Control of Moisture Variation in Fish Sheet Manufacturing Process

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***Abstract*—The focus of this paper is process improvement in a fish-sheet production line in a snack factory in Thailand. Preliminary measurement suggests that moisture of fish sheets after the roasting process significantly deviate from the provided specification, reporting a process capability index (C_{pk}) of post-roasting moisture to be only 0.04. Prior to the start of this project, the manufacturer relied on machine operators to subjectively adjust production parameters during production to reduce moisture variation in fish sheets. Despite experience of operators, data suggest that the method is ineffective in reducing moisture variation. Moreover, it is found that significant variation originates from frozen minced fish which is a key ingredient of fish sheets, resulting in high moisture variation in mixed ingredient. Two intervention procedures were implemented to improve the post-roasting moisture C_{pk} index. First, the mixing procedure was modified to allow flexible adjustment of water in mixing ingredients based on objective measurements. Second, post-mixing processes are operated under constant parameter values. Optimal values are solved using response surface method based on 3x3 factorial design of experiments of air-drying temperature and roasting conveyor belt speed. The C_{pk} index is predicted to improve to 0.59 after the water-adjusting intervention and production parameters are set up so that the air-drying temperature is set to 61 ℃ and the roasting conveyor belt speed is set to 64 Hz.**

***Index Terms*—design of experiment, food manufacturing, mass-production manufacturing, moisture variation control, response surface method**

I. Introduction

The process that this study will focus on is manufacturing of fish sheets in a snack-manufacturing factory in Thailand. Various snacks produced in this factory have roasted fish sheets as a common work-in-process. Due to their significance on production in the factory, fish sheets will be the main subject of process improvement in this paper to improve its quality control. A key quality metric in fish sheet production is the sheet's moisture after being roasted. At the beginning of the project, post-roasting moisture in fish sheets had very low process capability, with a Cpk index of only 0.04.

There are two major approaches that related works in food-drying literature uses to control moisture. The first group of literature focuses on finding optimal production parameter or conditions. These optimal conditions can be found by making mathematical modeling of the production system, properties of material and thermodynamic conditions in the process [1]-[3]. Alternatively, optimal parameter values can be found by conducting experiments on the process under various conditions [4], [5]. Optimal values can either be values of an experimented condition with the best response values [4] or be interpolated values using statistical techniques such as artificial neural network [5].

The second group of literature seeks to establish control over the production process so that target responses are within designated specification. Literature in this area generally agree that control of drying processes is challenging due to their non-linearity and long delays [6]-[8]. A simple and commonly used method for solving the problem is feedback control using basic PID controllers [7], [8]. Unlike PID controllers that uses only errors up to current time steps to determine the system's control, model-predictive control uses models of a system to optimize the system's response over finite future horizon in exchange for higher computational requirement [9], [10]. Other works incorporate fuzzy logic control, which allows inexact and natural language to be input to a control systems [8], [10].

The approaches that this paper pursued consists of two components. First, control over inputs to the drying process is implemented, but relies on process improvement rather than automatic controllers. Second, production parameters involved in the drying process are optimized using design of experiments and response surface method. More sophisticated methods such as automatic controllers and modification of machinery were not implemented because of very low baseline performance and limitation on production schedules. It is expected that the process capability index can be improved with better processes.

