Determining A Yarn Dyeing Process Configuration Using Response Surface Methodology

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***Abstract* - This research is conducted to determine a yarn dyeing process configuration that is capable of meeting a defined quality standard on color level, yarn tensile strength reduction, and yarn elongation reduction. The process consists of mixing materials with chemical substances and applying a heating treatment. There are three factors considered in this experiment which are the heating temperature and the amount of salt and soda. There are three aforementioned observed quality characteristics of which the level should be minimized, with the target value of zero. Response surface methodology is applied in this research. In the initial step, we conduct a 23 factorial experiment in order to look for the factors that significantly influence the quality characteristics. Based on this result and some additional experiments, we establish a regression model for each yarn quality characteristic. Analyzing the responses on their factors level area and also by considering dyeing cost into account, a configuration is developed that satisfies certain company's quality requirements as well as results in lower cost operation. The proposed configuration is a heating temperature of 73.63oC, soda and salt quantities of 0.38 gram and 1.2 grams, respectively. The impact on color level, tensile strength, and elongation resulted is superior to the previous composition used by the company. This configuration can also reduce the dyeing cost by as much as IDR 222/240 grams of yarn.**

Keywords - Response Surface Methodology, Yarn Elongation, Yarn Color Level, Yarn Tensile Strength

I. INTRODUCTION

According to Crosby, quality is defined as a conformance to requirement or specification [1]. The quality standard/specification is derived from customer needs/requirements so that conformance to this standard will determine customer satisfaction and loyalty. Hence, an effort to engineer the product quality so that it satisfies the requirements is compulsory. Quality engineering can be divided into two categories, i.e. off-line and on-line quality control method [2]. In the off-line category, design of experiment becomes the most fundamental method. It includes the variation identification and design optimization. Design of experiment is defined as a set of experiments with a number of necessary adjustments to be performed on the process input variables so that the system can be accurately examined to finally find causal factors of the output variable variations [3].

There are a number of factors that may affect certain product quality characteristic. There are signal factor, noise factor, scaling factor, and control factor [4]. Each factor should be well identified and carefully determined to gain a process that can guarantee product conformance. A proper experiment is needed to support this effort. In order to get a reliable conclusion from an experiment, someone has to accurately define the treatment needed in the experiment, a suitable unit of experiment, and understand on some errors that may happen in the experiment. Randomization, local control, and a representative number of replication are some techniques that can be considered to guarantee the validity of a result of an experiment [5]. Many literatures provide a technique to determine the necessary number of replications for a certain research confidence level and accuracy [3][5][6].

Considering some possible limitations in a research (e.g. time, funding, specimen), someone has to determine a suitable design of experiment. There are some common experimental models that include a completely randomized design, a randomized block design, factorial design, and latin-square design [1][3][6]. Furthermore, some data analysis techniques or methodologies for the data gathered by applying one or more combinations of the experimental models have also been introduced. These include ANOVA, Taguchi method, Yates method, and Response surface methodology [1]-[7]. These methods have their own level of analysis and objectives in order to answer a specific problem question. In this research, a response surface methodology is implemented to a textile company named PT Satya Sumba Cemerlang to find a yarn dyeing process configuration that is able to meet the company requirement.

Response surface methodology is a collection of statistical methods to find and conduct an analysis of some possible influences of independent variables to dependent variables and also to optimize the response of the experiment [8]. There are some previous works that use this methodology and its modification to determine yarn-related process configuration. It involves some parameters of linear density & twist factor of yarn [9], polymer concentration

[10], and rotor speed in yarn production process [11]. Research into yarn heat treatment [12] and modification on the spinning system [13] are also available. Some physical properties that are considered as response variables include yarn shrinkage, tenacity, tensile strength, hairiness, and diameter. In these researches, the response surface methodology has become the basis for an advanced analysis on factor relationships and behavior of yarn related process. An accurate model of response-factor relationship resulted from employing this methodology gives the researcher an ability to optimize the response with suitable values of process parameters. However, it cannot be denied that some specific cases in the above research make it necessary to integrate additional methods to accurately model the process properties. For instance, a certain research deals with an issue about non-linear relationship existing in its process [9].

Our research object of PT Satya Sumba Cemerlang is a textile company in Indonesia. The company produces two types of threads, which are polyester fiber thread and cotton fiber yarn. One of primary processes performed by the company is a dyeing activity. Quality characteristics observed from a dyed thread are color level (L*), tensile strength reduction (Δg), and elongation reduction (Δ%). The two quality reductions are measured by comparing the dyed yarn to the initial yarn used in the process. According to some interviews with the head of the company laboratory, it is found that the material most likely to experience quality reduction after the dyeing process is cotton fiber yarn. Therefore, we focus our research on this type of thread. There are many colors of cotton fiber produced by the company that can generally be classified into dark and light color yarn. The quality problem, especially in the case of non-conforming color level, often happens to dark color thread so that we take a dark color yarn process, especially a black color yarn to be our research focus. In addition to the color type of yarn, we also limit our observation to type 30s cotton yarn.

