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PRODUCTION & MANUFACTURING | RESEARCH ARTICLE

Reducing production variability using factorial optimisation: A case study from the food-packaging industry

Tomas Macak^{1*}, Jan Hron¹ and Ivana Ticha¹

Abstract: In industry, many phenomena and events that arise that cannot be predicted because they represent changes in production. Such random effects and events can significantly influence all aspects of the manufacturing process. The optimal design of any production system can be generated based on a complete, correct set of input information. However, such a requirement is unrealistic, as manufacturing systems are affected by several random factors. Current practice is based on determining the worst possible conditions in which a production system could run (the longest possible duration of outages in the supply chain, extreme weather conditions in agriculture, etc.). This article aimed to identify factors influencing the variability of the manufacturing process in the field of CNC (Computer Numerical Control) machining for food production. A secondary aim was to minimise the variability of the manufacturing process using a factorial design. The variability reduction was verified using statistical *F*-tests. The study on reducing variability in production was performed at the Czech Yuncheng Plate Making Co., Ltd., a professional rotogravure cylinder-making company. The cylinders are used for the food industry.

ABOUT THE AUTHORS

Tomas Macak earned his PhD at the Czech Technical University (Faculty of Mechanical Engineering), Prague in 2006. Currently, he is an associate professor of Cybernetics in Management at Czech University of Life Sciences in Prague and also of Applied statistics at the Masaryk Institute of Advanced Studies (Czech Technical University). In his current research, he deals with the use of factorial designs for optimizing production processes and transforming regression models of production into their causal form.

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PUBLIC INTEREST STATEMENT

We are currently experiencing a new generation of food packaging. The intelligent and active packages are influencing the properties of the stored food and also can communicate with the consumers. The gravure printing using CNC machining is a favourite way of their production. The high requirements of the manufacturing process result in extreme quality variability (high proportion of non-compliant products). We have performed factorial design to remove this variability. Then we verified the results using a statistical test. In this way, we have excluded the random effect on production variability. The production variable was reduced by 49% after the optimization process implementation.

Subjects: Food Engineering; Manufacturing Engineering; Engineering Management; Production Engineering; Technology; Packaging

Keywords: reduction of manufacturing variability; F-test; factorial design; food industry; rotogravure cylinder

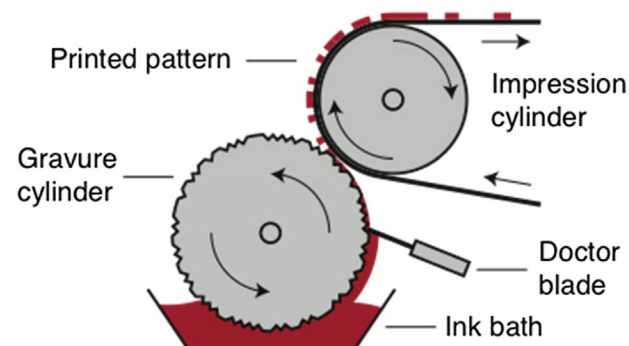
1. Introduction

Computer Numerical Control means a computer transforms the design produced by Computer Aided Design software (CAD), into quantities. The numbers can be considered to be the coordinates of a graph, and they control the action of the cutting tool. In this way, the computer controls the shaping of the material. Gravure printing using CNC machining is a traditional printing method for high-volume applications, such as in the production of magazines, catalogues or food packaging, with printing speeds beyond 15 m/s. It has been extended into printed electronics due to its potential for generating high-resolution prints and smooth layers, as well as the variety of processable materials.

The gravure printing principle is illustrated in Figure 1. The gravure cylinder is usually made from steel material with a thin copper layer that fixes the resulting image with a conglomeration of engraved cells. The finishing process involves adding a chromium layer as a wear-resisting layer. The cells of the printing form are sometimes fabricated using laser or electromechanical engraving (Sung, de la Fuente Vornbrock, & Subramanian, 2010). The cells have different shapes, sizes and screen rulings that define the print volume (ml/m²). The printing cylinder is immersed in an ink bath that fills the cells with ink while rotating. Then, a doctor blade scrapes off excess ink, leaving the unpatterned chrome surface blank. The colour is transferred to the substrate through surface interactions at the nip zone between the roller and gravure cylinder. The nip force between the gravure cylinder and the impression roller is much stronger compared to that in flexible printing (Shin, Joonhyuk, & Jyongsik, 2012). The ink transfer is based on complex interactions between the cell characteristics, printing parameters and ink rheology.

