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# APPLYING DMAIC PROCEDURE TO IMPROVE PERFORMANCE OF LGP PRINTING PROCESS COMPANIES

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**Abstract:**
The light-guide-plate (LGP) luminance plays an important role in producing liquid crystal displays (LCD) panels of quality images. Poor luminance usually results in producing LCD panels with color defects. This research aims at improving the performance of LGP printing process by following the define-measure-analyze-improve-control (DMAIC) procedure.

To improve the performance of LGP process, the DMAIC procedure will be implemented as follows. Process mapping and control charts will be established in the define-phase. The process capability analysis is conducted in the measure-phase. The Taguchi's experimental design and analysis will be performed in the analyze- and improve-phases. Finally, the grey model GM (1,1) will be employed in the control-phase.

Utilizing the Taguchi's $L_{27}$ ($3^{13}$) array, six key process factors were investigated concurrently; including scraper angle, scraper pressure, scraper speed, ink viscosity, ink paller bearing, and gap between board and LGP. It is found that the scraper's angle, pressure and speed, and ink viscosity significantly contributed to the luminance variability. The anticipated improvement in luminance is found 512 cd/m$^2$. The estimated process capability, $\hat{C}_{pl}$, is greatly enhanced from 0.69 to 2.44.

Statistical quality control tools, the Taguchi method, and GM (1,1) grey model are employed in the DMAIC procedure to improve the performance of LGP process. Product/process engineers can adopt this procedure in a similar manner to enhance the performance of any manufacturing process in a wide range of business applications.

**Key Words:** Taguchi Method, DMAIC, Statistical Quality Control, GM (1,1) Grey Model

## 1. INTRODUCTION

Because of its smaller space requirement, high-quality display and acceptable cost, the thin film transistor liquid crystal display (TFT-LCD) has become the most important visual display terminal screen today [1–4]. TFT-LCD is used widely in the industry of electronic information displays, including television, mobile phones, digital cameras and other consumer related communications hardware. In such products, image colour-quality has been recognized as one of the top considerations in the display manufacturing industry and has become a benchmark that influences consumers' purchasing decision.

The light-guide-plate (LGP) luminance plays an important role in producing LCD panels of quality images and it is used in assessing front-of-screen quality. Poor luminance results in producing LCD panel with colour defects, which increase quality costs. Hence, improving the performance of LPG process is the main focus of this research.

Six sigma [5] is a project-driven management approach to improve products and processes by continually reducing defects. A widely-accepted six sigma approach is the DMAIC procedure, which was adopted to improve the performance for numerous manufacturing processes [6, 7]. Further, the introduction of robust design proposed by Taguchi [8] in quality engineering resulted in significant quality and productivity improvements in product and manufacturing process design. Taguchi method [9] combines engineering ideas with statistical techniques in novel ways and offers tremendous potential for quality improvement with minimal cost in a wide range of industrial applications [7, 10].

This research, therefore, aims at improving luminance of LCD for LGP printing process using DMAIC procedure including the Taguchi method. The remaining of this paper is outlined in the following sequence. Section two performs the define-phase. Section three carries out the measure-phase. Section four performs the analyze- and improve-phases. Section five establishes the control-phase. Section six summarizes conclusions.

## 2. DEFINE-PHASE

### 2.1 Mapping Backlight Module Processes

A conventional LCD backlight module is composed of light sources, LGP, and optical sheets; such as, reflection, diffusion, and prism sheets. In this module, the light rays from the source are incident on one of the LGP sides and are guided inside it based on the principle of total internal reflection. At least one of LGP surfaces is coated with an ink layer. The ink layer contains a plurality of diffusing granules for diffusing lights to produce uniform luminance. The flow chart of backlight module is routed in Figure 1. Initially, the LGP cutting and cleaning take place. Dot patterns are then printed on its surface. The LGP is fitted with lamp set then assembled with module frame and optical film. Screen inspection, testing, and film protection activities follow. Packing of the back-light module is finally performed. Among the back-light module processes, the LGP printing process is a critical process in producing quality modules, which is performed on LGP printing machine shown in Figure 2.

### 2.2 Assessing the process performance

The $\bar{x}$ and $R$ control charts are widely applied for on-line monitoring of the mean and variability of the manufacturing processes [11]. They are a proven technique for improving productivity, defect prevention, preventing unnecessary process adjustment, and providing information about process capability. Let *UCL*, *CL*, and *LCL* denote the upper control limit, the central line, and lower control limit, respectively. The $\bar{x}$ and $R$ control charts are concluded in control if all points fall within control limits and no indication of significant patterns or runs between the control limits.

