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Taguchi-Based Optimization of Sheeting Machine Parameters for Improved Production Speed

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Abstract

Sheeting machines play a crucial role in the packaging industry, making parameter optimization essential for enhancing efficiency. This study applies the Taguchi method to optimize key operational factors: roller speed, brake frequency, and pressure. Using Analysis of Mean (ANOM) and Analysis of Variance (ANOVA), roller speed was identified as the most influential factor, contributing 82.76% in ANOM and 87.29% in ANOVA, followed by brake frequency (7.08% in ANOM, 7.36% in ANOVA). The F-test (95% confidence interval) confirmed that pressure had an insignificant effect, leading to its exclusion via a pooling-up strategy. Error contributions remained below 15%, ensuring that no critical factors were overlooked. Among interactions, only the roller speed–pressure (A × B) interaction significantly impacted production speed. The optimized parameters increased throughput from 33 to 42 sheets/min (27.3% improvement) and enhanced production robustness (S/N ratio) from 30 to 32.49 (8.3% increase). These findings confirm the effectiveness of the Taguchi method in refining sheeting machine performance.

Keywords:
ANOM, ANOVA, controllable factor, parameter optimization, sheeting machine

1 Introduction

Packaging is a functional concept that protects a product during storage. Additionally, the correct packaging process makes products easier to store and transport, thus reducing product-handling costs. The functional concept of packaging has become an important part of product marketing. To maximize the functional concept of packaging, packaging service providers must pay attention to two important factors in the packaging process, namely safety factors and economic factors. The safety factor is to protect the product from possible damage such as weather, light, drops, accumulation, germs, etc. Production speed and effective production cost are challenges of economic factors in the packaging process [1][2][3].

Wever [4] states that (a) volume is an important factor from an environmental perspective and (b) packaging whose primary function is related to marketing. To support his statement, Wever presents quantitative data of more than 1000 packaged durable goods, which include consumer electronics, household appliances, toys, power tools, and furniture. Several strategies for volume optimization are discussed concerning different packaging functions. Liu et al. [5] argue the need for universal application of automation equipment, and the packaging industry is no exception. This not only reduces the use of labor but also speeds up the production rate to increase productivity.

The packaging machine achieves high speed, and continuous, with high productivity, low power consumption, and the use of simple, reliable, and convenient maintenance.

Zhang et al. [6] have researched to design and simulate an automatic paper tube-cutting machine to produce precise and efficient products. Likewise, Demirtaş [7] conducted a prototype design of a paper-cutting machine, and the factors affecting the quality of paper-cutting results were analyzed.

The process of making product packaging involves several processes, the sequence of which can be seen in Fig. 1. The sheeting machine is one of several machines involved in making product packaging.

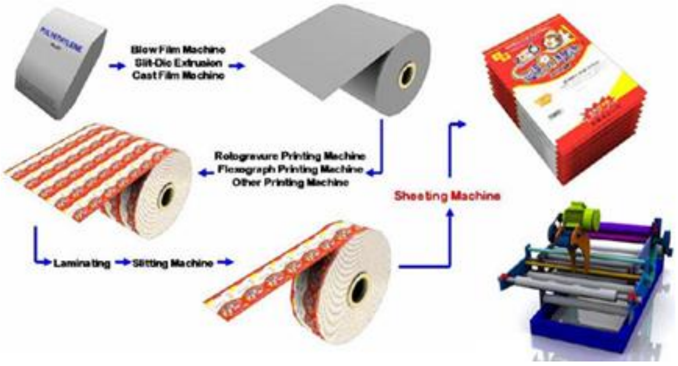

Fig. 1. Packaging manufacturing sequence

Considering the economic factors in the packaging process, the sheeting machine is one of the most influential packaging machines in the packaging industry. This machine is expected to cut sheet products quickly and produce few defects in the products. In cutting sheet products according to the buyer's request, the sheeting machine must have careful cutting capabilities.

