Design of experiments for the analysis and optimization of barcodes of food and agricultural products

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Abstract: The tools and modern techniques used in the Design of Experiments (DOE) have been proved successful in meeting the challenge of continuous improvement of food and agricultural products over the last fifteen years. The current methodological appliance of the DOE is represented by the set of scientific methods for identifying the significant and/or critical parameters associated with the process and thereby determining the optimal settings for those process variables which are able to enhance the performance and capability of the response (e.g. the selected character of a product quality). However, recent researches have shown that the application of these techniques in the food-processing industry and agricultural production are limited due to the lack of statistical knowledge required for their effective implementation (especially in small and medium-sized manufacturing companies). Therefore, this paper focuses on the modified DOE methods (for use in a community of scientists and product engineers), which overcome the problem of statistics by taking a unique approach using graphical tools. The same outcomes and conclusions are reached as by those approaches using statistical methods and the potential users will find the concept in this paper both familiar and easy to understand. In this way, it will ensure a broad practical application of the methodology that is described in this paper. From the theoretical point of view, the main objective of the paper is to optimize the barcode printing processes on food packaging through the effective application of the DOE techniques in order to discover the significant process parameters which affect the means of the so-called "Z-module" (defines the nominal width of the narrow elements), "GS1 International" (defines certain size ranges), "PCS measurement" (means Print Contrast Signal measurement) and also in order to discover the key parameters which affect their variabilities.

Key words: barcode, design of experiments, food packaging, manufacturing process, optimization, printing

Design of Experiments (DOE) can be (under certain conditions) a powerful technique used to study the effect of several process parameters affecting the response or quality characteristic of a process/product. The first step in the DOE field was created by Sir R. A. Fisher, at the Rothamsted Agricultural Field Research Station in London, UK, in the 1930s. His primary goal was to determine the optimum sunshine, water, amount of fertilizer and underlying soil condition needed to produce the best crop. Fisher introduced the technique and demonstrated its use in agricultural experiments, and Fisher's approach to the DOE was also a direct replacement of the traditional one-variable-at-a-time (OVAT) approach to experimentation. The OVAT approach to experimentation has the following limitations (Konda 1999):

(1) lack of reproducibility;
(2) interactions among the process parameters cannot be studied or analysed;
(3) risk of arriving at the false optimum conditions for the process;
(4) not cost-effective and time-consuming in many cases.

Besides the OVAT approach to experimentation, the DOE approach shows as one of the powerful tools used to investigate the deeply hidden causes of process variation. The DOE techniques are useful for surfacing the effects of hidden variables, and studying possible effects of variables during the process design and development. Experiments range from uncontrollable factors introduced randomly to

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carefully controlled factors. Some of the techniques (Antony 2001) are:
(1) trial and error methods;
(2) running special lots;
(3) pilot runs in which certain elements are set up in expectation of producing predicted results;
(4) simple comparison of pairs of methods;
(5) complex experiments involving many factors that are arranged in complex pattern.

Today, there are mainly three principal approaches of the DOE in practice. They are the classical or traditional methods, the Taguchi's methods, and the Shainin methods (Antony 2003).

The traditional method is based on the work of Sir Ronald Fisher. Professor Taguchi from Japan has refined the technique with the objective of achieving robust product designs against the sources of variation. The Shainin method, designed and developed by Shainin, uses a variety of techniques with the major emphasis on problem solving for the existing products.