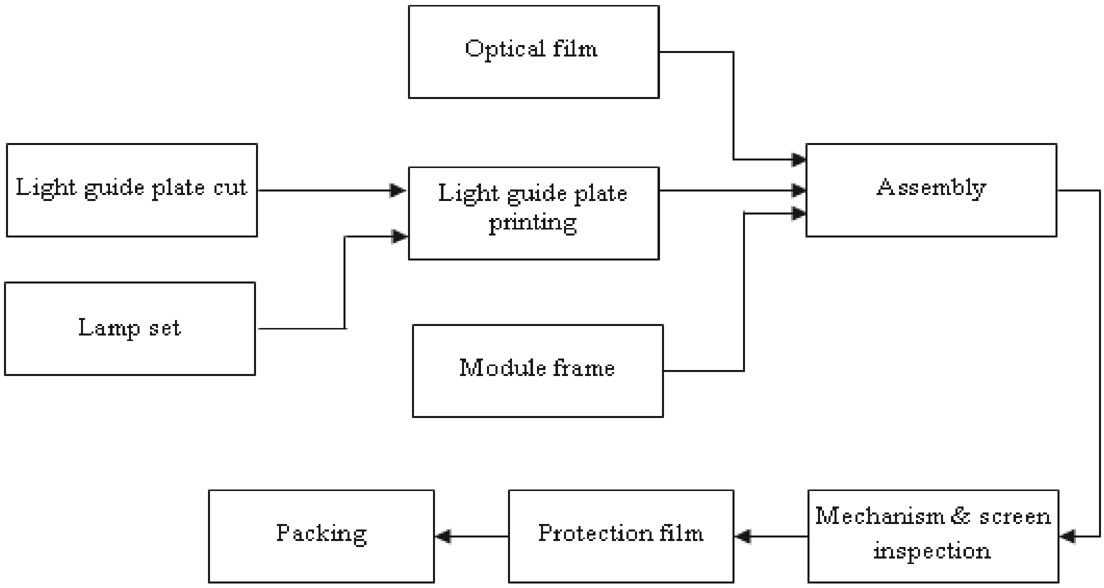



Figure 1: Flow chart for back-light module.


Figure 2: LGP printing machine.

Five LGP plates are randomly chosen then inspected every two hours for 15 working hours. On each plate, the luminance is measured with BM7 at five points ($L_1$, $L_2$, $L_4$, $L_7$, $L_9$) as depicted in Figure 3. The luminance average and range are calculated for each LGP. The corresponding $\bar{x}$ and *R* control charts are finally constructed then shown in Figure 4. The *LCL*, *CL*, and *UCL* for the $\bar{x}$ chart are calculated and found equal to 4480.3, 4625.2, and 4770.2 cd/m$^2$, respectively. For the *R* chart, the *LCL*, *CL*, and *UCL* are estimated 0.0, 251.3, and 531.4, respectively. In Figure 4, no point is detected outside the control limits nor are any significant patterns or runs observed within the limits of both control charts. Consequently, the $\bar{x}$ and *R* control charts are concluded in control.

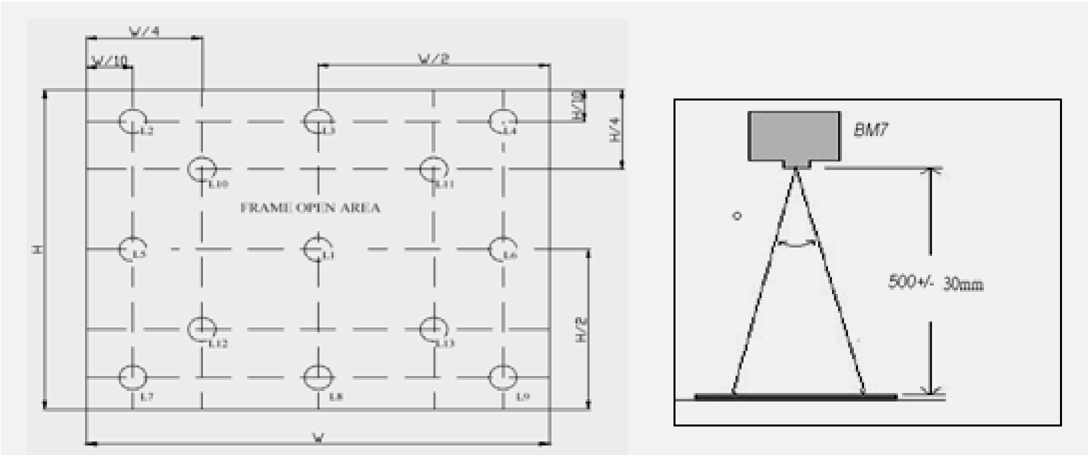



Figure 3: Luminance measurement (red circles) using BM7.

