Hands-on Approach*, Addison-Wesley Publishing Company, Reading.