At present, the DOE has gained an increased attention among many Six Sigma practitioners, as it is the key technique employed in the improvement phase of the Six Sigma methodology (Rowlands and Antony 2003). It is also recommended that the DOE is employed within the optimization phase of the Design for Six Sigma (DFSS). It is fair to say that the DOE will be a key technique for developing reliable and robust products or processes in the 21st century. Over the last 15 years or so, the DOE has gained increased acceptance in the USA and Japan as an important component for improving the process capability, driving down quality cost and improving the process yield. In Europe, this approach is not as much widespread yet. Nevertheless, a number of successful applications of the DOE for improving the process performance, product quality and reliability, reducing the process variability, improving the process capability, developing new products, etc. have been reported by many manufacturers over the decade (Sirvanci and Durmaz 1993; Green and Launsby 1995; Ellekjaer and Bisgaard 1998; Albin 2001; Antony 2001). In the Czech Republic, the implementation of DOE methodology was dealt by (Gozora 2011) in the field of agricultural research and in the field of economic optimization was dealt by (Tomšík and Svoboda 2010).

OBJECTIVES AND METHODOLOGY

This paper objective is based on the application of DOE to the barcodes of food and the agricultural products optimization.

The following methodology (for designing, performing, and analyzing experiments) was used for the purpose of obtaining the results from this paper:
1st phase: Identifying the potential factors by a cause case study using brainstorming and the effect-design diagram.
2nd phase: Choosing suitable factors from a basic set for their investigation.
3rd phase: Selecting the appropriate working range for each potential factor which has been considered in 2nd phase.
4th phase: Selecting experimental levels for each factor from within the extremes explored in 3rd phase.
5th phase: If possible, trial running or dry running experiments with all possible combinations within the range of each factor selected in an extremely short run to guard against a process failure owing to interactions.
6th phase: Choosing an orthogonal array for experiments or any experimental design (full factorial or fractional factorial).
7th phase: Running experiments as designed. Experiments must be performed randomly.
8th phase: Analyzing experimental results for the objective of the project and verifying them with the objective evidence.
9th phase: After 8th phase, if the results do not seem to be meeting the objective of the study, it could be owing to inappropriate factors considered in the study. Here, we have two choices: Those are either to start the experimentation all over with different factors, or the part design or processes design need to be modified. Additionally, one could potentially use a different technique using the knowledge gained in phases 1 through 8 to achieve the objectives set. Identifying potential factors by brainstorming a cause and effect design diagram.

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RESULTS

The Alcan Packaging Skrivany Ltd. is engaged in the manufacturing of printed flexible packaging for the food industry. This production takes place in three shift operations six days a week. The technology can be divided into several major operations and the associated support processes, which are: printing; lamination; cutting; import substrates, packaging and storage of products; washing; installation of cylinders; the preparation and mixing colour and waste gases.

Table 1. List of process parameters for the experiment

Process parameter	Units	Low level setting	High level setting	Lower level setting (coded units)	High level setting (coded units)
Feed-rate	m/min	200	250	−1	+1
Operation temperature	^{0}C	200	220	−1	+1
Contact pressure	KPa	45	55	−1	+1
Kinematic viscosity	mm^2/sec	90	110	−1	+1

The gravure (printing of depth) is a technique in which the printing elements, divided into a large number of cells, sunk below the surface of the print roller. These cells are then printing elements of the theme. Printing ink is soaked to the surface of the print roller and from the wiper, the excess paint is removed with a knife, so it adheres only to the deepened print cells. Subsequently, the rotating printing cylinder pressure is transmitted to the paint film substrate. This is from the other side while pressed by a print roller.

The objectives of the experiment

(1) to identify the key welding process parameters which influence the quality of the barcode printing;
(2) to identify the key welding process parameters which influence the variability in the barcode quality;
(3) to determine the optimal settings of the barcode printing process parameters which can meet the objectives (1) and (2).

The gravure printing process in this study is primarily used for printing the polymer foils. The material used for this study is monofoil. The Table 1 presents the list of the significant parameters (which remained in the process after all the previous parameters scan), along with their levels used for the experiment. As a part of the initial investigation, it was decided to study the process parameters at two levels. The purpose of this first experiment was to understand the process, especially the operating range of the important process parameters and their impact on the barcode quality printed on the foil. The purpose of the first designed experiment is not just to obtain good results, but rather to understand the worst and best operating conditions so that small sequential experiments can be conducted to gain more process knowledge. The actual values of settings of the parameters are not revealed in the paper due to confidentiality agreement between the authors and the company where the experiment was carried out. However, the data collected from the experiment are real and have not been modified in this study.