## 3. MEASURE PHASE

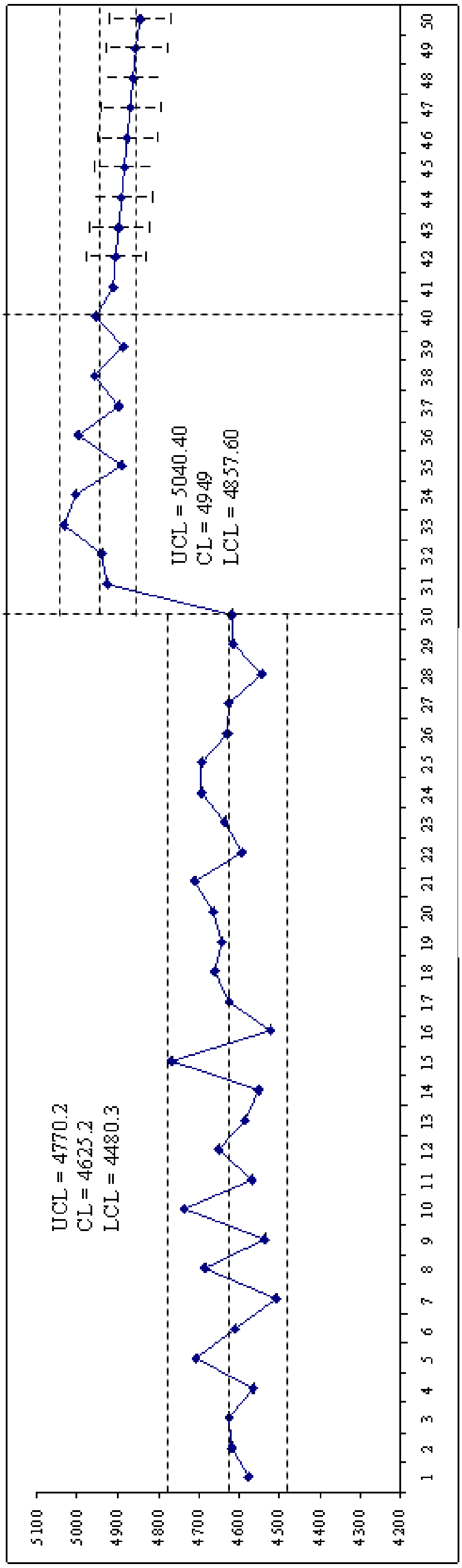
Process capability analysis [12] is a vital part of an overall quality-improvement program by which the capability of a manufacturing process can be measured and assessed. In practice, the process standard deviation, $\sigma$, is unknown and frequently estimated as:

$$\hat{\sigma} = \overline{R} / d_2 \quad (1)$$

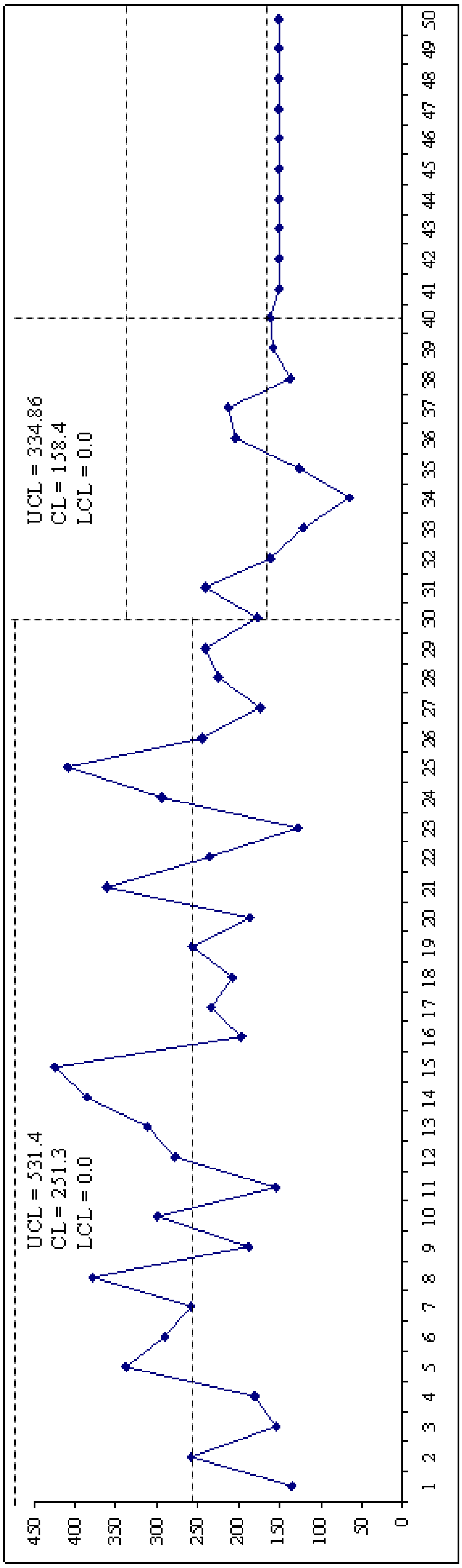
where $d_2$ is a constant related to sample size. The one-sided actual process capability, $C_{pk}$, attempts to take the process mean into account [13]. The estimator of $C_{pk}$, $\hat{C}_{pk}$, is calculated as:

$$\hat{C}_{pk} = \min(C_{pu} = \frac{USL - \hat{\mu}}{\hat{\sigma}}, C_{pl} = \frac{\hat{\mu} - LSL}{\hat{\sigma}}) \quad (2)$$

where *USL* and *LSL* are the upper and lower specification limits, respectively. The $\hat{\mu}$ is the estimate of $\mu$ and is equal to the *CL*, $\overline{\overline{x}}$, of the $\overline{x}$ chart. A value of 1.67 is considered the standard minimum boundary for $\hat{C}_{pk}$. In this research, the *LSL* of luminance is 4450 cd/m$^2$ (candelas per square meter). Using the $\overline{\overline{x}}$ (= 4625.2 cd/m$^2$) and $\overline{R}$ (= 251.3 cd/m$^2$), and the $d_2$ for a sample size of five is equal to 2.326, the $\hat{\sigma}$ and $\hat{C}_{pk}$ values are calculated by Equations (1) and (2) and found equal to 108.04 cd/m$^2$ (=251.3/2.326) and 0.695 (= (4625.2-4450)/(3×108.04)), respectively. Evidently, the LGP printing process is concluded incapable for providing acceptable luminance.




