Multi response optimization of quality characteristics in Offset printing industry using Taguchi approach and Grey relational analysis

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Abstract

This study was conducted to experimentally examine and improve the color variation as a major quality characteristic in printing on sheet-fed offset press. The experimental work considered seven main factors and three interactions. The L_{16} Taguchi experimental orthogonal array was chosen for defining the experimental treatments as it offered the fitting of the factors and interactions with all necessary degrees of freedom. The color variation of the four basic colors (Cyan, Magenta, Yellow and Black) was measured for every treatment. With these four responses for every treatment, the optimization problem became a multi-criteria one. The technique performed on observation data is Grey relational analysis results to transform multi response into a single one and optimum factor settings are defined.

Keywords: Offset printing, Print quality, Taguchi method, Grey relational analysis

1. Introduction

Printing industry is an important sector as it intersects with many other industries, whether directly through publishing work or indirectly through packaging processes. Offset printing is the most commonly used method in today's printing companies. In offset printing, the image is separated into its fundamental colors: Cyan, Magenta, Yellow and Black (CMYK). Quality of printed product depends on a large multitude of parameters like: impression pressure, plate properties, blanket cylinder, paper category, speed of press, ink, fountain solution, percentage of ink to paper, condition of printing machine and the experience of machine technician.

The idea of sheet-fed offset printing depends on the repulsion between water and ink. Region which contains the design adhere ink and non-image region adheres water and repel ink through dampening solution, also called fountain solution. The success of the whole printing process relies on dampening solution. Dampening solution consists of water and a percentage of isopropyl alcohol between 10 to 30 % of the entire volume. Properties of water affect the quality of fountain solution. The hardness, acidity and conductivity depend on water quality and additional additives added to water, while the percentage of isopropyl alcohol is responsible on water superficial tension.

Printing cylinder plate duplicate the inked design on blanket cylinder and the design is printed on paper when it passes between blanket cylinder and the impression cylinder. In order to guarantee a correct ink transfer on paper, a sufficient high pressure is needed between blanket and impression cylinders. Pressure is very important in Lithography (offset) printing process, and has a significant effect on printed product quality.

Another important factor affecting printing quality is the thickness of the under-packing sheets. Under-packing sheets are used to obtain optimum pressure on printing press. They are fitted in the gap between the blanket/plate and the blanket/cylinder to ensure proper ink transfer onto substrate and compensate any difference in thickness between them.

Printing a four colors design is performed when paper pass through four printing units. The aim is to put inks of different colors on top of each other in order to produce the required design. Colors printing sequence, called ink sequence, is very important for quality of printed product. It is the order in which ink colors are printed consecutively during printing process.

Concerning substrates printed on offset press, paper properties have significant effect quality of printed product such as surface roughness, viscoelasticity and compressibility of the paper surface. For example, uncoated paper absorbs ink more than coated paper. In general uncoated paper isn’t smooth as coated one and tends to be more pored. Therefore, uncoated papers are usually surface sized in order to improve their strength.

2. A Literature review of the Experimental Work in the Printing Field

Hsieh, 1997 conducted a full factorial to examine the impact of four factors varied at two levels each on the dot gain as a quality characteristic of the sheet-fed offset printing machine. The studied factors are: dampening solution, pressure between plate and blanket cylinder, pressure between blanket and impression cylinder and type of paper. He used main effect plot and normal probability plot as well as ANOVA to determine the significant factors. His results showed that paper type was the dominant variable affecting dot gain [1].

Bohan et al., 2000 studied the effect of four factors, three levels each, on color variation to determine the significant factors affecting quality of printed product on rotogravure press. The investigated factors are: blade load, blade angle, ink viscosity and impression pressure. Experimental orthogonal array was designed and the results were analyzed utilizing control charts. The results showed that ink viscosity was the dominant factor on color difference [2].

Sarela, 2004 utilized L_8 orthogonal array to examine the undesirable quality characteristic; set off, which could appear in four color newspapers printed on web offset printing machine. He studied a single color to simplify the set off phenomena as four color printing convert the problem into multi response problem. The examined factors are: paper grade, delay time and printing nip pressure with two levels each [3].