Interactions of interest

Further to a thorough brainstorming session, the following interactions of interest have been identified.

ISO 15416 / X3.182/ANSI-UCC5 Table

Scan:	1	2	3	4	5	6	7	8	9	10	Average
Decode	4	4	4	4	4	4	4	4	4	4	[4.0]
Edge contrast	4	4	4	4	4	4	4	4	4	4	[4.0 (64%)]
Symbol contrast	4	4	4	4	4	4	4	4	4	4	[4.0 (80%)]
Modulation	4	4	4	4	4	4	4	4	4	4	[4.0 (80%)]
Rmin/Rmax	4	4	4	4	4	4	4	4	4	4	[4.0 (1%)]
Defect	4	4	4	4	4	4	4	4	4	4	[4.0 (3%)]
Decodability	4	4	4	4	4	4	4	4	4	4	[4.0 (92%)]
Overall Profile Grade	4	4	4	4	4	4	4	4	4	4	
Symbol Grade											4.00
[Bar width deviation %	+0	+0	+0	+0	+0	+0	+0	+0	+0	+0	+0.0]

Figure 1. The CEN/ANSI Barcode evaluation with 4 (or A) results

Source: REA PC-Scan Baracode measuring device manual

Table 2. Conversion of the REA PC-Scan of the response to numerical values

REA PC-Scan		Belonging interval	Mean (central point) of response
ANSI	CEN		
A	4	<100–80)	90
B	3	<80–60)	70
C	2	<60–40)	50
D	1	<40–20)	30
E	0	<20–0>	10

(1) A <=> B
(2) B <=>D
(3) C <=> D
(4) A <=> C

The quality characteristic of interest for this study was the level of the quality EAN Code: ANSI/CEN is:
– Very good A 4
– Good B 3
– Sufficient C 2
– Readable D 1
– Insufficient F 0

Minimum values: for customers with an unspecified quality code D 1. There are customers' own specifications based on the minimum B3 value required for these producers: Aldi and Lidl, Bastin and Kuchemeister, Van Netten, Manner, Coppenrath, Schumann.

For obtaining the barcode quality responses, the "Barcode a REA PC-Scan" with a laser measuring device has been used. The REA PC-Scan is a precision measuring device for the verification of printed bar codes of different types and an accurate measurement of the barcode film masters. The unit consists of a measuring head (laser device) and the software to evaluate and display the results. The measuring head is motor-powered, and it is controlled by the evaluation software. The measurement results must be reproducible and comparable. All measurements must therefore be performed under the constant conditions. In the CEN/ANSI evaluation, for the individual parameters, the quality will be specified as a percentage, and as a grade from 4 to 0, or A-F. The grades are allocated to certain ranges of percentage values (e.g. symbol contrast of 40% to 55% is grade 3, or B) see Figure 1. In the multiple measurements, an average value will then be calculated from the results of the individual measurements (scan reflectance profile grade). The average value is the arithmetical average of the individual scan reflectance profile grades. The result is designated as the overall symbol grade (Table 2).

The aggregate indicator of the barcode quality provided by the REA PC-Scan was subsequently converted to the numeric value (percentage of the total level of quality). This conversion (Table 2) was done because of the possibility to express the response of the barcode quality as numeric (continuous) variables, instead of text variables.