(a) The $\bar{x}$ control chart.




(b) The $R$ control chart.

Figure 4: The $\bar{x}$ and $R$ charts at initial and optimal factor settings.

## 4. ANALYZE- AND IMPROVE- PHASES

### 4.1 Investigating critical QCH and process factors

The LGP luminance is considered the key measurable and continuous QCH of main interest. The cause-and-effect diagram for non-uniformity of LGP luminance is shown in Figure 5.

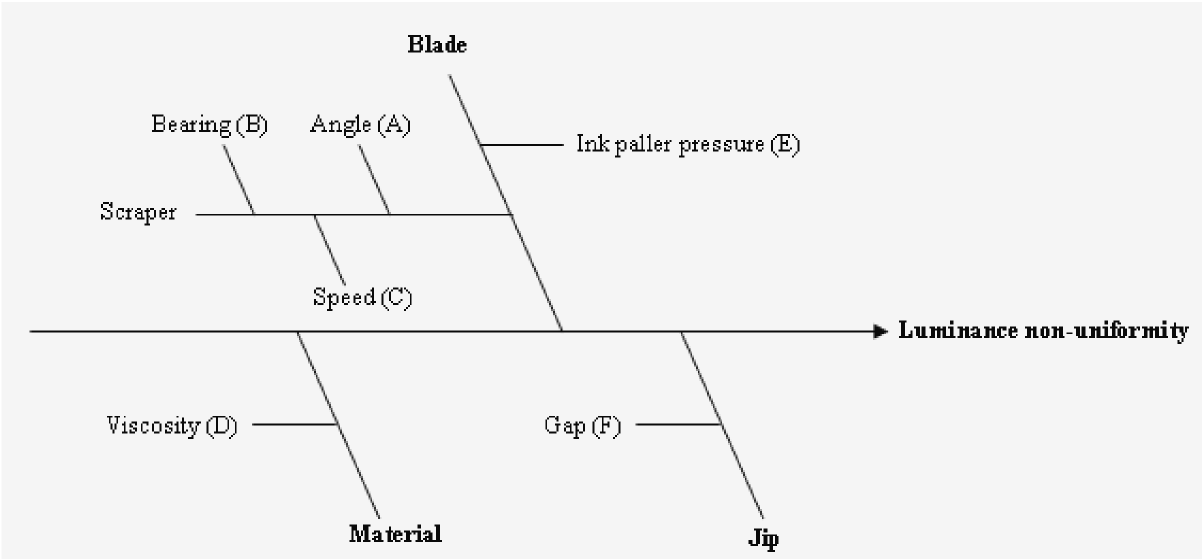



Figure 5: The cause-and-effect diagram for luminance non-uniformity.

Six control factors may affect the capability of the LGP printing process including: (A) scraper angle, (B) scraper pressure, (C) scraper speed, (D) ink viscosity, (E) ink paller bearing, and (F) gap between board and LGP. Based on process knowledge, all factors A to F are assigned at three levels. The corresponding level values are displayed in Table I. The combination of factor settings of the LGP printing process at initial stage is $A_1B_2C_2D_2E_1F_2$.

Table I: The physical values of factor levels.

| Control factor | Level 1 | Level 2 | Level 3 |
|---|---|---|---|
| A. Scraper angle (degree) | $\underline{65°}$ | 75° | 85° |
| B. Scraper pressure (bar) | $P_0$-1 | $\underline{P_0}$ | $P_0$+1 |
| C. Scraper speed (mm/sec) | $S_0$-20 | $\underline{S_0}$ | $S_0$+20 |
| D. Ink viscosity (cP)* | $C_0$-5 | $\underline{C_0}$ | $C_0$+5 |
| E. Ink paller bearing (bar) | $\underline{T_0}$ | $T_0$+5 | $T_0$+10 |
| F. Gap (mm) | 3 | $\underline{5}$ | 7 |

* The poise is the most commonly encountered unit of viscosity, often as the centipoise (cP).

### 4.2 Improving performance using Taguchi method

Taguchi method mainly focuses on finding the optimal setting of control factors involved in a system to make its performance insensitive to noise. An orthogonal array (OA) is used to provide an experimental design. Signal-to-noise (S/N) ratio is then employed to measure performance and decide optimal factor levels. In this research, the $L_{27}$ ($3^{13}$) array shown in Table II is selected to investigate the six process factors concurrently.