Vlachopoulos, 2010 employed L_{18} Taguchi experimental orthogonal array to investigate the effect of six factors varied at two levels each on misting and ribbing phenomena associated with ink film splitting at the rollers nip in offset press. The six studied factors are: rollers ratio, thickness of ink film, ink temperature, ink distribution speed, ink distribution time, and ink viscosity. He developed laboratory simulations to examine the two phenomena under ideal conditions to avoid the dynamic effect caused by ink transients [4].

Rastko et al., 2014 studied the effects of internal pressure in printing machine at 3 levels on quality of paper printed by using Lithography press. Six quality characteristics were measured as follows: color variation, rise in tone value, gray balance, variation of ink density, contrast and color gamut. They concluded that applied pressure has no clear effect on print quality. The results were quite conflict for evaluated factors [5].

Basio et al., 2015 utilized L_9 Taguchi experimental orthogonal array to validate the modification they developed in the oscillating ink roller system in HAMADA sheet-fed offset press in order to overcome the weakness in the system. HAMADA is a Japanese manufacturer of offset printing machines and related equipment. They investigated the effect of four factors with three levels each on quantity of paper waste. The investigated factors are: diameter of roller, material of roller, impression pressure and temperature [6].

Nandakumar and Bose, 2016 derived a mathematical model to understand the relationship between ink density and color variation (ΔE) for uncoated paper printed on sheet-fed offset press. A polynomial regression model was fit to represent the mathematical relationship between ΔD as an independent variable and color difference ΔE as a dependent variable. It was as follows:

$$\Delta E = a + b\Delta D + c\Delta D^2 \qquad (1)$$

The values of the coefficients a, b and c were obtained from experimental data and the least square method is applied to get the best fit parameters [7].

Sharma, 2016 used 2^4 full factorial experimental design to study the effect of printing machine speed, percentage of isopropyl alcohol, ink tack, and impression pressure on color difference (ΔE) printed on offset printing machine. The experimental data was analysed using ANOVA, and main and interaction plots to determine the optimal combination. He found that the optimal combination was lower level of percentage of isopropyl alcohol with higher levels of speed, ink tack, impression pressure. In addition, the results indicated that all the main factors are significant [8].

Nguyen et al., 2017 examined three factors varied at three levels each affecting three quality characteristics printed on web gravure press. He proposed to compute response weight using principal component analysis (PCA) to solve the multi response problem [9]. Nam and Nguyen, 2019 used 2^3 full factorial experimental design to investigate the effect impression pressure, percentage of isopropyl alcohol and printing machine speed on the color variation (ΔE). ANOVA was employed for the analysis of observed data and to decide the optimal levels of factors. Results showed that the interaction between printing pressure and percentage of isopropyl alcohol has the most significant effect on color variation [10].

Considerable research work was conducted to study the factors affecting quality characteristics of offset printing using experimental design, but most of them avoid solving the problem of multi response optimization. Literature review of experimental work in printing field focused on studying undesirable quality characteristics of offset press such as: dot gain, set off, gray balance, ink density and color variation. Regarding color variation of printed paper on 4 color Lithography printing machine, the literature work showed that studied factors include ink film (thickness, viscosity, speed of distribution, etc…), printing pressure, percentage of isopropyl alcohol and press speed.

In this research, the authors used the Taguchi approach to examine seven factors and three interactions varied at two levels affecting undesirable quality characteristics: color variation of four color sheet-fed offset press. The authors deal with color variation (ΔE) as a multi response where ΔE is measured for the four colors (Cyan, Magenta, Yellow and Black). The effects of other factors that aren't studied before are examined. These factors include the thickness of under-packing sheets, batch size, ink sequence and paper type in addition to the previously studied factors press speed, printing pressure and percentage of alcohol.

3. Methods to solve multi response problems

Taguchi strategy is applied to reduce the number of runs by applying orthogonal array. As Taguchi approach is used only in optimization of single response, many approaches were proposed to deal with multi response optimization. Many have used engineering judgment based Taguchi approach such as Phadke [11] who studied the factors affecting two responses in a manufacturing process, and Reddy et al., who employed engineering judgment to deal with the conflict between the optimum levels when there are a difference among the optimum levels of factors resembling to each response [12].