The quality characteristic of interest for this analysis was the barcode quality measured in percentage of the total level of quality. Having identified the quality characteristic and the list of the process parameters, the next step is to select an appropriate design matrix

Table 3. Estimated Effects and Coefficients for the EAN code quality (coded units)

0	Term	Effect	Coef	SE Coef	*T*	*P*
1	Constant		48.75	2.562	19.03	0.000
2	Feed rate	–17.50	–8.75	2.562	–3.42	0.019
3	Oper. temperature	22.50	11.25	2.562	4.39	0.007
4	Contact pressure	–27.50	–13.75	2.562	–5.37	0.003
5	Viscosity	–22.50	–11.25	2.562	–4.39	0.007
6	Feed rate*Oper. temperature	–2.50	–1.25	2.562	–0.49	0.646
7	Feed rate*Contact pressure	–2.50	–1.25	2.562	–0.49	0.646
8	Feed rate*Viscosity	2.50	1.25	2.562	0.49	0.646
9	Oper. temperature*Contact pressure	–2.50	–1.25	2.562	–0.49	0.646
10	Oper. temperature*Viscosity	2.50	1.25	2.562	0.49	0.646
11	Contact pressure*Viscosity	–7.50	–3.75	2.562	–1.46	0.203

S = 10.2470 PRESS = 5376
R-Sq = 94.28% *R*-Sq(pred) = 41.41% *R*-Sq(adj) = 82.83%

Table 4. Estimated Coefficients for the EAN code quality using data in uncoded units

Term	Coef
Constant	–470.000
Feedrate	0.70000
Oper.temperature	2.25000
Contactpressure	12.2500
Viscosity	–1.12500
Feedrate*Oper.temperature	–0.0050000
Feedrate*Contactpressure	–0.0100000
Feedrate*Viscosity	0.0050000
Oper.temperature*Contactpressure	–0.0250000
Oper.temperature*Viscosity	0.0125000
Contactpressure*Viscosity	–0.0750000

for the experiment. The design matrix shows all the possible combinations of process parameters at their respective levels. The choice of the design matrix or experimental layout is based on the degree of freedom required for studying the main and interaction effects. The total degrees of freedom required for studying four main effects and four interaction effects is equal to eight. A $2^{(5-1)}$ factorial design was selected to study all the main features and interaction effects stated above. The degree of freedom associated with this design is 15. In order to minimize the effect of noise factors induced into the experiment, each trial condition was randomized. Randomization is a process of performing experimental trials in a random order, not that in which they are logically listed. The idea is to evenly distribute the effect of noise across (those that are difficult to control or expensive to control under standard production conditions) the total number of experimental trials.

Results from the analysis

The analysis of experimental data and the interpretation of results are essential to meet the objectives of the experiment. If the experimenter has designed and performed the experiment correctly, the statistical analysis would then provide effective and statistically valid conclusions. The first step in the analysis was to identify the factors and interactions which influence the mean barcode quality. The results of the analysis are shown in Table 3. For the significance test, it was decided to select the significance levels of a = 5% (0.05). If the p-value is less than the significance level (0.05), the factor or interaction effect is then regarded to be statistically significant. For the present experiment, the main effects of the feed-rate, operational temperature, contact pressure, kinematic viscosity and no interaction effects are statistically significant. It is important to note that these effects have a significant impact on the average barcode quality. This finding is further supported by a Pareto plot (Figure 2) of factor and interaction effects. In the Pareto plot, any factor or interaction effect which extends past the reference line is considered to be significant. The calculated effect factor in the coded values (response factor to change from –1 to +1) is in the first column of Table 3. The second column is represented by the regression coefficient (that is a half effect of each factor).