Given the importance of the sheeting machine in the packaging industry, it is necessary to optimize the sheeting machine. Process optimization on the sheeting machine can be achieved by selecting pressure parameters, roller speed parameters, eye marks, temperature, and brake frequency. Fig. 2 shows the schematic of the sheeting machine.

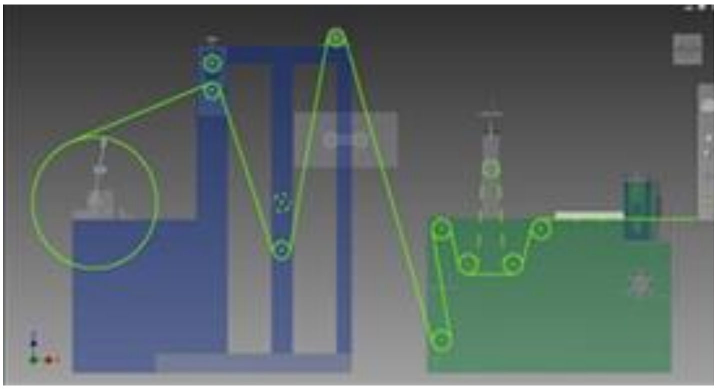

Fig. **2**. Schematic of the sheeting machine

Carrick and Kim proposed a novel packaging optimization method for convex objects. Their method solves the packaging optimization problem through dynamic simulation of object positions and rotations over time [8]. Ceyhan et al. developed a mathematical model and solved it by using the IBM™ ILOG CPLEX program for base, headboard, marquise and cupboard (nightstand) product categories and optimal package sizes [9].

Determining the optimum parameters can be done by designing experiments. The design of experiments aims to improve performance and reduce the sensitivity of the performance system to disturbances (robustness). One of the reliable experimental design methods to determine the optimum parameters is the Taguchi method. The Taguchi method is a technique to improve productivity. The Taguchi method is believed to be a method to reduce costs, improve quality, and increase production speed.

Not many studies have discussed the application of Taguchi methods to packaging process optimization, especially paper packaging. Research by Nataraj et al. [10] applied the Taguchi method to optimize the planar cam mechanism on a printing press. Ginghtong et al. [11] applied the Taguchi method to optimize plastic injection process parameters for manufacturing super thin polypropylene baskets. Bahauddin et al. [12] combined Lean Six Sigma and DoE to reduce defects and improve packing process efficiency in a packing company.

No studies have attempted to use the Taguchi method to optimize the sheeting machine process. This paper describes the methods of sheeting machine process optimization, using the Taguchi method. Taguchi's experimental design was used to predict the optimum process parameters in the sheeting machine process. This approach identifies the important factor settings to develop a setting design for the optimum operating condition that can stand from noise variables (robust design).

2 Implementation of the Taguchi Method

2.1 Taguchi parameter design for the sheeting machine

There are two factors in designing Taguchi parameters for sheeting machines; controllable factors and uncontrollable factors/noise [13][14]. The controllable factors in the sheeting machine are brake frequency, pressure, and roller speed. These factors are controlled by the operator. These three controllable factors are also referred to as signal factors because they are dynamic factors that can influence the response. Furthermore, the control factors need to be reviewed to achieve optimum performance.

Uncontrollable factors describe the functional characteristics of sheeting machine products that deviate from the production target value. These uncontrollable factors are divided into two parts, namely outer uncontrollable factors and inner uncontrollable factors. Outside uncontrollable factors are factors that come from outside (external). External uncontrollable factors are dust, operator performance, material, humidity, and temperature. The inner uncontrollable factors on the sheeting machine are the age and oxidation that occurs on the sheeting machine.

The Taguchi method has several advantages such as experiments involving many factors and quantities so that it is more efficient and provides product results by the disturbance factor. In addition, the Taguchi method can produce an optimum response [15][16].

The stages of the Taguchi method are as follows [17]:

A. Planning the experimental design.
B. Experiment implementation stage.
C. Analysis stage.

Analysis of Mean (ANOM) and Analysis of Variance (ANOVA):

1. F test
2. Pooling-up strategy
3. Signal-to-Noise ratio (S/N).

D. Interpretation of experimental results.
E. Confirmation experiment.

2.2 Taguchi method analysis

ANOM and ANOVA will be considered in the application of the Taguchi method on the sheeting machine. ANOVA is a technique that allows quantitative calculation of the contribution of each factor so that the estimated results can be determined.