The dyeing process performed in this company includes two steps which are scouring and matching process. Scouring is a process performed to clean the material from any unwanted substances. It uses H202 (Hydrogen Peroxide) and NaOH (Natrium Hydroxide) as the cleansing material. After getting a clean yarn, the next step is matching. Matching is a coloring process of yarn. The company usually runs an initial process using a sample of 2 grams of yarn to determine a suitable composition of chemical substances for the process. The final composition found from the initial experiment will be applied to the whole yarn proportionally. There are two additive materials included in this process, i.e. salt and soda. The estimation of the amount of salt and soda used in the current matching process are 1-1.5 grams and 0.6 gram, respectively for 2 grams of yarn. These additive substances plus the coloring material are mixed with white cotton yarn and heated to the temperature of 90oC. One hour is required to complete this matching process. The product of the matching process will be cleaned using fresh water until there is no more residual colloring material on the cotton yarn. After completing this process, the quality of product is tested using some suitable measurement methods.

The current configuration of the yarn matching process is unfortunately not capable of producing satisfying quality characteristics level. There is always a reduction in tensile strength and elongation in dyed yarn compared to the initial white yarn. The black color produced from the process is also not satisfactory. Ideally, there is no reduction in yarn tensile strength and elongation. In other words, the differences in these two responses compared to initial material should be zero. In addition to these characteristics, the ideal level of black color should also be zero, measured by the color level. According to the problem identified, an experiment is conducted to find a required configuration for the dyeing process that includes three process parameters, i.e. matching temperature, and the quantities of salt and soda.

The rest of this paper is organized into three sections. Section II explains the quality measurement standard employed in the experiment. Section III provides the detail of experiment and the result obtained for a conforming yarn-process configuration. Finally, section IV closes the paper with a conclusion on the research.

II. QUALITY MEASUREMENT METHOD

In this research, two national measurement standards are used to determine the desired responses. These are SNI ISO 105-J03:2010 and SNI 7650:2010, which respectively determine how to measure the color, the strength, and the elongation of an object. The measurement method in SNI ISO 105-J03:2010, especially in the ICS.59.080.0 standard, will produce a quantitative result of color intensity which can be used for our analysis. A spectrometer is used to measure color intensity. By using a spectrometer, a measurement can be performed for several color indicators, including lightness (L*), red and green intensity (A*), brightness for blue and yellow color (B*), and chroma (C*). These indicators can be used to define a specific coordinate of a color. Fig. 1 illustrates the machine used in the measurement activity.

Fig.1. Spectrometer

In this research, the lightness indicator value is used. The process configuration currently used by the company can produce a yarn with 14.31 point of lightness, while the ideal black color yarn should have a lightness value of zero. Some experiments are conducted in this research to obtain a better process parameter that can minimize the lightness of this black yarn.

The remaining two responses considered in this research are tensile strength and elongation of a dyed yarn. A specific standard in SNI 7650:2010 used for measuring these two responses is ICS 59.080.20. The yarn tensile strength test is performed by stretching the yarn for 20 seconds. Some parameter values used in this test are 10 N of load cell, 50 mm of gauge length, and 50 mm/min of test speed. The device used in this test is called the Statimat Me, which is illustrated in Fig. 2.

The tensile strength and elongation level of a yarn tested can be read on the monitor. These values are compared to the white yarn tensile strength and elongation level, which are the initial characteristics of yarn before the dying process is implemented. The objective of the experiment is to minimize the deterioration of tensile strength and elongation of a yarn after processing. Twelve samples of white yarn are tested using the explained method to obtain the initial value of tensile strength and elongation of the yarn. From this test it is established that the average values of tensile strength and elongation of the white yarn are 275.71 grams and 8.47% respectively. These numbers will be respectively subtracted from the tensile strength and elongation values of dyed yarn that results in responses we need for analysis.

Fig.2. Statimat Me

III. COTTON YARN EXPERIMENT & RESULT

For the initial stage, 23 factorial experiments are conducted using three factors. This experiment is performed to verify the impact of the factors on the responses. Table I illustrates the configuration level of each factor used in the initial stage. The factors are represented by X1, X2, and X3 respectively for temperature, soda, and salt.