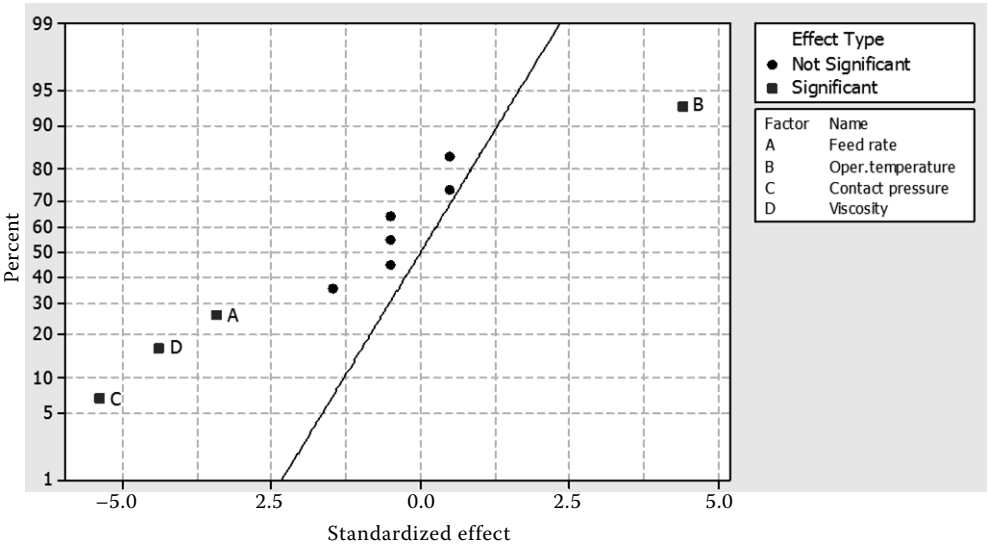

Figure 2. Normal plot of the standardized effect

Source: own calculation

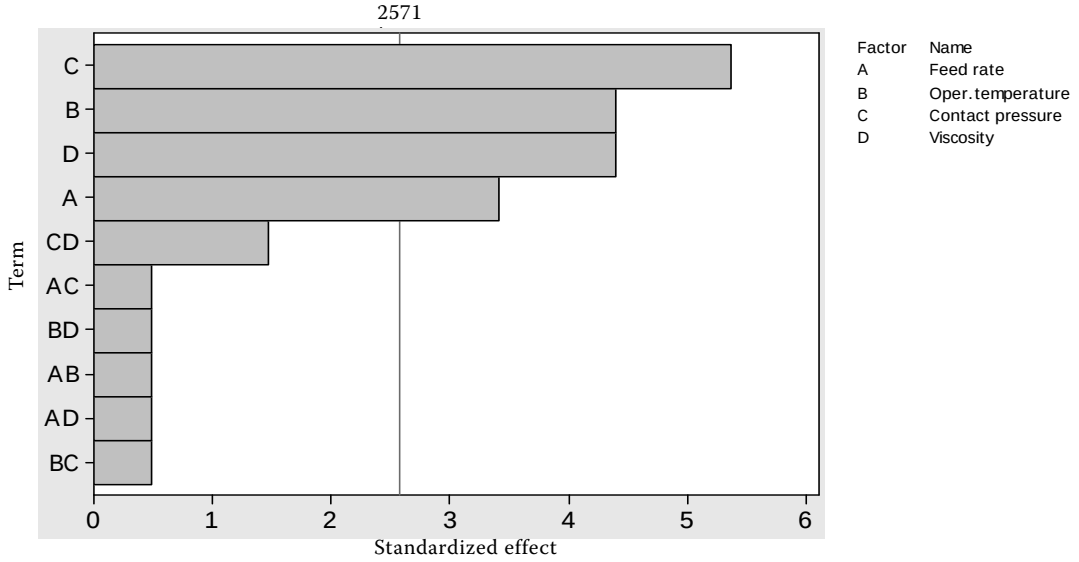

Figure 3. The Pareto chart of the standardized effects (response is EAN code quality, Alpha = 0.05)

Source: own calculation

The statistical significance of each factor or interaction, expressed as a *p*-value, is noted in the fifth column. Full members of the model to predict the quality of printing (EAN) barcodes on the food package are those that have a relatively large (statistical) significance. This would mean that their *p*-value is close to zero. The interaction between two process parameters (say *A* and *B* i.e. $I_{A,B}$) can be computed using the following equation:

$$I_{A,B} = \frac{1}{2} \times \left(E_{A,B(+1)} - E_{A,B(-1)}\right) \quad (1)$$

where $E_{A,B\,(+1)}$ is the effect of parameter (factor) '*A*' at the high level of factor '*B*' and where $E_{A,B\,(-1)}$ is the effect of factor '*A*' at the low level of factor '*B*'.