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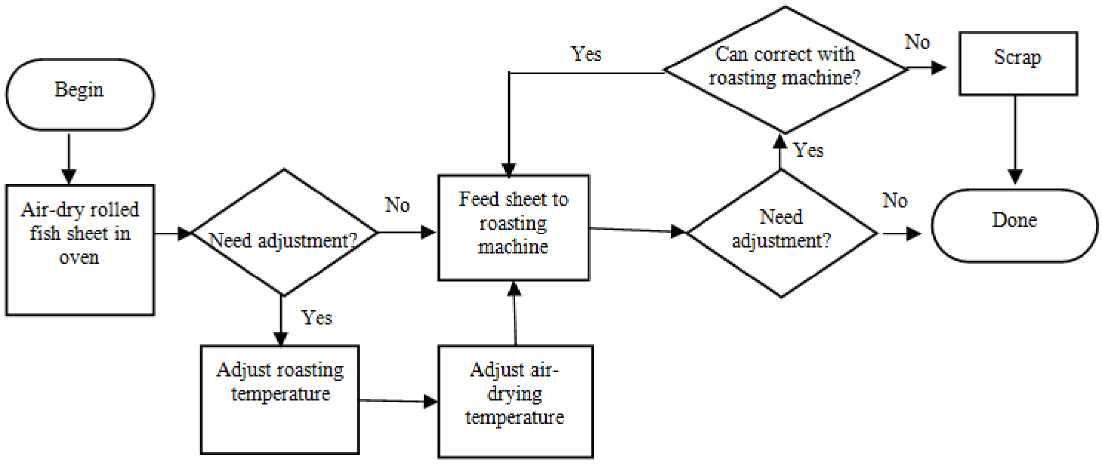

Figure 1. Moisture correction procedure in air-drying and roasting process before the beginning of project

II. Description of Production Processes

Production of fish sheets consist of four key steps including

1. *Mixing* — Ingredients are thoroughly mixed. These ingredients include frozen minced fish, water, ice, starch, and other dry ingredients. Multiple batches of ingredients are mixed throughout the day.
2. *Sheet-forming* — The fish mixture is rolled into sheets with a heated roller. The formed sheets are directly fed into an air-drying oven with a conveyor belt.
3. *Air-drying* — Rolled fish sheets are passed through an air-drying oven with a conveyor belt to remove majority of excess moisture. The process takes about an hour before the sheet exits the oven at the other end of the machine.
4. *Roasting* — Air-dried sheets are then put on a conveyor belt through a natural-gas-fueled roasting machine to give "roasted" texture to the sheets and remove remaining moisture from the sheets.

III. Statement of Problem

Despite importance of the post-roasting moisture to production process, prior to the start of the project, fish sheet's moisture is measured infrequently. Because the main purpose of measurement was for retrospective investigation to find root causes of scraps or product rejection, the manufacturer measured fish sheet's moisture at post-air-drying and post-roasting stage only once per day. The main obstacle to more frequent moisture measurement was long measurement time as the loss-on-drying measurement takes between 30 to 40 minutes per sample. Therefore, the production team allow on-site operators and their supervisor to subjectively determine moisture level of roasted fish. Prior to manually feeding air-dried sheets into the roasting machine, operators would determine whether air-dried sheets are too dry or moist by touching the sheets. If operators consider moisture to be unacceptable, they would adjust natural gas flow rate in the roasting machine and the air-drying oven's temperature. Sheets with excess moisture were re-roasted until they are sufficiently dried. Fish sheets that cannot be corrected are scrapped. No objective measurements are taken in these correction process. A flow chart describing the moisture correction procedure is summarized in Fig. 1.

The described procedure has six problems. First, the current moisture correction procedure is not based on any objective data. The only source of objective data is loss-on-drying moisture measurement which was recorded only once a day which does not give enough resolution to provide insights into operations throughout the day and is not useful for real-time adjustment. Second, real-time moisture adjustment is impractical due to long production latency in air-drying stage which takes one hour, and imprecise control on temperature in the roasting stage. At a fixed setting, data show that the roasting temperature has high variation with values at 167.54 ± 8.68 ℃. Real-time parameter adjustment, especially in the air-drying stage would result in non-uniform treatment across fish sheet.

Third, the current procedure is expensive because it requires for products to be processed first before defects can be detected and corrected. Fourth, despite the belief that operators can correct moisture in fish sheets, the process capability index (C_{pk}) of post-roasting moisture is only 0.04. Fifth, the procedure heavily relies on workers' skills in subjectively measuring fish sheets' moisture and making correction, which will require intensive training to transfer the skills to other workers.