ANOM is conducted to test the effect of interaction factors and the similarity of population means in an experimental design where the experimental design factors have been determined in advance. The calculation method of ANOM is the same as the calculation method of the ANOVA technique. The difference lies in the factor values used by each method. The factor value used in the ANOM technique is the average production value. The variant method calculation technique uses the variant value of the product.

ANOVA uses S/N as the ratio between signal and disturbance of a control parameter to select the qualified characteristics. The three types of S/N in the Taguchi method are nominal the best, smaller the better, and larger the better. The S/N ratio that will be used in this analysis is the larger the better S/N. This type of S/N optimizes the parameters of a product with unlimited desired ideal values. In this case, it is the production speed that is discussed. The larger the S/N, the more productive the production process, as seen in Eq. (1) [18][19].

$$ {}^{S}/_{N} = -10\log\left(\frac{1}{\mathrm{n}}\sum_{\mathrm{i}=1}^{\mathrm{n}}\frac{1}{{y_i}^2}\right) \tag{1} $$

ANOM and ANOVA are the calculation techniques that allow the contribution of each factor to be quantified so that the estimated yield can be determined. The following is the equation for the sum of squares in the mean and variance analysis equations.

The total sum of squares Eq. (2):

$$ Sq_T = \sum_{\mathrm{i}=1}^{n} y^2 \tag{2} $$

The sum of squares of the factors shown in Eq. (3) (for example factor A).

$$ Sq_A = \sum_{i=1}^{k_A}\left(\frac{y_i^2}{n_{Ai}}\right) - \frac{{T_A}^2}{N_A} \tag{3} $$

The sum of squared errors (Eq. 4):

$$ Sq_e = Sq_T - Sq_A - Sq_B - Sq_{AxB} -) \tag{4} $$

The mean squared shown in Eq. 5 (for example factor A).

$$ Mq_A = \frac{Sq_A}{Dk_A} \tag{5} $$

Mean square error Eq. (6):

$$ Mq_e = Mq_T - Mq_A - Mq_B - Mq_{AxB} \tag{6} $$

Fratio test used Eq. (7) (for example factor A).

$$ Fratio_A = \frac{Mq_A}{Mq_e} \tag{7} $$

The actual sum of squares (factor A) is as follows Eq. (8):

$$ Sq'_A = Sq_A - Dk_A.Dk_e \tag{8} $$

Percentage of contribution used Eq.(9).

$$ \rho = \frac{Sq'_A}{Sq_T}\ x\ 100\% \tag{9} $$

In calculating ANOM and ANOVA, the F-test is also used to prove whether there is a difference and influence of factors in the experiment carried out by comparing the variance caused by each factor with the variance error. The error variance is the variance of any error in observation arising from external factors that are difficult to control.

The calculated F value is compared with F in the distribution table [20], namely Eq.(10).

$$F = (F_\alpha, Dk_1, Dk_2) \quad (10)$$

After conducting the F-test, a pooling strategy was performed to estimate the variance error in ANOVA and ANOM. The pooling strategy produces better variance estimation errors because the pooling strategy accumulates the variance error of some meaningful factors. Pooling strategies typically involve running F-tests from the smallest column level to the next largest column level to determine significance based on the Fratio. If no significant relationship exists, the factors are combined to test the next largest column until a significant relationship occurs.

If the Dk error is not equal to zero, then pooling is done directly based on the Mean Square (Mq) value. Pooling-up is performed on factor values of Mq that are smaller than the error value of Mq. If the Dk error is equal to zero, half of the Dk error is the factor that will undergo pooling-up. Factors will be pooled up based on the Mq value.

The calculation of contribution is done after the pooling-up strategy. The sum of squares of the relevant factors can be divided after ANOVA and ANOM have been used on a set of data and the sum of squares has been calculated. Comparison of this value with the total sum of squares gives the percent contribution of each factor.