The Table 4 shows the calculation of the coefficients to determine the predictive equations of the barcode quality responses.

Normal plot of the standardized effect shows the same results as Pareto plot (Figure 2).

Pareto plot shows 4 significant parameters and no significant interaction (Figure 3).

Model development and prediction of barcode quality

This stage involves the development of a simple mathematical model which depicts the relationship between the weld strength and the key factors or interactions which influence it. For this study, it was found that the main effects of the feed-rate, operational temperature, contact pressure, kinematic viscosity and no interaction effects are statistically significant. The predicted model is based on these four significant effects. The average barcode quality based on the current process settings is C3 (50% of the barcode quality maximum). The predicted barcode quality is given by the following general formula of a regression model for factors at 2-levels:

$$\hat{y} = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \cdots + \beta_{12} x_1 x_2 + \\ + \beta_{13} x_1 x_3 + \cdots + \varepsilon \quad (2)$$

where β_1, β_2, ... are the regression coefficients and β_0 is the average response in the factorial experiment. The term ε is the random error component which is approximately normally independently distributed with the mean zero and the constant variance σ^2. The regression coefficient β_{12} corresponds to the interaction between the process parameters x_1 and x_2. The average barcode quality (BCQ) based on the current process settings is C3 (50% of the barcode quality maximum). The predicted barcode quality is, after substituting the actual values of the significant factors and interactions in the general equation (2), given by the following equation:

$$BCQ = -470 + 0.7A + 2.25B + 12.25C - 1.125D - \\ - 1.125D - 0.075(C \times D) + \varepsilon \quad (3)$$

The coefficient of multiple determination *R*-Sq(adj) = 82.83% indicates that this equation is well suited to the acquired response data. The model is able to explain the variability to 82.9%. With non-negligible interactions, the following figures show us the optimal settings for printing the food packaging. The

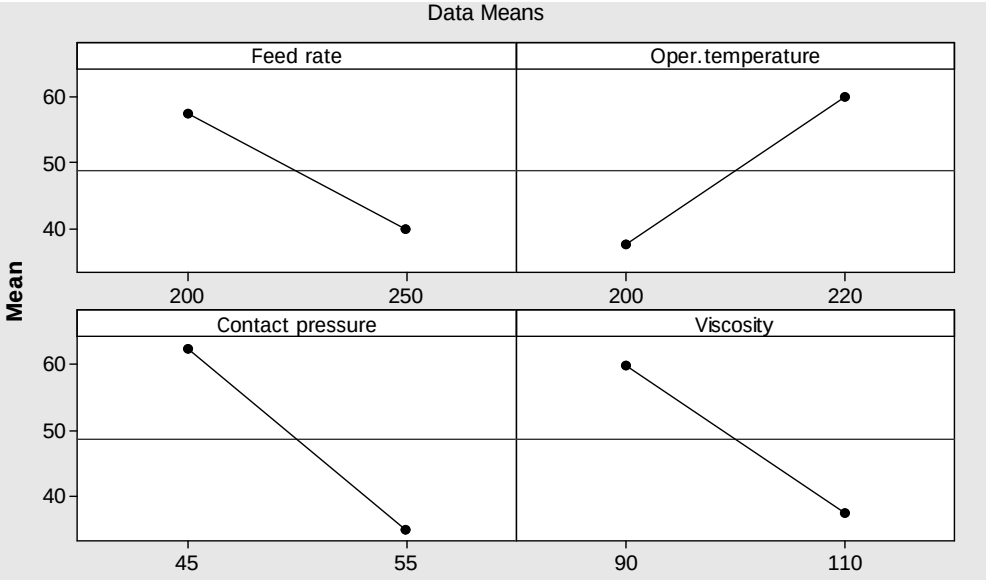

Figure 4. The main effects plot for the experiment (EAN code quality)

Source: own calculation

optimal process settings for the maximizing quality of barcodes were:
– feed-rate 200m/min,
– operating temperature 220^{0}C,
– contact pressure 45 KPa,
– kinematic viscosity 90 mm^2/sec.