Table II: Experimental results for $L_{27}$ ($3^{13}$) array.

| Exp. ($j$) | Factor-columns assignment | | | | | | | | | | | | | Test QCH value ($y_i$) | | | Average luminance | S/N ratio ($\eta_i$) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | A | B | C | D | E | F | *e* | *e* | *e* | *e* | *e* | *e* | *e* | Test 1 | Test 2 | Test 3 | | |
| 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 4498 | 4536 | 4536 | 4523.33 | 73.11 |
| 2 | 1 | 1 | 1 | 1 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 4526 | 4550 | 4522 | 4532.67 | 73.13 |
| 3 | 1 | 1 | 1 | 1 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 4584 | 4692 | 4552 | 4609.33 | 73.27 |
| 4 | 1 | 2 | 2 | 2 | 1 | 1 | 1 | 2 | 2 | 2 | 3 | 3 | 3 | 4850 | 4740 | 4740 | 4776.67 | 73.58 |
| 5 | 1 | 2 | 2 | 2 | 2 | 2 | 2 | 3 | 3 | 3 | 1 | 1 | 1 | 4868 | 4858 | 4824 | 4850.00 | 73.71 |
| 6 | 1 | 2 | 2 | 2 | 3 | 3 | 3 | 1 | 1 | 1 | 2 | 2 | 2 | 4920 | 4908 | 4894 | 4907.33 | 73.82 |
| 7 | 1 | 3 | 3 | 3 | 1 | 1 | 1 | 3 | 3 | 3 | 2 | 2 | 2 | 5044 | 5080 | 5156 | 5093.33 | 74.14 |
| 8 | 1 | 3 | 3 | 3 | 2 | 2 | 2 | 1 | 1 | 1 | 3 | 3 | 3 | 5160 | 5084 | 5176 | 5140.00 | 74.22 |
| 9 | 1 | 3 | 3 | 3 | 3 | 3 | 3 | 2 | 2 | 2 | 1 | 1 | 1 | 5216 | 5096 | 5048 | 5120.00 | 74.18 |
| 10 | 2 | 1 | 2 | 3 | 1 | 2 | 3 | 1 | 2 | 3 | 1 | 2 | 3 | 4732 | 4838 | 4912 | 4827.33 | 73.67 |
| 11 | 2 | 1 | 2 | 3 | 2 | 3 | 1 | 2 | 3 | 1 | 2 | 3 | 1 | 4850 | 4752 | 4698 | 4766.67 | 73.56 |
| 12 | 2 | 1 | 2 | 3 | 3 | 1 | 2 | 3 | 1 | 2 | 3 | 1 | 2 | 4904 | 4794 | 4784 | 4827.33 | 73.67 |
| 13 | 2 | 2 | 3 | 1 | 1 | 2 | 3 | 2 | 3 | 1 | 3 | 1 | 2 | 4882 | 4954 | 4964 | 4933.33 | 73.86 |
| 14 | 2 | 2 | 3 | 1 | 2 | 3 | 1 | 3 | 1 | 2 | 1 | 2 | 3 | 4878 | 4796 | 4942 | 4872.00 | 73.75 |
| 15 | 2 | 2 | 3 | 1 | 3 | 1 | 2 | 1 | 2 | 3 | 2 | 3 | 1 | 4838 | 4944 | 4940 | 4907.33 | 73.82 |
| 16 | 2 | 3 | 1 | 2 | 1 | 2 | 3 | 3 | 1 | 2 | 2 | 3 | 1 | 5058 | 4940 | 4924 | 4974.00 | 73.93 |
| 17 | 2 | 3 | 1 | 2 | 2 | 3 | 1 | 1 | 2 | 3 | 3 | 1 | 2 | 5072 | 5112 | 5222 | 5135.33 | 74.21 |
| 18 | 2 | 3 | 1 | 2 | 3 | 1 | 2 | 2 | 3 | 1 | 1 | 2 | 3 | 5238 | 5160 | 5180 | 5192.67 | 74.31 |
| 19 | 3 | 1 | 3 | 2 | 1 | 3 | 2 | 1 | 3 | 2 | 1 | 3 | 2 | 4904 | 4994 | 4912 | 4936.67 | 73.87 |
| 20 | 3 | 1 | 3 | 2 | 2 | 1 | 3 | 2 | 1 | 3 | 2 | 1 | 3 | 4850 | 4930 | 4922 | 4900.67 | 73.80 |
| 21 | 3 | 1 | 3 | 2 | 3 | 2 | 1 | 3 | 2 | 1 | 3 | 2 | 1 | 5064 | 4954 | 4944 | 4987.33 | 73.96 |
| 22 | 3 | 2 | 1 | 3 | 1 | 3 | 2 | 2 | 1 | 3 | 3 | 2 | 1 | 4882 | 4954 | 4804 | 4880.00 | 73.77 |
| 23 | 3 | 2 | 1 | 3 | 2 | 1 | 3 | 3 | 2 | 1 | 1 | 3 | 2 | 4878 | 4796 | 4942 | 4872.00 | 73.75 |
| 24 | 3 | 2 | 1 | 3 | 3 | 2 | 1 | 1 | 3 | 2 | 2 | 1 | 3 | 4838 | 4944 | 4812 | 4864.67 | 73.74 |
| 25 | 3 | 3 | 2 | 1 | 1 | 3 | 2 | 3 | 2 | 1 | 2 | 1 | 3 | 5058 | 4940 | 4924 | 4974.00 | 73.93 |
| 26 | 3 | 3 | 2 | 1 | 2 | 1 | 3 | 1 | 3 | 2 | 3 | 2 | 1 | 5072 | 5112 | 5222 | 5135.33 | 74.21 |
| 27 | 3 | 3 | 2 | 1 | 3 | 2 | 1 | 2 | 1 | 3 | 1 | 3 | 2 | 5238 | 5160 | 5180 | 5192.67 | 74.31 |