The part of the error that comes from the sum of squared deviations for a source should be added to the sum of squares to keep the total sum of squares Sq_T. Thus, the percent contribution of all sources including error should be 100%. If the error contribution percentage is less than 15%, it indicates that no influential factor is being ignored. However, if the error contribution percentage is more than 15%, this case indicates that there is no controlled condition or there is a large error in the measurement caused by overlooking an influential factor.

The method of calculating the predicted confidence interval for estimating the optimum process mean is as follows Eq. (11).

$$Cl = \sqrt{(F_\alpha, Dk_1, Dk_2)\ x\ Dk_e\ x\ (\frac{1}{n_{eff}})} \quad (11)$$

The calculation of the average prediction process in the optimum condition is Eq. (12).

$$\mu_{prediction} = \bar{y} + (\overline{A_1} - \bar{y}) + (\overline{B_2} - \bar{y}) + (\overline{C_1} - \bar{y}) \quad (12)$$

Assuming the average influential factors are A level 1, B level 2, and C level 1. The prediction confidence interval of the calculation result is Eq. (13).

$$\mu_{prediction} - Cl \leq \mu_{prediction} \leq \mu_{prediction} + Cl \quad (13)$$

2.3 Experiment on the sheeting machine

Several factors are considered while determining the signal factor value, one of which is that each level's value must remain within the range specified by the machine maker (minimum and maximum values are selected, often used for the basic screening experiments to understand if a factor is significant). Factory data, which includes operator experience and the Standard Operating Procedure manual, is the source of information used to calculate the amounts of these elements. The control factor values of the paper cutter are shown in Table 1. The three control factors of roller speed (A), pressure (B), and braking frequency (C) are the control factors that the operator can control. These three control factors are the most important parameters in the operation of the sheeting machine.

The research process on the sheeting machine is shown in Fig. 3. The experiment started by setting parameters representing the control factors of the sheeting machine, and then forward counting sheets of the same size every minute, conducting three trials for each control factor. After recording the sheet production data for each control factor of the sheeting machine, the experiment continues with data processing, analysis, and conclusion.

Table 1. Control factor values of the sheeting machine

Parameters	Control Factor	Level 1	Level 2
Roller Speed	A	600 mm/s	850 mm/s
Pressure	B	2.5 bar	3.5 bar
Breaking Frequency	C	15 Hz	12 Hz

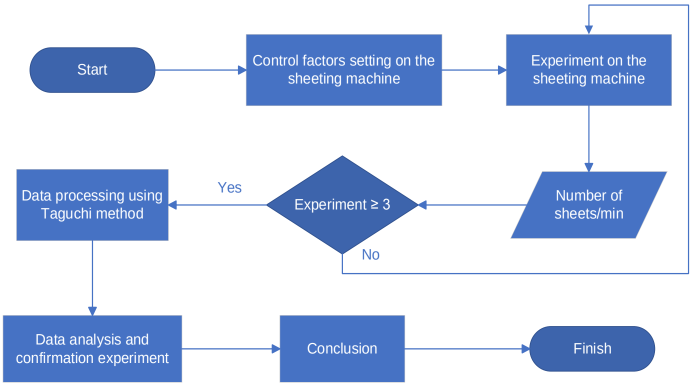

Fig. 3. Research flowchart

3 Results and Discussion

Table 2 shows the results of the production experiment on the sheeting machine per minute with three repetitions of the experiments. S/N values are calculated using Eq. 1. Tables 3 and 4 show the ANOM and ANOVA results calculated using Eqs. 2 to 9. The roller speed factor (A), braking frequency factor (C), interaction between roller speed and pressure factor (AB), and interaction between pressure and braking frequency (BC) influence the production speed of the sheeting machine. The production response of the sheeting machine from the influencing factors is shown in Table 5. The optimum parameters of factors affecting production results based on Table 5 are shown in Table 6.