Many studies have been conducted on the design of gravure printing for food packaging and the analysis of food packaging printability under different conditions (Lee, Hakyung, Jeong, Shin, & Lee, 2016; Noh, Kim, & Park, 2013). Many previous designs focussed on analysing the dynamics of colour transfer in various printing methods, such as inkjet and gravure offset printing. Most of these studies were conducted from the static point of view (Ahmed & Sung, 2011; Hagberg & Leppävuori, 2004; Hyun & Lim, 2015; Sung, Lee, & Kim, 2009). Some authors deal with the optimization of the CNC process itself from a cost perspective. In order to minimize the cost of machining, modern components are highly unitized to use functions of multi-axis CNC machining centers (Hu, Mo, Ding, & Brandt, 2016; Wan, Wen-Jie, Zhang, Ma, & Yang, 2014). Other authors are concerned with the use of Taguchi Factorial Design for surface roughness optimization in the CNC process (Patole & Kulkarni, 2017). Lee et al. (2016) analysed the width and thickness of a printed line by its angle; they proposed a theoretical model to show the shear force on the ink according to the angles of printed patterns when the ink in the engraved cell is transferred to the substrate. Pudas, Päivänranta, & Pitkänen

Figure 1. Principle of gravure printing.



(2009) conducted experimental studies on the effect of the solid content of colour and the effect of doctoring and nipping conditions on the width of the printed pattern (Hagberg & Leppävuori, 2004). In addition, Fukuda, Sekine, and Kumaki (2013) analysed the dynamics of ink between an engraved cell and the substrate according to the characteristics of the substrate and ink.

The main aim of this article is to identify factors influencing the variability of the gravure printing process using CNC machining for food package. Another objective is to minimise the variability of the manufacturing process using a factorial design.

2. Methodology and data

This study involves the development of a simple factorial model that describes the relationship between the ratio of the identical products (%)—response from the full factorial experiment, depending on the relevant parameters of the engraving process in the production of printed food-packaging cylinders. The full factorial model is based on three significant factors. The predicted ratio of the identical products \hat{y} is given by the following general formula of a regression model for factors at two levels (Montgomery, 2011; Vining, Kowalski, & Montgomery, 2005):

$$\hat{y} = \beta_0 + \beta_1x_1 + \beta_2x_2 + \dots + \beta_{12}x_1x_2 + \beta_{13}x_1x_3 + \dots + \varepsilon, \quad (1)$$

where β_1, β_2, \dots are the regression coefficients and β_0 is the average response in factorial experiment. The term ε is the random error component, which is approximately normally independently distributed, with mean zero and constant variance of σ^2 . The regression coefficient β_{12} corresponds to the interaction between the process parameters x_1 and x_2 .

If we symbolically mark the three factors of the two-level full-factorial design as A, B and C, then the effect for each factor and the interactions between factors can be formally calculated according to the formulas below (Antony, 2001).

Estimation of the effect of factor A:

$$A = \bar{y}_{A^+} - \bar{y}_{A^-} = \frac{1}{4n} [a + ab + ac + abc - b - c - bc - (1)] \quad (2)$$

Estimation of the effect of factor B:

$$B = \bar{y}_{B^+} - \bar{y}_{B^-} = \frac{1}{4n} [b + ab + bc + abc - a - c - ac - (1)] \quad (3)$$

Estimation of the effect of factor C:

$$C = \bar{y}_{C^+} - \bar{y}_{C^-} = \frac{1}{4n} [c + ac + bc + abc - a - b - ab - (1)] \quad (4)$$