In order to determine whether two process parameters are interacting or not, there could be used a simple but powerful graphical tool called the interaction graph. If the lines in the interaction plot are parallel, there is no interaction between the process parameters. This implies that the change in the mean response from the low to high level of a factor does not depend on the level of the other factor. On the other hand, if the lines are non-parallel, an interaction exists between the parameters (factors). The Figure 5 illustrates the moderate interaction plot between 'C' (contact pressure) and 'D' (viscosity).

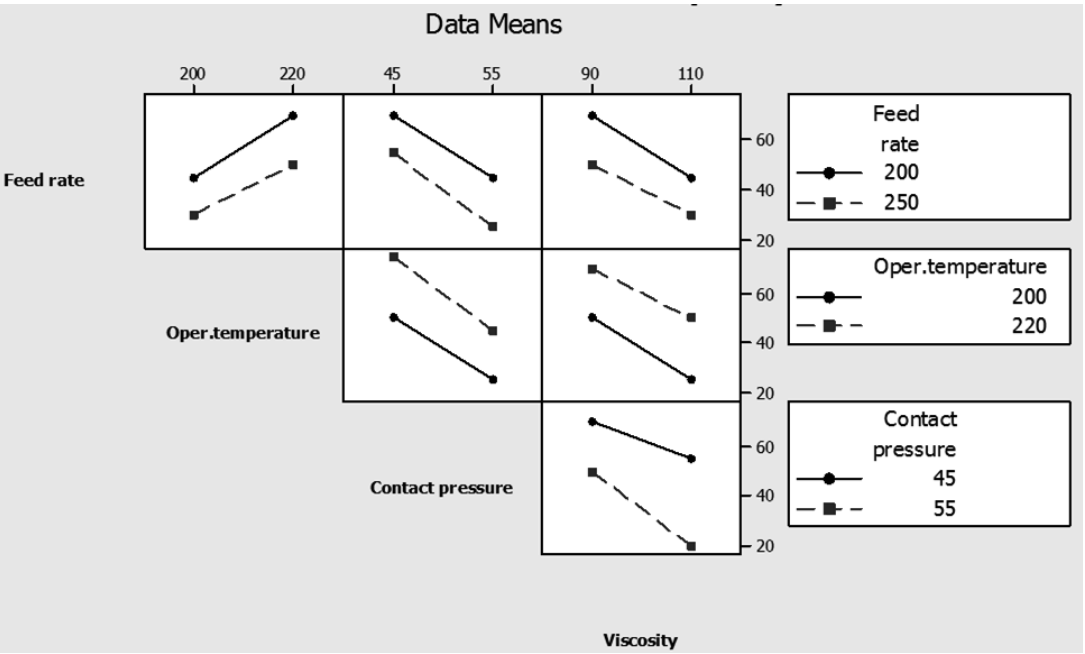

Figure 5. Interactions graph for the experiment (EAN code quality)

Source: own calculation

CONCLUSION

The purpose of this paper is to illustrate the application of the DOE to the barcode doing process.

The objectives of the experiment in this study were two-fold. The first objective was to identify the critical barcode printing process parameters which influence the response quality of printing. The second objective is to identify the process parameters that affect the variability in the quality. The barcode quality has been increased by 18 per cent. The next phase of the research is to perform more advanced methods such as the response surface methodology (RSM) by adding centre points and axial points to the current design. The results of the experiment have stimulated the engineering team within the company to extend the applications of the DOE in other core processes for the performance improvement and the variability reduction activities.

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