TABLE I. FACTOR LEVEL OF 2^3 EXPERIMENT

Factor	1st Level	2nd Level
Temperature (X1)	60^o C	90^o C
Soda (X2)	0.3 g	0.6 g
Salt (NaCl) (X3)	1.05 g	1.5 g

This 23-factorial experiments results in 8 combinations of treatment that are applied randomly. The combination can be shown in Table II. Twelve replications were run for every treatment so that 12 responses can be obtained for each treatment on lightness index (L*), tensile strength, and elongation differences.

By using the Yates analysis method with a 5% significance level, conclusions can be drawn regarding the factor that significantly influences the responses. The results demonstrate that for lightness index, X1, X2, X1*X2, and X3 are the terms that have significant influences on the value. For the tensile strength and elongation, there are X2 and X1*X3 that have significant effect. Therefore, it is concluded that these three factors can be used for further experiments.

The next step is to build a regression model. For this reason, one additional level is included for every factor so that we can identify whether there is a non-linear relationship between factors and responses. All levels in the first experiment are coded as shown in Table III. Twelve responses for the three kinds of responses are gathered for this new treatment.

TABLE II. 2^3 EXPERIMENT TREATMENTS

Factor-Level Combination			
No	**Temperature**	**Soda**	**Salt**
1	60^o C	0.3 g	1.05 g
2	60^o C	0.6 g	1.05 g
3	60^o C	0.3 g	1.5 g
4	60^o C	0.6 g	1.5 g
5	90^o C	0.3 g	1.05 g
6	90^o C	0.6 g	1.05 g
7	90^o C	0.3 g	1.5 g
8	90^o C	0.6 g	1.5 g

TABLE III. CODE OF TREATMENT

Temperature	Soda	Salt	*Code*
60ºC	0.3 g	1.05 g	-1
75ºC	0.45 g	1.225 g	0
90ºC	0.6 g	1.5 g	1

A total of 108 x 3 responses that include the light index, tensile strength, and elongation of the dyed yarn resulted from 9 combinations of treatments are used to develop regression models. As mentioned before, the response of tensile strength and elongation will not be used directly, but the value of the white yarn (initial material) characteristics are firstly subtracted that results in the reduction value of both factors on the dyed yarn specimens. The lightness index, tensile strength and elongation reduction become three dependent variables for the regression models, while the temperature, soda, and salt are the independent variables. The coded values of independent variables are used in the regression model construction. Furthermore, it also considers some significant interactions among the independent variables so that it results in second order regression models. The three corresponding regression models are presented in (1)-(3).

Lightness Index:

$$Y = 13.5308 + 0.2443\,X1 - 0.5166\,X2 - 0.1684\,X3 + 0.7186\,X12 - 0.2114\,X1X2 - 0.0657\,X1X3 + 0.0201\,X2X3 \quad (1)$$

Tensile Strength:

$$Y = -87.176 - 4{,}23\,X1 - 13.02\,X2 + 4.764\,X3 + 65.097X12 + 7.989\,X1X2 - 13\,X1X3 + 1.213\,X2X3 \quad (2)$$

Elongation:

$$Y = -1.2 - 0.03302X1 - 0.33469\,X2 - 0.0074\,X3 + 0.1301\,X1X2 - 0.34927\,X1X3 - 0.07656\,X2X3 \quad (3)$$

The R-squared values for these three consecutive regression models are 46.31%, 27.63% and 15.28%. Based on these values, it can be concluded that the models do not adequately represent the responses characteristics. Therefore, we use another method, i.e. Steepest Ascent [6] to help develop a better understanding. We examine a smaller area of responses which is the area of 0 code treatment level. Other treatment combinations around this area are generated and applied and then an optimal response is chosen. Table IV presents the additional treatment combination for lightness response/color level of yarn.

Fig. 3 is an example of response characteristics on lightness index produced by performing the Steepest Ascent Method. The optimal and feasible factor configuration is determined using this data, which goes to the sixth treatment.