Estimation of the effect of interaction between factors A and B:

$$AB = \bar{y}_{AB^+} - \bar{y}_{AB^-} = \frac{1}{4n} [ab + (1) + abc + c - b - a - bc - ac] \quad (5)$$

Estimation of the effect of interaction between factors A and C:

$$AC = \bar{y}_{AC^+} - \bar{y}_{AC^-} = \frac{1}{4n} [ac + (1) + abc + b - a - c - ab - bc] \quad (6)$$

Estimation of the effect of interaction between factors B and C:

$$BC = \bar{y}_{BC^+} - \bar{y}_{BC^-} = \frac{1}{4n} [bc + (1) + abc + a - b - c - ab - ac] \quad (7)$$

Finally, estimation of the effect of interaction between factors A, B and C:

$$ABC = \bar{y}_{ABC^+} - \bar{y}_{ABC^-} = \frac{1}{4n} [abc - bc - ac + c - ab + b + a - (1)] \quad (8)$$

Figure 2. CNC manufacturing facility where the experiments were performed.



Where: \bar{y}_{A^+} = mean response factor for the upper level of factor A; \bar{y}_{A^-} = mean response factor for the lower level of A, (1), a , b , and c = all eight combinations of the responses for the two setting levels of the three factors, and n = number of replications of this design.

3. Results

The study for variability reduction in the gravure printing process using CNC machining for food packaging was performed at the Czech Yuncheng Plate Making Co., Ltd., which is a professional rotogravure cylinder-making company. These cylinders are used for the food industry. The company belongs to Shanxi Yuncheng Plate Making Group. In the machining facility where the experiments were performed, a high-speed CNC-Daerwyl GS 2215 HS was used (see Figure 2).

The quality characteristic of interest for this study was the quality level of the gravure printing process, as measured by the following scale:

- Very good: A 4;
- Good: B 3;
- Sufficient: C 2;
- Readable: D 1; and
- Insufficient: F 0.

In terms of minimum values, for customers with an unspecified quality code, the minimum was D 1. Some customers had their own specifications based on the minimum value of B3 required for these producers; these customers were Aldi and Lidl, Bastin and Kuchemeister, Van Netten, Manner, Coppenrath and Schumann.

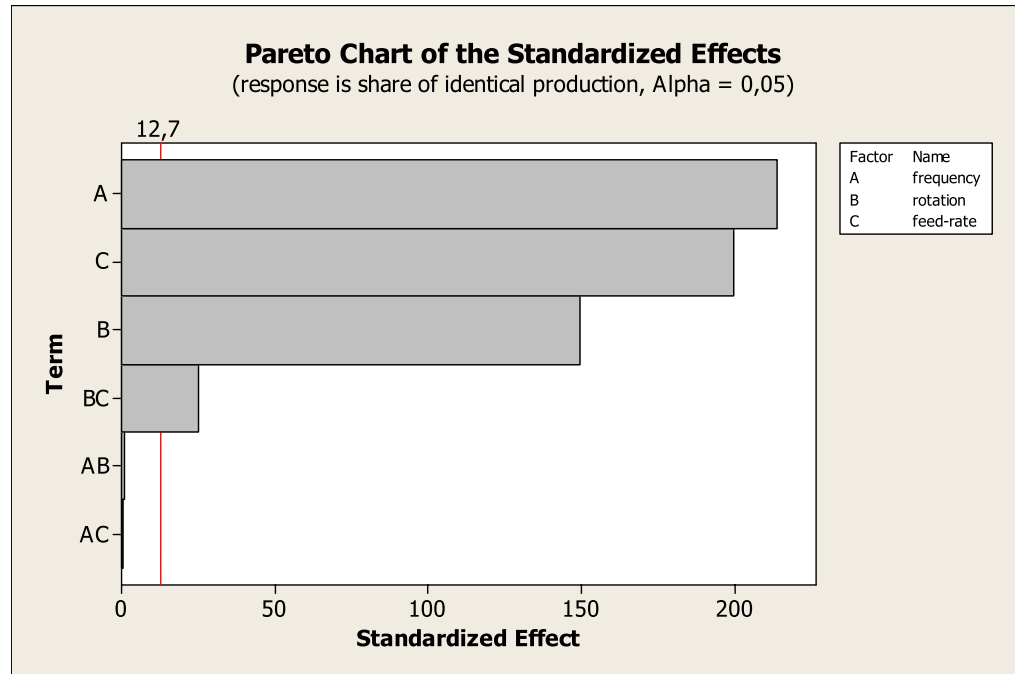
To obtain the quality results, an REA PC-Scan with laser measuring device was used. The REA PC-Scan is a precision-measurement device for the verification of food packaging quality and accurate measurement of printing film masters. The unit consists of a measuring head (laser device) and software to evaluate and display the results.