Another approach included giving a weight for each S/N ratio of response [13]. Then, the weighted S/N ratios are combined as follows:

The overall S/N ratio $$S/N_o = w_1 \left(S/N_1\right) + w_2 \left(S/N_2\right) + \cdots + w_i \left(S/N_i\right) \quad (2)$$

Where i: number of responses

w_i: weight of i^{th} response

Others normalized the S/N ratio of responses before computing the weight then used multi response S/N ratio to determine the optimal levels of process parameters such as Tong et al [14]. Nevertheless, it is difficult to determine the weight of each response in real industrial conditions [15].

Logothetics and Haigh, 1998[16], and others studied process parameters affecting five responses using one at a time manner, but they ignored the interaction between responses.

Principal Component Analysis "PCA" is a statistical approach used to reduce observed data via extracting a small number of factors which are responsible of most of the variation in the data. Many used PCA to undergo a transformation of multivariate response into few uncorrelated responses such as: Su and Tong [17], and Antony [18]. However, PCA has two shortcomings: [19]

1- When multiple eigenvalue is greater than one, no method off to decide the feasible solution.
2- The performance index of multi responses may not be enough to replace the original response variables if PCA has fewer variations than needed to explain total variation.

Data Envelopment Analysis (DEA) based ranking approach (DEAR) was employed to determine optimal levels of factors for multi response optimization in Taguchi approach [29, 30]. Unluckily, the majority of DEA models permit for complete weight flexibility which could lead to the identification of a decision making unit with an unreal weight scheme [20].

Genetic algorithm was used to locate the optimal weights for each response in order to maximize S/N ratio values, and then converted the multi response optimization problem into optimization of a single weighted S/N ratio [21].

Al Refaie et al., 2010 transformed every response into S/N ratio, and calculated the average S/N ratio for every treatment. After that the weight is computed with respect to the level of the highest average S/N ratio for this parameter. The treatment with the highest level weight is selected as the optimal level for that process parameter[19].

Grey relational analysis is used for solving interrelationships among the multivariate. Lin et al., 2002[22] suggested to deal with multi response problems based Taguchi strategy by utilizing grey relational approach. It has been proven that Grey based Taguchi approach can optimize the processes with multi responses through the settings of factors. In Grey relational method, data are normalized then the Grey coefficient (GC) is computed to define the connection between the desired and actual observed data. The Grey relational grade is calculated as the average of GC corresponding to every response.

4. Research methodology

This research includes examination of quality characteristic: color variation of the four colors (CMYK) for sheet-fed offset printing. Color variation is the inconsistent color reproduction within printed job. Color variation is gauged by variation in ink transfer which is governed by color difference (ΔE). ΔE which is measured by using spectrophotometers, describes the distance between two colors in the “CIE Lab color space” as follows:

$$\Delta E = \sqrt{(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2} \tag{3}$$

where ΔL^*: += lighter – = darker
Δa^*: += redder – = greener
Δb^*: += yellower – = bluer

The concern in the experiments was measuring the impact of seven factors which vary at two levels each, on color variation as an important quality characteristic. These factors are: printing pressure, printing speed, ink sequence, percentage of isopropyl alcohol, thickness of under-packing sheets, paper types and batch size. In addition, three interactions are studied:

1. Interaction of printing pressure with thickness of under-packing sheets
2. Interaction of printing pressure with percentage of isopropyl alcohol
3. Interaction of paper type with batch size

Table (1) displays the set of experimental factors and their levels.

Table (1): Experimental factors and their levels

No.	Factor Code	Factors	Factor levels	
			Low	High
1	A	Printing pressure (mm)	0.13	0.1
2	B	Thickness of under-packing sheets (mm)	0.3	0.4
3	C	percentage of isopropyl alcohol	10	13
4	D	Paper type	uncoated	coated
5	E	Printing speed (sheets/hr)	5000	8000
6	F	Ink sequence	CMYK	MCYK
7	G	Batch size (sheets)	Small (500)	Large (5000)

For this study, positive thermal CtP plates were initially prepared. The printing experiments were implemented on a four color sheet-fed Heidelberg SX102 offset press. The relative humidity of pressroom was about 45% while the temperature was about 32ºC. Spectrophotometer was employed to measure of the responses.

