DEVELOPING A LINEARIZATION METHOD TO DETERMINE AN OPTIMUM FORMULATION IN SURIMI BLEND WITH VARIED MOISTURE CONTENT USING LINEAR PROGRAMMING

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ABSTRACT

Novel algorithm to determine the least cost formulation of a surimi blend using linear programming and each surimi properties was developed. Texture properties and the unit cost of surimi blend at the target moisture content were used as constraint functions and the objective function, respectively. The mathematical models to describe the moisture content dependence of the breaking force and the penetration distance were developed using critical moisture content, and the model parameters were used for linearization of moisture content dependence before applying linear programming to determine the optimum formulation. The LCLP model successfully predicted the quality of surimi blend ($p < 0.05$). Sensitivity analysis was used to provide an additional information when the perturbations of design variables are provided. A standard procedure to determine the least cost formulation of surimi blend having varied moisture content was systematically developed.

Keywords: surimi, linear programming, critical moisture content, texture map

1. INTRODUCTION

Surimi, stabilized fish myofibrillar protein, is the major ingredient to produce surimi seafood, such as crab stick, kamaboko, and fish ball. The price of surimi has been unstable because of the limited harvest of valuable species of fish (Guenneugues and Morrisey 2005, Morrisey and Tan 2002, Park 2013) and the increase of oil price. Traditionally, the surimi made from the Alaska pollock has been mainly used to produce the surimi seafood, but the recent development of surimi technology enabled to utilize many other underutilized species from South East Asia and Southern China, such as Threadfin bream (Itoyori) and ribbon fish. It is an essential process for surimi seafood manufacturers to blend various types and grades of surimi lots to develop commercial surimi seafood products, due to the followings: 1) fluctuation of surimi price, 2) unstable supplying of specific species of fish, and 3) maintaining a consistency of quality of surimi seafood.

The myofibrillar protein in surimi is able to form 3 dimensional networks by thermal treatment. The 3 dimensional networks change the rheological properties of surimi paste from liquid-like sol to solid-like gel. The unique texture properties of surimi seafood are mainly from the 3 dimensional networks from myofibrillar proteins and the interaction between protein networks and other ingredients, such as starch, egg white, and soy proteins (Park 2005). Texture properties of surimi seafood are considered as the most important quality characteristics of commercial surimi seafood products. Numerous studies have been conducted to evaluate the texture properties (Park 2005) and to control the texture properties of surimi seafood by formulating the ingredients (Kim et al. 2005, Lanier 1992; Lei-Lei et al. 2014, Yin and Park 2014, Zhang et al. 2015). Punch test is the most widely adopted method to evaluate the texture properties of surimi gels in surimi and surimi seafood industry due to the convenience of the test, although the values obtained from the punch test cannot provide fundamental mechanical properties. Conventionally, the gel strength indicating the texture properties of surimi is defined by a product of the breaking force and penetration distance from the punch test.
Linear programming (LP) is an optimization technique (Eppen et al. 1993, Hiller and Frederick 2012), and has been applied to determine the least cost optimum formula for surimi blending since 1980's (Lanier 1992, Yoon et al. 1997a, Park 2013). The aim of the least cost optimization was to determine the blending ratio of different surimi types to maintain a consistent quality at a least cost. The LP is a simple and useful mathematical tool to determine the optimum formula as long as the functions are expressed in the linear forms (Solow 2014, Ficken 2015, Skau et al. 2014). The simplicity of using LP can be found in that the coefficient of each variable of the linear function is simply determined by measuring the property at 100% of each variable, once the linearity of the function is approved,. Yoon et al. (1997a) proposed a systematic procedure to find an optimum formulation for surimi blending using LP. The procedure was widely adopted in the surimi and surimi seafood

industry to find an optimum ratio of surimi blend with different kinds and grades of surimi. However, the method includes limitations of its use: 1) the moisture content of each surimi lot to be blended was assumed to be the same and 2) the moisture content of the blended surimi was assumed to be the same as the each surimi lot used before blending. Such limitations were minor concerns in 1990's, because the moisture content of surimi lots were nearly identical, i.e., 74.5 ~ 75.5%. In addition, the fish species to produce surimi seafood were mainly either Alaska pollock or Pacific whiting. Most of manufacturers which produced surimi with Alaska Pollock or Pacific whiting Surimi well controlled the moisture content of final product and the deviation of moisture content was very little. However, these days many different kinds of fishes are available to produce surimi and also the moisture contents in the surimi are widely varied from 74.5% to 78.0% upon their grades. The LP methods proposed by Yoon et al. (1997a) have caused significant errors to find the least cost formulation using different surimi lots, especially produced in the South East Asia and China, due to the various moisture contents in the surimi. Especially the non-linear characteristics of moisture dependence of texture properties caused a great limitation of using LP to determine the optimum formulation for the final products which might include varied moisture contents.

Regardless of the importance, very few studies on the optimization techniques for surimi seafood were reported and mainly published in late 1990's (Kim et al. 2005, Yoon et al. 1997a, Yoon et al. 1997b, Hsu 1995). Besides Yoon et al. (1997a), most studies focused on describing the non-linear properties due to the interaction between surimi and other ingredients using response surface methodology and mixture design. The non-linear programming approaches provide detailed information to understand the interaction of each ingredient, but they require whole new set of experiments when a new ingredient is introduced to the ingredient system. Due to such complexity, the surimi seafood industry is reluctant to use the non-linear programming method for surimi blending.

In this study, to eliminate the great obstacle for using LP in the surimi and surimi seafood industry, a linearization method was mathematically developed. The objective of this study was to develop a new algorithm and a systematic procedure to use the LP to find a least cost formulation by blending surimi lots with various moisture contents.