The first step in this full factorial experiment was to detect the factors and interactions influencing the mean variability of ratio of identical products. The results of the experiment are shown in Table 1. For the significance test, a significance level of $\alpha = 5$ per cent (0.05) was selected. In this

Table 1. List of process parameters for the experiment

Process parameter	Unit	Low setting	High setting	Lower setting (coded units)	High setting (coded units)
Oscillation frequency	kHz	4	8	-1	+1
Cylinder rotation	sec ⁻¹	10	15	-1	+1
Shift feed rate	mm/min	15	20	-1	+1

Figure 3. Pareto plot showing the significance of three parameters (A, B, C) and the BC interaction.



case, if the *p*-value was less than the significance level (0.05), then the factor or interaction was statistically significant. This experiment showed that the main effects of needle oscillation frequency (*f* or factor A [kHz]), rotation of the cylinder (*o* or factor B [sec⁻¹]) feed rate (*v* or factor C [mm/rev]) and the BC interaction effect were statistically significant. This finding is further supported by a Pareto plot (see Figure 3).

In the Pareto plot (Figure 3), any factor or interaction effect extending past the reference line is considered significant. The calculated effect factor in the coded values (response factor to a change from -1 to +1) is shown in the first column of Table 1. The second column represents the regression coefficient (half of the effect of each factor) (Figure 4 and Tables 2 and 3).

$$\text{Ratio of identical products [\%]} = 51.163 + 8.012A [\text{kHz}] - 5.612B \left[\frac{1}{\text{sec}} \right] - 7.488C \left[\frac{\text{mm}}{\text{min}} \right] + 0.937CB \quad (9)$$

The coefficient of multiple determination R^2 (adj.) = 97.19% indicates that this equation is well suited to the acquired response data. The model can explain the variability to 97.19% with non-negligible interactions, the following equation shows that the optimal settings for the gravure printing process using CNC machining are as follows:

Figure 4. Normal plot of the standardised effect shows the same results as the Pareto plot.