Taguchi strategy consists of two major components: Orthogonal Arrays and S/N ratio. Taguchi method utilizes orthogonal array for defining the experimental treatments with lowest number of experiments, thereby cost and time are minimized. In this study, the selected number of factors and their interactions are 10, and each has 2 levels. If full factorial design is used, the number of experimental runs will be 2^{10} = 1024 experimental runs. Using L_{16} Taguchi experimental orthogonal array reduces the number of experiments into only 16 runs. L_{16} was chosen as an experimental design for this work as it fits the seven factors and three interactions and offers needed degrees of freedom. The allocation of the factors and the interactions into the array columns is shown in Table (2), and Table (3) displays the experimental treatments and factor and interaction levels in every treatment.

5. Results and Discussions

Step 1: Calculation of S/N ratio from observed data

The quality characteristics or responses are normally divided into three types: "the-smaller-the-better", "the-nominal-the-best" and "the-larger-the-better" which govern the form of S/N ratio. In this work, every experimental treatment was replicated five times. Since color variation ΔE is a characteristic that is not desired and has to be minimized, it is of "the smaller-the better" type and S/N ratio to be used is as follows:

$$S/_{N}\, ratio(\eta) = -10log\left[\left(\frac{1}{n}\right)\sum_{i=1}^{n} Y_{ij}^{2}\right] \quad (4)$$

For all colors (C, M, Y, K), the S/N ratios are calculated and listed in Table (4). Usually S/N ratios are transformed into standard values (between 0 and 1) to avoid the dominance of particular responses over the others in the subsequent analysis.

Table (2): Allocation of factors and interactions to L_{16} OA column

OA column	Factor/Interaction	OA column	Factor/Interaction
1	A	9	-
2	B	10	E
3	AB	11	-
4	C	12	F
5	AC	13	-
6	-	14	-
7	DG	15	G
8	D		

Table (3): Experimental design

OA Column	1	2	4	8	10	12	15	3	5	7
	A	B	C	D	E	F	G	AB	AC	DG
Treatment 1	1	1	1	1	1	1	1	1	1	1
Treatment 2	1	1	1	2	2	2	2	1	1	1
Treatment 3	1	1	2	1	1	2	2	1	2	2
Treatment 4	1	1	2	2	2	1	1	1	2	2
Treatment 5	1	2	1	1	2	1	2	2	1	2
Treatment 6	1	2	1	2	1	2	1	2	1	2
Treatment 7	1	2	2	1	2	2	1	2	2	1
Treatment 8	1	2	2	2	1	1	2	2	2	1
Treatment 9	2	1	1	1	1	1	2	2	2	2
Treatment 10	2	1	1	2	2	2	1	2	2	2
Treatment 11	2	1	2	1	1	2	1	2	1	1
Treatment 12	2	1	2	2	2	1	2	2	1	1
Treatment 13	2	2	1	1	2	1	1	1	2	1
Treatment 14	2	2	1	2	1	2	2	1	2	1
Treatment 15	2	2	2	1	2	2	2	1	1	2
Treatment 16	2	2	2	2	1	1	1	1	1	2

Step 2: Values normalization

The S/N ratios are normalized by using the following equation:

$$Z_{ij} = \frac{\eta_{ij} - \min(\eta_{ij}, i = 1,2,\ldots,n)}{\max(\eta_{ij}, i = 1,2,\ldots,n) - \min(\eta_{ij}, i = 1,2,\ldots,n)} \quad (5)$$

Where Z_{ij}: normalized value of *i*th experiment for *j*th dependant responses.

Equation (5) is employed for S/N ratio of type “smaller-the-better”. Z_{ij} values of ΔE are calculated and displayed in Table (5).