In practice, larger luminance provides better performance. The corresponding S/N ratio, $\eta_j$, is expressed as:

$$\eta_j = -10\ log_{10}(\frac{1}{n}\sum_{i=1}^{n} 1/y_{ij}^2),\ i=1,...,I;\ j=1,...,J \qquad (3)$$

where $y_{ij}$ is the luminance average of each test $i$ for experiment $j$. Three repetitions ($n$ = 3) are conducted at the same factor levels of each experiment. The last column of Table 2 summarizes the estimated S/N ratios values for all experiments. For illustration, the S/N ratio, $\eta_1$, of 73.11 dB for the first experiment is calculated as using Eq. (3) as follows

$$\eta_1 = -10\log_{10}(1/4498^2 + 1/4536^2 + 1/4536^2)/3 = 73.11 \text{ dB}$$

The $\eta_j$ values for the other 26 experiments are estimated similarly.

Typically, a larger S/N ratio indicates better performance. The S/N ratios averages are calculated at each factor level then depicted in Figure 6**.** Consequently, the combination of optimal factor levels is $A_3B_3C_3D_2E_3F_2$. Table 3 tabulates the luminance averages for all factor levels. The anticipated improvement in luminance, due to setting process factors at $A_3B_3C_3D_2E_3F_2$, is calculated for each factor as the luminance at optimal factor level minus that at initial factor level. The last column of Table 3 lists the obtained results. The total anticipated improvement is calculated and found equal to 512 cd/m$^2$, where factors A, B, and C contributed the largest effect on the anticipated improvement of luminance.

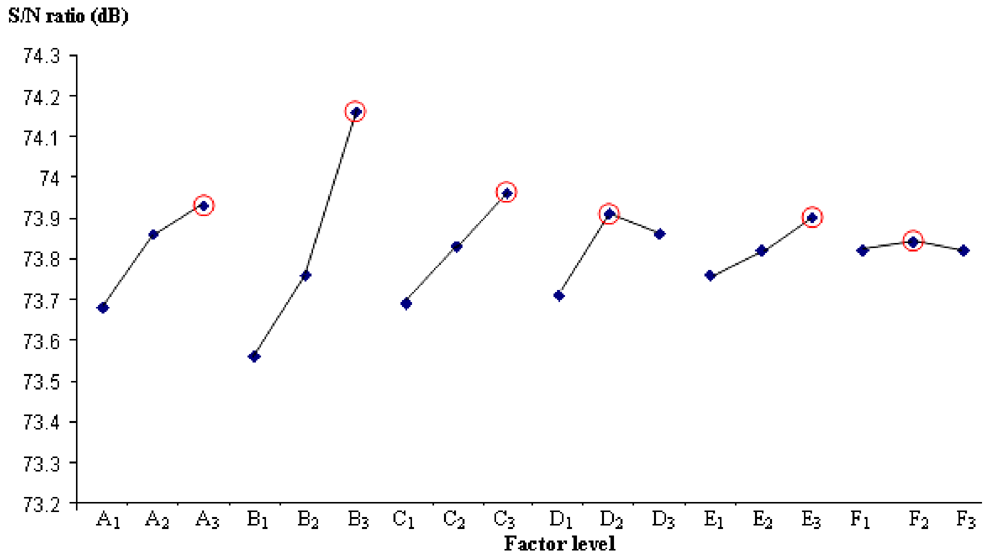



Figure 6: Plot of S/N ratios averages (optimal level is identified by circle).

Table III: Luminance averages for all factor levels.

| Factor | Luminance (cd/m$^2$) | | | Anticipated Improvement |
|---|---|---|---|---|
| | Level 1 | Level 2 | Level 3 | |
| A. Scraper angle (degree) | <u>4839</u> | 4937 | **4971** | 132 |
| B. Scraper pressure (bar) | 4768 | <u>4874</u> | **5106** | 232 |
| C. Scraper speed (mm/sec) | 4843 | <u>4917</u> | **4988** | 71 |
| D. Ink viscosity (cP) | 4853 | <u>**4962**</u> | 4932 | 0 |
| E. Ink paller bearing (bar) | <u>4880</u> | 4912 | **4957** | 77 |
| F. Gap (mm) | 4914 | <u>**4922**</u> | 4911 | 0 |
| Total Improvement (cd/m$^2$) | | | | 512 |

### 4.3 Determining significant factor effects

To determine the process factor with significant effects on LGP luminance, analysis of variance (ANOVA) is conducted. The results are displayed in Table IV.