Finally, there is waste in waiting time and labor between the air-drying and the roasting process. Because of potential need for parameter adjustment, the two processes cannot be integrated into a continuous production line. Moreover, two workers need to be stationed to manually feed air-dried fish sheets into the roasting station. If parameter adjustment can be eliminated, these workers can be allocated to more productive works.

As such, this project's primary objective is improving process capability index (C_{pk}) of post-roasting moisture of fish sheets in the fish-sheet production. Ideally, the project aims to improve the process capability index to over 1.33 which is the recommended minimum process capability for two-sided specification in an existing process as suggested by Montgomery [11]. With low baseline C_{pk} index of 0.04, it is expected that improvement can be achieved using only process improvement that does not require significant modification of production machines.

IV. Methodology

The four stages that are the focus of process improvement include mixing, sheet-forming, air-drying and roasting processes. Unlike other processes, the mixing process is not a part of continuous production line because ingredients are mixed in large batches some time before being gradually fed into sheet-forming rollers. The wait time allows for time-consuming intervention to be applied to the mixture or ingredients without significant disruption on the production process. On the contrary, the possibility for time-consuming intervention is more limited in later processes, which will be referred henceforth as *post-mixing processes*.

As discussed in Section III, changing values of production parameters during production can have adverse effects. Instead, this project pursued a different approach by attempting to minimize moisture variation in incoming raw material (i.e. the mixed fish solution from the mixing process) and to fix production parameters in post-mixing processes. As such, this project will consist of two parts of process improvement: minimization of moisture variation in mixed fish solution in the mixing process, and finding values of production parameters in post-mixing processes that maximizes the C_{pk} index.

A. *Minimization of Fish Mixture Moisture*

Based on the collected data on mixed fish solution's moisture prior to any interventions, the mixed solution had moisture at 61.73±3.78%, indicating significant moisture variation in the mixture. The fish mixture has three major ingredients including frozen minced fish (40% by weight), water and ice (30% by weight) and other seasoning ingredients (30% by weight). It is hypothesized that frozen minced fish which is the most significant non-water ingredient is a major source of variation in the fish mixture's moisture. It is found that moisture of frozen minced fish from two suppliers (denoted as Supplier 1 and Supplier 2) have significant variation with values at 75.6 ±2.87% and 73.97 ±3.13% respectively. Considering that the manufacturer's specification is between 70 and 78%, C_{pk} of minced fish from both suppliers are 0.28 and 0.42 respectively, which are relatively low.

In addition to pressuring suppliers to better comply with the given specification, this project introduced a procedure to lower moisture variation of the mixed solution despite high moisture variation in ingredients. The main idea is to increase or decrease amount of water added to the mixture based on difference of ingredients' moisture from the moisture assumed in the recipe. Before the start of a mixing session, moisture of frozen minced fish samples would be measured. The amount of water to be increased or decreased from the amount designated in the recipe by the amount is then derived from a formula in Eq. 1, where target moisture is calculated from assumed moisture of ingredient *i* and the weights of ingredients in the mixture. For convenience, MS Excel spreadsheet based on Eq. 1 is provided for calculation in production line.

$$\Delta W = \frac{m_{target}\left(\sum_i^n r_i\right) - \sum_i^n m_i r_i}{1 - m_{target}} \qquad (1)$$

where

ΔW is the amount of water to be adjusted from the standard recipe

m_{target} is the target moisture of the mixture

r_i is weight of ingredient *i*

m_i is moisture of ingredient *i* based on mixing recipe

To evaluate significance of the described procedure, a two-variance F-test was used to determine whether the variance of the fish mixture after the intervention is significantly less than the moisture prior to intervention. The result will be presented in Section V.