Table (4): S/N ratios for color variation of all colors

Treatment No.	S/N ratio (ΔE C)	S/N ratio (ΔE M)	S/N ratio (ΔE Y)	S/N ratio (ΔE K)
1	-16.1310	-11.5915	-9.4783	-22.5303
2	-22.7166	-28.7355	-31.5731	-21.2811
3	-16.2126	-15.0295	-13.9358	-21.4272
4	-21.1343	-28.6700	-32.0267	-18.2602
5	-15.1476	-14.1920	-8.8559	-21.3758
6	-23.5750	-27.1204	-31.4100	-14.2180
7	-14.8578	-12.8668	-8.2672	-22.4143
8	-24.1359	-29.5669	-32.7739	-22.2582
9	-13.3582	-10.0268	-9.0428	-20.6842
10	-15.8304	-22.9387	-27.4598	-8.9785
11	-18.4525	-17.8573	-13.2329	-23.6676
12	-21.1347	-24.1806	-28.5985	-14.5864
13	-8.7064	-11.1945	-14.3020	-19.8864
14	-22.7934	-26.6103	-31.6985	-14.5969
15	-16.6304	-11.4333	-10.2276	-21.9627
16	-21.0868	-28.3767	-32.8325	-15.9982

Table (5): Normalized S/N ratios for color variation ΔE of (C, M, Y, K colors)

Treatment	Normalized S/N ratio			
	C.V.* of C	C.V.* of M	C.V.* of Y	C.V.* of K
1	0.519	0.920	0.951	0.077
2	0.092	0.043	0.051	0.162
3	0.514	0.744	0.769	0.153
4	0.195	0.046	0.033	0.368
5	0.583	0.787	0.976	0.156
6	0.036	0.125	0.058	0.643
7	0.601	0.855	1.000	0.085
8	0.000	0.000	0.002	0.096
9	0.699	1.000	0.968	0.203
10	0.538	0.339	0.219	1.000
11	0.368	0.599	0.798	0.000
12	0.195	0.276	0.172	0.618
13	1.000	0.940	0.754	0.257
14	0.087	0.151	0.046	0.618
15	0.486	0.928	0.920	0.116
16	0.198	0.061	0.000	0.522

*C.V.: Color Variation

Step 3: Grey Relational Coefficient calculations

The Grey Relational Coefficient (GC) is calculated using the following equation:

$$GC_{ij} = \frac{\Delta_{min}+\lambda\Delta_{max}}{\Delta_{ij}+\lambda\Delta_{max}} \tag{6}$$

where $i = 1, 2, \ldots, n$-observations and $j = 1, 2, \ldots, m$-responses

GC_{ij}: Grey Relational Coefficient

Δ: The quality loss. The target value in our case is one.

Δ_{min} = 0 (the min. value)

Δ_{max} =1 (the max. value)

λ: The distinguishing coefficient and its value: $0 \le \lambda \le 1$ If all the process responses have equal weighting, λ = 0.5[23].

For every experimental treatment, a grey relational grade is computed as the mean of the four corresponding GC. With these grades, the multi response optimization is transformed into a single response optimization one. Table (6) displays (**Δ**), (GC) for the four colors and the grey grades for the experimental treatments.

Table (6): (Δ), (GC) and Grey grades

N	Δ_C	Δ_M	Δ_Y	Δ_K	GC_C	GC_M	GC_Y	GC_K	G
1	0.481	0.080	0.049	0.923	0.510	0.862	0.910	0.351	0.658
2	0.908	0.957	0.949	0.838	0.355	0.343	0.345	0.374	0.354
3	0.486	0.256	0.231	0.847	0.507	0.661	0.684	0.371	0.556
4	0.805	0.954	0.967	0.632	0.383	0.344	0.341	0.442	0.377
5	0.417	0.213	0.024	0.844	0.545	0.701	0.954	0.372	0.643
6	0.964	0.875	0.942	0.357	0.342	0.364	0.347	0.584	0.409
7	0.399	0.145	0.000	0.915	0.556	0.775	1.000	0.353	0.671
8	1.000	1.000	0.998	0.904	0.333	0.333	0.334	0.356	0.339
9	0.301	0.000	0.032	0.797	0.624	1.000	0.941	0.386	0.737
10	0.462	0.661	0.781	0.000	0.520	0.431	0.390	1.000	0.585
11	0.632	0.401	0.202	1.000	0.442	0.555	0.712	0.333	0.511
12	0.805	0.724	0.828	0.382	0.383	0.408	0.377	0.567	0.434
13	0.000	0.060	0.246	0.743	1.000	0.893	0.671	0.402	0.742
14	0.913	0.849	0.954	0.382	0.354	0.371	0.344	0.567	0.409
15	0.514	0.072	0.080	0.884	0.493	0.874	0.862	0.361	0.648
16	0.802	0.939	1.000	0.478	0.384	0.347	0.333	0.511	0.394

Step 4: Defining optimum factor setting

The Grey grade data (response G) is analysed to decide the optimal levels for the factors as tabulated in Table (7).