TABLE IV. ADDITIONAL TREATMENTS FOR LIGHTNESS RESPONSE

No.	Temp.	Salt	Soda
1	75	0.452	1.23
2	75	0.453	1.23
3	75	0.455	1.23
4	75	0.456	1.23
5	75	0.458	1.23
6	75	0.459	1.23
7	75	0.461	1.23
8	74	0.462	1.23
9	74	0.464	1.23
10	74	0.465	1.23

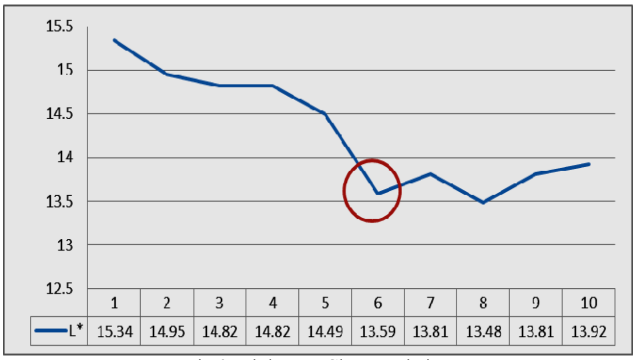

Fig.3. Lightness Characteristics

From this point configuration, a further experiment can be conducted. Central Composite Design (CCD) is used to perform an experiment around the sixth treatment configuration. Fig. 4 illustrates the form of CCD for lightness response. The central point will be the sixth configuration of heating temperature, amount of soda, and salt obtained from the Steepest Ascent method. The parameter values used in this CCD experiment are 3 for both k and alpha (α).

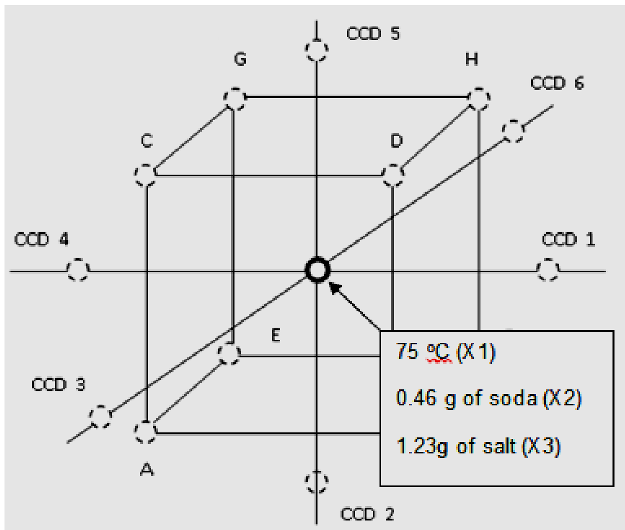

Fig.4. CCD Lightness Response

The experiment conducted around the center point includes 15 treatments that are shown in Table V.

TABLE V. CCD TREATMENTS FOR LIGHTNESS INDEX

Treatment	Temp.	Soda	Salt
Centroid	75°	0.46 g	1.23 g
A	72°	0.56 g	1.13 g
B	78°	0.56 g	1.13 g
C	72°	0.56 g	1.33 g
D	78°	0.56 g	1.33 g
E	72°	0.36 g	1.13 g
F	78°	0.36 g	1.13 g
G	72°	0.36 g	1.33 g
H	78°	0.36 g	1.33 g
CCD1	80.19°	0.46 g	1.23 g
CCD2	75°	0.46 g	1.06 g
CCD3	75°	0.63 g	1.23 g
CCD4	69.8°	0.46 g	1.23 g
CCD5	75°	0.46 g	1.40 g
CCD6	75°	0.29 g	1.23 g

The dyeing processes are conducted for 2 replications for every treatment. Each quality characteristic has their own CCD treatment configuration that is applied for this number of replications in order to get the response data. From these data together with the coded treatment levels, a regression model is developed. The resulting equation terms and parameter values are presented in Table VI. R1, R2, and R3 refer to lightness index, tensile strength, and elongation differences, respectively.

TABLE VI. SECOND STAGE REGRESSION MODEL

R1	R2	R3	Model Term
13.6650	11.24473	0.152495	
0.0226	0.821416	0.020311	X1
-0.444	-1.16867	-0.08095	X2
-0.1417	0.156683	-0.06305	X3
0.0387	-0.72188	0.002875	X1X2
0.015	0.430625	0.016375	X1X3
-0.0725	-0.30563	-0.04588	X2X3
-0.0325	-0.48971	-0.00713	$X1^2$
0.2575	-4.58912	-0.07414	$X2^2$
0.3708	-0.48138	-0.0378	$X3^2$

The R-squared values derived from this data are 83.70%, 86.39% 91.38%, respectively, for R1, R2, and R3. Therefore, it can be concluded that the model adequately explains the dyeing process characteristic around the observed area. Using these three regression models, contour plots and surface plots are created in order to describe the second-order equations in 2-dimensional and 3-dimensional space. Fig. 5 and 6 show the plots for lightness response. The X3 is determined as a hold variable because of the limitation in plotting multidimensional data. The X3 is held on the 0 coded factor level.