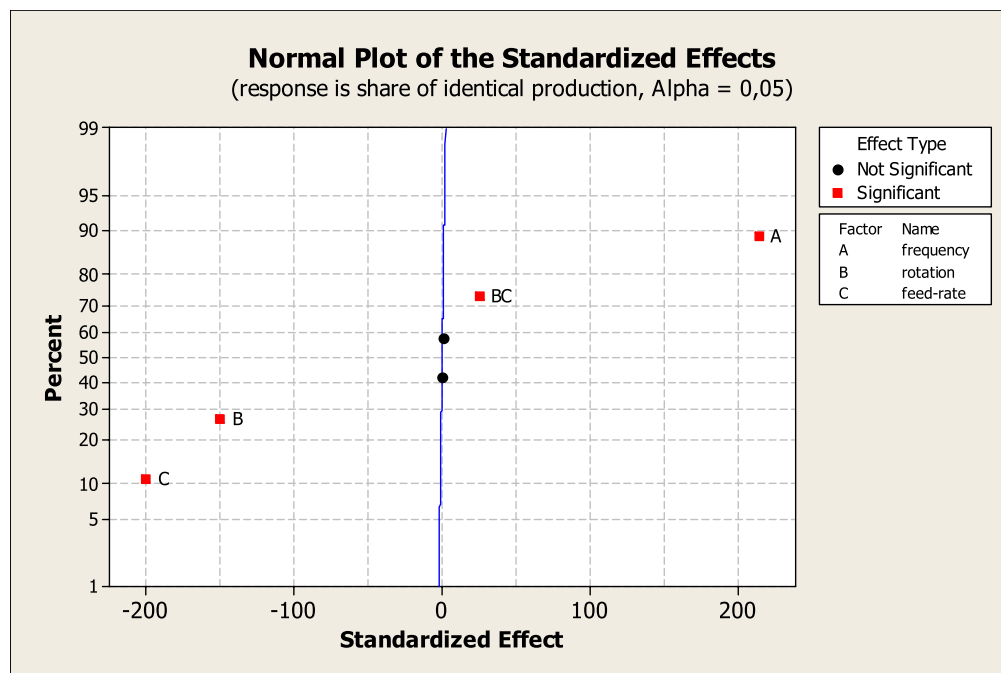


Table 2. Results for 2³ combinations in the ratio of identical products (uncoded units)

RunOrde	Frequency	Rotation	Feed rate	Ratio of identical products %
	kHz	sec ⁻¹	mm/min	
5	4	10	25	47.4
3	4	15	15	44.1
8	8	15	25	47.7
2	8	10	15	73.2
7	4	15	25	30.9
6	8	10	25	56.3
4	8	15	15	60.1
1	4	10	15	57.2

Table 3. Estimated effects and coefficients for the share of identical production (coded units)

Term	Effect	Coefficient	p-value
Constant		51.163	0.000
Frequency	16.025	8.012	0.003
Rotation	-11.225	-5.612	0.004
Feed rate	-14.975	-7.488	0.003
Frequency*rotation	0.075	0.037	0.500
Frequency*feed-rate	0.025	0.012	0.795
Rotation*feed-rate	1.875	0.937	0.025

Notes: S = 0.106066; PRESS = 0.72; R² = 98.560%; R² (pred.) = 97.94%; R² (adj.) = 97.19%.

- Frequency: 8 kHz;
- Rotation: 10 s⁻¹; and
- Feed rate: 0.15 mm/min.

After determining the optimisation settings for the engraving process, we tested whether we could reduce production variability using the test of significant difference of two variances (*F*-test).

4. Discussion and conclusions

The results of the gravure printing process were observed and then deviations from the optimal (maximum) achievable gravure process were analysed before and after full factorial optimisation. We chose the *F*-test for verification of the significance of imbalance reduction in terms of the quality of production:

$$F = \frac{\sigma_1^2}{\sigma_2^2} = \frac{n_1 \times (n_2 - 1) \times S_1^2}{n_2 \times (n_1 - 1) \times S_2^2} \quad (10)$$

which has a Fisher–Snedecor distribution of $F(n_1 - 1, n_2 - 1)$.

If $F > F_{\frac{\alpha}{2}}(n_1 - 1, n_2 - 1)$, we reject the hypothesis H_0 (H_1 is accepted). In this case, we chose a significance level of $p = 0.05$. We determined the required characteristics in both groups (swapping the order so that $F > 1$), and we obtained the following results:

Before full factorial optimisation,

$$n_1 = 28; s_1^2 = 1,4521$$

After full factorial optimisation,

$$n_2 = 33; s_2^2 = 0,7302.$$

After substitution into (10), we obtain

$$F = \frac{\sigma_1^2}{\sigma_2^2} = \frac{n_1 \times (n_2 - 1) \times S_1^2}{n_2 \times (n_1 - 1) \times S_2^2} = 2.551 \geq F_{0,025}(27, 32) = FINV(0, 025; 27; 32) = 2.0689 \quad (11)$$

The test criterion exceeded the critical value (2.0689) at 27 degrees of freedom of the first set and 32 degrees of freedom of the second set. Therefore, H_0 was rejected. There was a statistically significant difference between the variances; therefore, the factorial optimisation represents a noticeable improvement in the quality of the process.

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