B. *Selecting the Best Combination of Post-Mixing Process Parameters*

The second part of process improvement is selection of production parameter values for post-mixing processes that maximize the process capability index. To accomplish the objective, a Design-of-Experiment (DOE) experiment with 3-level factorial design was conducted. Factors used in the experiment are factors over which operators have precise control and are considered to have significant impacts on values of post-roasting moisture. Significance of factors are determined using priority ranking performed by supervisors and operators in the factory. Two factors are selected including the air-drying temperature in the air-drying process and the roasting machine's conveyor belt's speed in the roasting process. Both processes can be easily controlled using the digital controller.

Other factors that might have effects on post-roasting moisture have also been considered as candidates for the experiment. Considered factors include roasting temperature, the sheet-forming roller's temperature, the sheet-forming rollers' gap width and the factory's humidity and ambient temperature. However, these factors are not used in the experiment because controls over them are difficult to quantify, cannot be precisely controlled, or require significant investment in infrastructure.

In the DOE experiment, three levels of factors for the air-drying temperature and the roasting conveyor belt speed were designated in collaboration with the manufacturer. The collaboration is essential because the experiment would be run on the large-batch production line and all parties involved would like to minimize scraps due to the experiment. The three levels of air-drying temperature selected by the manufacturer are 60, 61 and 62 ℃. The levels of roasting conveyor belt speed are 60, 65 and 70 Hz.

The response of this experiment is the post-roasting moisture which would be calculated into C_{pk} values for further analysis. Production parameter values are changed only once to values designated in the experiment's schedule. The sequence of these parameter values is randomized. Because one data point is collected per mixing batch to ensure independence between data points, only five data points can be collected per day. At the end of the experiment, fifteen data points of post-roasting moisture could be collected for each set of parameter values. To find parameter values that optimize the C_{pk}, A linear regression was used to determine relationship between parameter values and the post-roasting moisture C_{pk}. The result will be discussed in Section V.

V. Result and Analysis

A. Result of Intervention on the Mixing Process

After implementing water adjustment procedure, moisture of fish mixture is changed from 61.73 ±3.78% to 62.48 ±1.05%. A two-variance F-test is conducted to confirm whether the variance of moisture distribution after the intervention is significantly less than the distribution before the intervention, using a significance level (α) of 0.05. The number of samples for moistures before intervention and those after intervention are 171 and 173 samples respectively. The result shows a p-value less than 0.001 which is below the significance level at 0.05. Therefore, it can be concluded that the moisture distribution after the intervention has significantly less variance than that before the intervention.

With variation in fish mixture significantly reduced, the post-roasting moisture's C_{pk} is improved to 0.32, compared to the pre-intervention level of 0.04. An experiment on 38 data points reported post-roasting moisture at 16.36 ±1.69%.

B. Result of Finding Optimal Parameter Values in Post-Mixing Processes

As discussed in the methodology section, the objective of the parameter-optimization phase is finding values of post-mixing process parameters that optimizes the process capability index (C_{pk}) of post-roasting moisture. C_{pk} indices for 9 different combinations of parameter values calculated using data from the DOE experiment are summarized in Table I. As mentioned earlier, C_{pk} value for each treatment is calculated from 15 data points. The best C_{pk} index reported in the experiment is 0.56 when the air-drying temperature is 61 ℃ and the roasting conveyor belt's motor speed is 65 Hz.

TABLE I. C_{PK} Values of Post-Roasting Moisture under 9 Different Production Conditions

		Roasting conveyor belt motor speed		
		60 Hz	**65 Hz**	**70 Hz**
Air-drying Temperature	**60 ℃**	0.24	0.38	0.16
	61 ℃	0.56	0.56	0.28
	62 ℃	0.43	0.50	0.23

TABLE II. Regression Statistics of Coefficients in Regression Function with Post-Roasting Moisture C_{PK} Based on Eq. 2

	Coefficient	SE Coefficient	t-value	p-value
Constant	-588.011	122	-4.83	0.017
O	18	3.95	4.55	0.020
R	1.179	0.326	3.62	0.036
O^2	-0.1440	0.0323	-4.46	0.021
R^2	-0.00654	0.00129	-5.06	0.015
OR	-0.0057	0.00457	-1.25	0.301