Table (7): Average per factor levels

Factors	**Levels**			
	1		**2**	
A (Printing pressure)	**0.5010**		**0.5574**	
B (Thickness of under-packing sheets)	**0.5266**		**0.5318**	
C (percentage of isopropyl alcohol)	**0.5672**		**0.4912**	
D (Paper type)	**0.6457**		**0.4127**	
E (Printing speed)	**0.5016**		**0.5568**	
F (Ink sequence)	**0.5406**		**0.5178**	
G (Batch size)	**0.5434**		**0.5150**	
Interaction Levels				
AB (Interaction A&B)	**A_1B_1: 0.4865**	**A_1B_2: 0.5480**	**A_2B_1: 0.5668**	**A_2B_2: 0.5480**
AC (Interaction A&C)	**A_1C_1: 0.5162**	**A_1C_2: 0.4859**	**A_2C_1: 0.6183**	**A_2C_2: 0.4965**
DG (Interaction D&G)	**D_1G_1: 0.6454**	**D_1G_2: 0.6461**	**D_2G_1: 0.4414**	**D_2G_2: 0.3840**

From Table (7), the optimal factor levels for color variation are: $A_2B_2C_1D_1E_2F_1G_1$ and for interactions: A_2B_1, A_2C_1 and D_1G_2. This means that the optimal combination which reduce the color difference is higher level of: printing pressure, thickness of under packing sheets and press speed, with lower level of: percentage of isopropyl alcohol, paper type, ink sequence and batch size.

Step 5: Prediction of color variation at optimum factor setting

The predicted value of color variation is predicted as follows:

For Cyan color:

$$P = O_C + \left(F_{1,op} - O\right) + \left(F_{2,op} - O\right) + \cdots + \left(F_{n,op} - O\right) \quad (8)$$

Where P: Value predicted

O_C: Overall average of Cyan color

$F_{n,op}$: Factor levels from A to G at optimum level

Similarly, the predicted color variations of other colors are computed (Magenta, Yellow and Black), and the results are listed in Table (8).

Table (8): Color variation at Optimum factor levels

	Overall Average	**Average Color Variation per Optimum Factor Level**							**Predicted Color Variation**
		A (H)	**B(H)**	**C(L)**	**D(L)**	**E(H)**	**F(L)**	**G(L)**	
ΔE C	**9.0263**	**8.083**	**9.588**	**8.458**	**5.740**	**7.860**	**8.640**	**8.3100**	**2.5200**
ΔE M	**13.7438**	**11.908**	**14.563**	**12.538**	**4.533**	**12.523**	**14.278**	**13.6325**	**1.5100**
ΔE Y	**19.9263**	**18.518**	**22.053**	**18.835**	**3.480**	**17.730**	**20.953**	**19.9225**	**1.9325**
ΔE K	**9.6713**	**8.468**	**9.585**	**8.790**	**12.238**	**9.315**	**9.725**	**9.1725**	**9.2650**

6. Conclusion

This research proposed a method for dealing with multi response problem in Taguchi approach. In this method, an experiment of 16 runs using orthogonal array were designed to study the impact of 7 factors and 3 of their interactions on the quality characteristics of printed paper on sheet-fed offset printing machine. The measured quality characteristic is the color difference ΔE of the 4 printed colors: Cyan, Magenta, Yellow and Black. As 4 responses were measured, a multi response optimization is needed.

The S/N ratio of every response is estimated. Next, the S/N ratio is normalized and (GC) is calculated for each response. The average GC is calculated for the 16 experimental runs. At that moment, the problem can be resolved as a single response problem. The GC data is analysed to determine the optimal factors levels. It is found that the optimal factor combinations to minimize color variation are: small batch size, 10% of isopropyl alcohol, uncoated paper, ink sequence (CMYK) and printing speed of 8000 sheets/hr with higher printing pressure and thickness of under packing sheets. The results show that the predicted color variation will be as follows: for Cyan: 2.52, for Magenta: 1.51, for Yellow: 1.93 and for Black: 9.265.

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