Table IV: ANOVA for luminance.

| Factor | $SS_f^*$ | $df_f$ | $\rho_f$ (%) | $MS_f$ | $F$ ratio | $SS'_f$ | $\rho'_f$ (%) |
|---|---|---|---|---|---|---|---|
| A | 84905.73 | 2 | 9.99 % | 42452.87 | 10.35 | 76705.03 | 9.02% |
| B | 539602.07 | 2 | 63.5 % | 269801 | 65.80 | 531401.4 | 62.50 % |
| C | 94882.98 | 2 | 11.16 % | 47441.49 | 11.57 | 86682.28 | 10.19 % |
| D | 57047.48 | 2 | 6.71 % | 28523.74 | 6.96 | 48846.78 | 5.75% |
| E | <u>26707.76</u> | 2 | 3.14 % | | | | |
| F | <u>602.23</u> | 2 | 0.07 % | | | | |
| Error | 46496.35 | 14 | | | | | |
| Pooled error | (73806.34) | 18 | | (4100.35) | | | 12.54 % |
| Total | 850244.61 | 26 | | | | | 100 % |

* Pooled sum of squares (SSs) are identified by an underscore.

In ANOVA, the sum of squares ($SS_f$) contributed by each of the control factors A to F. The percentage contribution ($\rho_f$) by factor $f$ in total sum of squares ($SS_T$) is then adopted to evaluate its importance on the quality characteristic of interest, which can be expressed as [14]:

$$\rho_f = SS_f \,/\, SS_T \times 100\ \% \tag{4}$$

The pure percentage contribution by factor $f$, $\rho'_f$, is calculated as:

$$\rho'_f = SS'_f \,/\, SS_T \times 100\ \% \tag{5}$$

where $SS'_f$ is the pure sum of squares contributed by factor $f$. Given the degrees of freedom, $df_f$, associated with factor $f$, the $SS'_f$ is calculated as:

$$SS'_f = SS_f - df_f \times V_e \tag{6}$$

where $V_e$ is the pooled error mean square obtained as pooled error variance divided by degree of freedom associated with pooled error. In this research, a factor effect is considered negligible if it is associated with a percentage contribution ($\rho_f$) less than 5 %. Consequently, the effects of factors E ($\rho_E$ = 3.14%) and F ($\rho_F$ = 0.07%) are considered negligible and hence their sum of squares values are pooled into error. Moreover, the effects of factor A to D are significant as their corresponding $F$ ratios of 10.35, 65.80, 11.57, and 6.96, respectively, are greater than 4. The values of $\rho'_A$, $\rho'_B$, $\rho'_C$ and $\rho'_D$ for factors A to D are found 9.02 %, 62.50%, 10.19 %, and 5.75, respectively. Obviously, the scraper pressure (factor B) contributes the largest pure sum of squares and hence is considered the most influential factor on luminance. Moreover, factors A, B, C, and D contribute about 87 % of the total variability in LGP luminance.

### 4.4 Confirmation experiments

Conducting confirmation experiments is a crucial final step of a robust design which verifies that the optimal factor levels do indeed the projected improvement. Settings process factors at the combination of optimal levels $A_3B_3C_3D_2E_3F_2$, five samples are randomly selected every half hour for 15 working hours. Their corresponding $\bar{x}$ and $R$ control charts are constructed then also shown in Figure 4. At improvement stage, the $LCL$, $CL$, and $UCL$ values for the $\bar{x}$

chart are estimated 4857.60, 4949, and 5040.40 cd/m$^2$, respectively. Whereas, for the *R* chart the *LCL*, *CL*, and *UCL* values are calculated 0, 158.4, and 334.86 cd/m$^2$, respectively. Obviously, the $\bar{x}$ and *R* control limits at improvement stage are tighter than those at initial stage. Moreover, the $\hat{\sigma}$ value at improvement stage is 68.10 cd/m$^2$. The $\hat{C}_{pk}$ value at improvement stage is enhanced to 2.44, which indicates that the LGP printing process become highly capable.

## 5. CONTROL–PHASE

The grey system theory, originally presented by Deng [15], focuses on model uncertainty and information insufficiency in analyzing and understanding systems via research on conditional analysis, forecasting and decision making. The grey model GM(1,1) has been successfully applied to various applications [16]. The benefits from the use of grey forecasting models are that: (i) it can be used to situations with the minimum data down to four observations; (ii) it utilizes a first-order differential equation to characterize a system; and (iii) the computation is very simple using computer software. The GM(1,1) grey model is summarized as follows [17]:

**Step 1**. For an initial time sequence

$$X^{(0)} = \left\{ x^{(0)}(1),\ x^{(0)}(2),\ \dots,\ x^{(0)}(i), \dots,\ x^{(0)}(n) \right\} \tag{7}$$

where $x^{(0)}(i)$ the time series data at time *i*, *n* must be equal to or larger than four.