Based on Tables 5 and 6, the most significant effect is the roller speed factor (A), followed by the braking frequency factor (C), the roller speed-pressure interaction factor (AB), the pressure factor (B), the interaction factor between roller speed-braking frequency (AC), the interaction of 3 factors (ABC). The interaction between pressure and braking frequency (BC) has the lowest level of influence compared to other factors.

Based on the calculation using the Taguchi method and average variance with a 95% confidence interval, the influential factors are roller speed, braking frequency, interaction factor of roller speed and pressure, and interaction between pressure and braking frequency. In the average analysis, the optimum condition is chosen based on the largest production response, and in the variance analysis, the optimum condition is selected based on the largest S/N because the greater the S/N, the smaller the variation around the target. Based on ANOM and ANOVA, the optimum condition occurs when the roller speed factor (A) is at level 2 (850 mm/s), pressure (B) at level 2 (3.5 bar), braking frequency factor

(C) at level 2 (12 Hz), and interaction factor A at level 2 - B at level 2 (850 mm/s - 3.5 bar).

Table 2. Production experiment results on the sheeting machine

No. Exp.	Factor Level							Results (Sheets/min)			S/N
	A	B	AB	C	AC	BC	ABC	Y_1	Y_2	Y_3	
1	1	1	1	1	1	1	1	34	33	33	30.46
2	1	1	1	2	2	2	2	35	35	35	30.88
3	1	2	2	1	1	2	2	32	33	33	30.28
4	1	2	2	2	2	1	1	33	34	33	30.46
5	2	1	2	1	2	1	2	37	38	36	31.36
6	2	1	2	2	1	2	1	38	40	39	31.82
7	2	2	1	1	2	2	1	37	38	39	31.59
8	2	2	1	2	1	1	2	40	39	39	31.89

Table 3. ANOM results

Factor Level	Pooling Up	Sq	Dk	Mq	Fration	Sq’	ρ (%)	Conclusion
A		135.37	1.00	135.37	270.74	134.87	82.76	Reject H0
B	Y	0.38	1.00	0.38	-	-	-	-
C		12.04	1.00	12.04	24.08	11.54	7.08	Reject H0
AB		5.04	1.00	5.04	10.08	4.54	2.79	Reject H0
AC	Y	0.38	1.00	0.38	-	-	-	-
BC		1.04	1.00	1.04	2.08	0.54	0.33	Accept H0
ABC	Y	0.04	1.00	0.04	-	-	-	-
Error	Y	8.67	16.00	0.54	-	-	-	
Pooled (e)		9.47	3.00	3.16	1.00	11.47		

Table 4. ANOVA results

Factor Level	Pooling Up	Sq	Dk	Mq	Fratio	Sq’	ρ (%)	Conclusion
A		2.62	1.00	2.62	374.29	2.61	87.29	Reject H0
B	Y	0.01	1.00	0.01	-	-	-	-
C		0.23	1.00	0.23	32.86	0.22	7.36	Reject H0
AB		0.10	1.00	0.10	14.29	0.09	3.01	Reject H0
AC	Y	0.00	1.00	0.00	-	-	-	-
BC		0.02	1.00	0.02	2.86	0.01	0.33	Accept H0
ABC	Y	0.00	1.00	0.00	-	-	-	-
Error	Y	0.01	0.00	-	-	-	-	
Pooled (e)		0.02	3.00	0.007	1.00	0.06		

Description:
Y : the factor to be pooled up
H0: there is no influence of factors in the experiment
H1: there is an influence of factors in the experiment

Table 5. Ranking of influential factors on the sheeting machine

Factors	A	B	AB	C	AC	BC	ABC
Level 1	33.58	36.08	36.42	35.25	36.08	35.75	35.92
Level 2	38.33	35.83	35.50	36.67	35.83	36.17	36.00
Difference	4.75	0.25	0.92	1.42	0.25	0.42	0.08
Ranking	1	4	3	2	4	7	6

Table 6. Determination of optimum parameters of factors affecting production results

Factor	ANOM	ANOVA	Selected
A (Roller Speed)	A2	A2	A2
B (Pressure)	-	-	-
C (Braking Frequency)	C2	C2	C2
AB (Interaction of Roller Speed and Pressure)	A2B2	A2B2	A2B2
AC (Interaction of Roller Speed and Braking Frequency)	-	-	-
BC (Interaction of Pressure and Braking Frequency)		Accept H0	
ABC (Interaction A, B, and C)	-	-	-

It is necessary to calculate the confidence interval of the prediction of the mean and variance of the output under optimum conditions. Tables 7 and 8 show the confidence intervals for the mean and variance predictions for the sheeting machine (which are calculated using Eqs. 11 to 13).