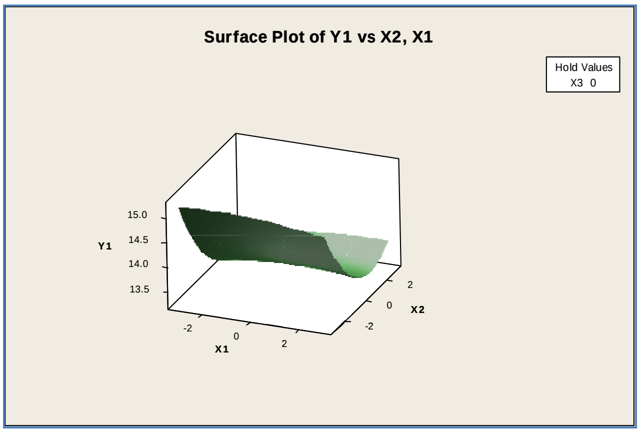

Fig.5. Surface Plot of R1

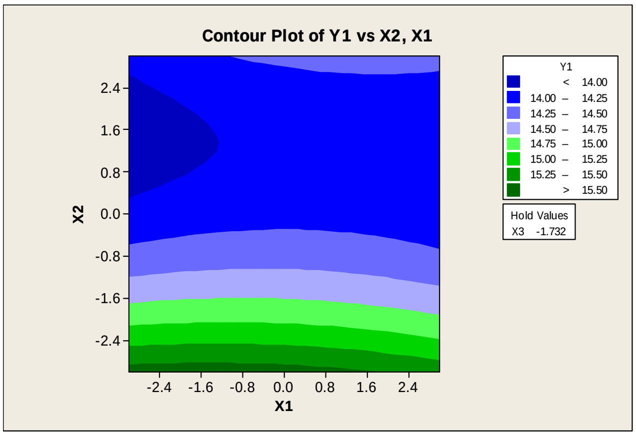

Fig.6. Contour Plot of R1

From every surface plot, contour plot, and response optimizing process conducted using Minitab, we can determine the optimal factor configuration. Table VII lists the optimal configuration for each response.

TABLE VII. SECOND STAGE REGRESSION MODEL

Objective Function	Response Value	Factor		
		Temp.	Soda	Salt
Min R1	13.2534	66°C	2.24 g	1.80 g
Min R2	0.0001	72.52°C	0.14 g	1.25 g
Min R3	0.0004	74.63°C	0.16 g	1.33 g

Ideally, each response should be minimized, but unfortunately, they have their own different optimal configurations. This condition requires the research objectives of some yarn quality characteristics to be compromised. In addition, the final process configuration for the dyeing process is subject to the process cost reduction expected by the company. This considers the cost of using a certain amount of soda and salt, which are IDR 5/gram and IDR 2.5/gram, respectively. Therefore, there is one additional objective function which is minimizing the total dyeing process cost. Iterations on the combination of temperature, soda, and salt composition are performed around the CCD treatment combinations that can reduce the lightness level, tensile strength and elongation differences, and also result in cost reduction compared to current production cost. From 92 process configurations applied to the previous regression models, the company determines a combination parameter value of 76.630C, 0.38 g, and 1.2 g for temperature, amount of soda, and salt to use. This configuration results in 14.09 lightness index, 0.533 tensile strength differences, 0.035 elongation reduction, and IDR 4.9 of production cost. The first three responses values resulting from this configuration are all superior to the current condition. When this configuration is converted into the one required for the smallest production unit of yarn (240 grams), it results in an IDR 558 of production cost which is smaller than the current production cost of IDR 810.

IV. CONCLUSION & FURTHER RESEARCH

In this research, the response surface methodology has been applied to determine an optimal process configuration for yarn dyeing activity. However, some initial mathematical models to accurately represent the characteristic of yarn dyeing process cannot be obtained so that further examination just focuses on a local area of the yarn quality characteristics. This obviously results in local area optimization which is a limitation of this research. However, the models generated from this way of experiment are still able to help determine a satisfying process configuration for the company. It results in better yarn characteristics for all the quality aspects compared to the current dyeing method. In addition, the proposed process configuration also produces IDR 252 cost reduction for every 240 grams of yarn, which is the smallest production unit of yarn in the company.

Further research can be performed by considering other regression models to accurately represent the global characteristic of yarn dyeing process. In addition, a multi-response model will be beneficial to overcome the difficulty of choosing a final process configuration to be applied as we have dealt in this research. It will be more convenient because this kind of model will be able to simultaneously optimize the responses by providing a single process configuration.

ACKNOWLEDGMENT

We would like to thank PT Satya Sumba Cemerlang that permits us to conduct a research and observation on their yarn dyeing process. We also thank Balai Besar Tekstil that helps us with all the yarn quality measurements.

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