To find optimal parameter values, a regression with linear, quadratic and interaction terms is conducted using MiniTab software to find a relationship between these factors and the post-roasting moisture. The solved regression function is as reported in Eq. 2 where O is the air-drying oven temperature and R is the roasting machine's conveyor belt's speed. Statistics of the regression are summarized in Table II. With the significance level at 0.05, coefficients of all terms except for that of the interaction term (OR) has p-value below the significance threshold. There is a strong relationship between factors and the response, as suggested by the R-squared value of 96.50% and adjusted R-squared value of 90.67%.

$$C_{pk} = -588.011+180+1.179R - 0.144O^2 - 0.00654R^2 - 0.0057OR \quad (2)$$

Because the interaction term, OR, in Eq. 2 has a higher p-value than the significance level, a new regression is conducted without using the term. A new regression equation is reported in Eq. 3 and its statistics are reported in Table III.

$$C_{pk} = -565.411+17.629o+0.832R - 0.144O^2 - 0.00654R^2 \quad (3)$$

TABLE III. Regression Statistics of Coefficients in Regression Function with Post-Roasting Moisture C_{PK} Based on Eq. 3

	Coefficient	SE Coefficient	t-value	p-value
Constant	-565.411	128	-4.4	0.012
O	17.629	4.21	4.19	0.014
R	0.832	0.179	4.64	0.010
O^2	-0.1440	0.0345	-4.18	0.014
R^2	-0.00654	0.00138	-4.74	0.009

All coefficients in Eq. 3 are statistically significant because reported p-values of terms in the function is below a significance level of 0.05 as reported in Table IV. Moreover, there is a strong relationship as suggested by the R-squared value of 94.69% and adjusted R-squared value of 89.38%.

Based on the regression function in Eq. 3, local optimal values for air-drying oven's temperature and the roasting machine's conveyor belt speed, under constraint that the control values must be integers, are 61 ℃ and 64Hz respectively. The post-roasting moisture's C_{pk} under production using these parameter values are predicted to be 0.59. Residuals of the data used for regression have been checked to have approximately normal distribution with zero mean, common variance and to be independent from one another.

TABLE IV. Effects of Different Experimental Conditions on Post-Roasting Moisture C_{PK} Indices

Experimental Conditions	Post-roasting moisture C_{pk}
No water adjustment and post-mixing parameters can be freely adjusted	0.04
Water adjustment procedure is implemented and post-mixing parameters can be freely adjusted	0.32
Water adjustment procedure is implemented and the best experimented parameter values (61 ℃ and 65 Hz) are used	0.56
Water adjustment procedure is implemented and the optimized parameter values (61 ℃ and 64 Hz) are used	0.59 (prediction)

To sum up, a comparison of post-roasting moisture C_{pk} index under different experimental conditions is summarized in Table IV. All intervention described in this paper helped increase value of the process capability index. The best value of Cpk index experimented in this study is 0.56, which is a considerable improvement from the baseline performance at 0.04. Under optimal conditions, the index is expected to improve to as much as 0.59. Despite the improvement, the result still falls short of the target level of C_{pk} at 1.33.

VI. CONCLUSION

The study provides a case study for application of design of experiments for optimizing process capability index response in a mass-production setting. By adaptively adjusting water in fish mixture based on minced fish's moisture and by setting air-drying temperature at 61 ℃ and roasting conveyor belt speed at 64Hz, it is predicted that the C_{pk} index of post-roasting moisture in fish sheets will improve from 0.04 to 0.59, as summarized in Table IV. Despite the improvement, it falls short of the target C_{pk} level of 1.33. Further improvement can involve investment on better control equipment in post-mixing processes using digitization of controls (such as digital controllers for natural-gas flow and digital servos for controlling sheet-forming roller's gap width). The modification would reduce variation in control parameters, and allow for DOE experiments involving these digitized parameters.

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