Table 7. Confidence interval for predicting average of production results (sheets/min)

A1	33.58
A2	38.33
B1	36.08
B2	35.83
AB1	36.42
AB2	35.50
C1	35.25
C2	36.67
AC1	36.08
AC2	35.83
BC1	35.75
BC2	36.17
ABC1	35.92
ABC2	36.00
A2B2	38.67

y	35.96
µprediction	41.75
neff	6.00
CI	0.60
µprediction (confidence interval)	
µmin	41.15
µmax	42.35

It is seen from Table 7 that the predicted average production results under optimum conditions are 41.75 (rounded to 42) sheets/min, where the confidence interval is between 41.15 and 42.35 sheets/min (rounded to between 41 and 42 sheets/min). The predicted average production under optimum conditions can be greater than the production results before optimization (increased by 27.3%) and was confirmed by experiments using optimum parameters resulting in 41 sheets/min (2.4% difference to the predicted average).

Table 8 shows the predicted variance at optimum conditions resulting in an S/N of 32.49 with a confidence interval between 32.30 and 32.68. The S/N of the expected variance under optimum conditions is greater than the S/N before optimization, so the prediction is more robust (increased 32.49 from 30). Confirmation experiments were conducted using the optimum conditions: roller speed of 850 mm/s, pressure of 3.5 bar, and braking frequency of 12 Hz. The average production result obtained from the confirmation experiment was 41 sheets/min.

Table 8. Confidence interval for predicting variance of production results (S/N)

A1	30.52
A2	31.67
B1	31.13
B2	31.06
AB1	31.21
AB2	30.98
C1	30.92
C2	31.26
AC1	31.11
AC2	31.07
BC1	31.04
BC2	31.14
ABC1	31.08
ABC2	31.10
A2B2	31.74

y	31.09
µprediction	32.49
neff	2.00
CI	0.19
µprediction (confidence interval)	
µmin	32.30
µmax	32.68

The procedure of comparing the predicted outcomes of the Taguchi method with the confirmation experiment was also carried out by many researchers to verify the predicted results; among them, Aamir et al. [21] show that there is a small difference between the response optimization prediction and the experiment (3.2%). Aslani et al. [22] indicate the optimized process parameter levels possess good dimensional accuracy, which is consistent with the permissible range of tolerance grades as per ISO standards. Daniyan et al. [23] compared the results obtained from the simulation with the physical experimentations, and it was observed that there was significant agreement between the two (2.02% difference). Hikmat et al. [24] reported a comparison between the confirmation experiment and the linear regression model, and the error percentage between the confirmation experiment and statistical data is about 4.5%. Vijayakumar et al. [25] state that the errors associated with the experiment are very small and regression model equations are negligible.

4 Conclusion

This study optimized sheeting machine parameters to maximize production speed using the Taguchi method. The recommended settings for optimal performance are roller speed (850 mm/s), brake frequency (12 Hz), and roller speed–pressure interaction (850 mm/s, 3.5 bar). Roller speed was identified as the dominant factor, contributing 82.76% (ANOM) and 87.29% (ANOVA) to process efficiency. The interaction between roller speed and pressure significantly influenced production speed, while brake frequency had a minor effect. The optimized parameters led to a 27.3% increase in throughput (33 to 42 sheets/min) and an 8.3% improvement in production robustness (S/N ratio from 30 to 32.49). These findings validate the Taguchi method as a robust approach for enhancing sheeting machine efficiency, reducing variability, and improving production performance.

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