**Step 2**. Establish a new sequence $X^{(1)}$ through the accumulated generating operation in order to provide the middle message of building a model and to weaken the variation, that is

$$X^{(1)} = \left\{ x^{(1)}(1),\ x^{(1)}(2),\ \dots,\ x^{(1)}(i), \dots,\ x^{(1)}(n) \right\} \tag{8}$$

where

$$x^{(1)}(k) = \sum_{i=1}^{k} x^{(0)}(i) \qquad k=1,\ 2, \dots,\ n \tag{9}$$

**Step 3**. Construct a first-order differential equation of grey model GM(1,1) as follows

$$\frac{dX^{(1)}(k)}{dt} + aX^{(1)} = b \tag{10}$$

and its difference equation is

$$X^{(1)}(k) + aZ^{(1)}(k) = b \qquad k=2,3,\dots,n \tag{11}$$

where *a* and *b* are the coefficients to be estimated using

$$[a,\ b] = \left( \begin{bmatrix} -Z^{(1)}(2) & 1 \\ -Z^{(1)}(3) & 1 \\ \vdots & \vdots \\ -Z^{(1)}(n) & 1 \end{bmatrix}^T \begin{bmatrix} -Z^{(1)}(2) & 1 \\ -Z^{(1)}(3) & 1 \\ \vdots & \vdots \\ -Z^{(1)}(n) & 1 \end{bmatrix} \right)^{-1} \begin{bmatrix} -Z^{(1)}(2) & 1 \\ -Z^{(1)}(3) & 1 \\ \vdots & \vdots \\ -Z^{(1)}(n) & 1 \end{bmatrix}^T \left[ x^{(0)}(2), x^{(0)}(3), \dots, x^{(0)}(n) \right]^T \tag{12}$$

and $Z^{(1)}(k+1)$ is the ($k$+1)$^{th}$ background value calculated as

$$Z^{(1)}(k+1) = (x^{(1)}(k) + x^{(1)}(k+1))/2 \qquad k=1,2,...,(n\text{-}1) \tag{13}$$

Solving Equation (12) gives

$$a = \frac{\sum_{k=2}^{n} z^{(1)}(k) \sum_{k=2}^{n} x^{(0)}(k) - (n-1)\sum_{k=2}^{n} z^{(1)}(k) x^{(0)}(k)}{(n-1)\sum_{k=2}^{n}\left[z^{(1)}(k)\right]^2 - \left[\sum_{k=2}^{n} z^{(1)}(k)\right]^2} \tag{14}$$

and

$$b = \frac{\sum_{k=2}^{n}\left[z^{(1)}(k)\right]^2 \sum_{k=2}^{n} x^{(0)}(k) - \sum_{k=2}^{n} z^{(1)}(k) \sum_{k=2}^{n} z^{(1)}(k) x^{(0)}(k)}{(n-1)\sum_{k=2}^{n}\left[z^{(1)}(k)\right]^2 - \left[\sum_{k=2}^{n} z^{(1)}(k)\right]^2} \tag{15}$$

**Step 4**. Obtain the predicted $\hat{x}^{(0)}(n+p)$ at time ($n$+$p$) using

$$\hat{x}^{(0)}(n+p) = \left(x^{(0)}(1) - \frac{b}{a}\right).(1-e^{a}).e^{-a(n+p-1)} \tag{16}$$

Utilizing the 10 confirmation experiments in Figure (4) as an initial sequence, the steps of GM (1,1) grey model were performed. The $a$ and $b$ values are calculated using Equation (14) and (15) and found equal to 0.00153233 and 4993.25839, respectively. The predicted luminance is calculated using Equation (16) and found as:

$$\hat{x}^{(0)}(n+p) = 4989.53104.e^{-0.00153233(10+p-1)} \tag{17}$$

where $p$ is the number of periods to be predicted ahead from the 10*th* period. Figure 4 also displays the predicted luminance for samples 11–20. The above model was verified by predicting the confirmation values, where the square root of mean square error is found equals 47.69 cd/m$^2$, which is considered negligible. For a three sigma quality-level, the range for predicted luminance is about 150 cd/m$^2$. which is very small. Consequently, the prediction model may provide good estimate of luminance for future production.

## 6. CONCLUSIONS

This research aims at improving LGP printing process by adopting DMAIC methodology. The process mapping, $\bar{x}$ and $R$ control charts, process capability, Taguchi method, and GM(1,1) model are the main tools used in this methodology. Six process factors were investigated concurrently, including: scraper angle, scraper pressure, scraper speed, ink viscosity, ink paller bearing, and gap between board and LGP utilizing the $L_{27}$ ($3^{13}$) array. The S/N ratio was then employed to decide optimal factor levels. By implementing DMAIC, the anticipated improvement in luminance is 411.13 cd/m$^2$. The $\hat{C}_{pk}$ was greatly enhanced from 0.69 to 2.44. Moreover, the scraper's angle, pressure and speed, and ink viscosity were found significantly contributing to the total variations of LGP printing process.

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