2. MATERIALS AND METHODS

2.1. Surimi gel preparation

A high grade (A) and two medium grades (KA1 and KA2) of Threadfin bream (Itoyori) surimi were kindly provided by Pulmuone (Seoul, Korea). The high grade surimi (A) and two medium grades of surimi (KA1 and KA2) were produced from Thailand and Vietnam, respectively. Those surimi contained 4% sugar, 4% sorbitol, and 0.3% sodium tripolyphospates as cryoprotectants. Two blocks (10 kg each) of surimi were cut into small pieces (~ 1 kg each) and vacuum packed. Each surimi sample was stored at -18°C. The initial moisture content of each surimi lot was measured according to the AOAC method (1990). A constant level of salt (2%) was applied to the all treatments. The moisture contents of surimi gel were adjusted from 74.5% to 82% to evaluate their texture properties at various moisture contents. The amount of water added to adjust the moisture content in the surimi gel was calculated by solving the material balance (Eq. (1) and (2)):

$$\mathrm{SG} = \mathrm{S} + \mathrm{W} + \mathrm{ST} \tag{1}$$

$$\mathrm{MSG} = \mathrm{MS} + \mathrm{MW} + \mathrm{MST} \tag{2}$$

where SG is the mass % of the surimi gel, i.e. 100%, S, W, and ST are the mass % of surimi, water, and salt, respectively, and MSG, MS, MW, and MST are the mass % of moisture content of surimi gel, surimi, water and salt, respectively. In order to solve the material balance equation (1) and (2), it is necessary to determine the moisture content of each surimi lot and to decide the target moisture content of surimi gel.

The cost of surimi at target moisture content was calculated according to the material balance (Eq (3)):

$$UCS_{tms} = UCS_{ims} \times (SS_{tms}/SS_{ims}) \tag{3}$$

where UCS is a unit cost of surimi, SS is % of solid content of surimi, subscript tms and ims indicate a target moisture content and an initial moisture content, respectively.

For this study, the unit cost of water and salt were assumed to be zero for simplification. By solving equation (1), (2), and (3), it is possible to calculate the approximate cost of surimi gel at the target moisture content of surimi blend. This provides critical information to apply the LP to find the least cost formulation, because the objective function of the LP must include the cost of surimi blend at the target moisture content. This is one of the major differences from the LP method introduced in Yoon et al. (1997a). Previous approach used a constant moisture content which had to be the moisture content of each surimi lot. Practically the moisture content of surimi gels, i.e. the final product of surimi seafood, could be varied from 75% to 80%. In addition, the moisture content of each surimi lot could be varied as well. The LP must consider the target moisture content of final product and must adjust the cost of each surimi lot based on the target moisture. Consequently, the texture properties of each surimi lot has to be adjusted based on those at the target moisture content. The surimi gel was prepared according to Yoon et al. (1997a). The cooked gels were refrigerated for 12 hrs before the analysis of texture properties.

2.2. Measuring texture properties

To measure texture properties, cooled gels were held at room temperature for 2 hrs. Ten gels were cut into the cylindrical shape (length = 3 cm, diameter = 1.9 cm), and tested for the breaking force and the penetration distance by punch test (diameter of the probe = 0.5 cm, probe speed = 30 cm/min) using a rheometer (Fudoh, model NOrM-3002D rheometer, Tokyo, Japan), according to Hsu (1995).

2.3. Modeling

It has been reported that the failure shear strain or any texture properties related to the deformation ability of surimi gels showed a nonlinear function upon the moisture content, while the failure shear stress or texture properties related to the hardness of surimi gels showed a linear function upon the moisture content (Park 2013, Yoon et al. 1997a). In this study, the critical moisture content (CMC) was empirically defined as the moisture content where the slope of penetration distance function dramatically changed. Based on the observation from Yoon et al. (1997a), the function of the failure shear strain of surimi gels on the moisture contents showed two linear segments upon the moisture content. Empirical equations (Eq. (4), (5a) and (5b)) were developed to describe the moisture content dependence of the breaking force and the penetration distance of each surimi lot, respectively:

$$\text{Breaking force} = F_i \times MC + F_i^0 \tag{4}$$

$$\text{Penetration distance} = D1_i \times MC + D1_i^0, at\ MC \leq CMC \tag{5a}$$

$$\text{Penetration distance} = D2_i \times MC + D2_i^0, at\ MC > CMC \tag{5b}$$

where F_i and F_i^0 are the slope and the intercept of breaking force function of i_{th} surimi lot, respectively; $D1_i$ and $D1_i^0$ are the slope and the intercept of penetration distance of i_{th} surimi lot when the moisture content is lower than CMC, respectively; $D2_i$ and $D2_i^0$ are the slope and the intercept of penetration distance of i_{th} surimi lot when the moisture content is higher than CMC, respectively. If a surimi lot did not show a CMC, the moisture content dependence can be described by eq. (5a). Each empirical model was developed by conducting the linear regression analysis from experimental data averaged from 10 measurements.

2.4. Optimization

Once the breaking force and the penetration distance of each surimi lot at the target moisture content were determined from eq. (4) and equation (5a and 5b) respectively, the breaking force and the penetration distance of a surimi blend at the target moisture content can be expressed as linear canonical models (Yoon et al. 1997a):

$$\text{Breaking force of surimi blend} = \alpha_1 X_1 + \alpha_2 X_2 + \cdots + \alpha_n X_n \tag{6}$$

$$\text{Penetration distance of surimi blend} = \beta_1 X_1 + \beta_2 X_2 + \cdots + \beta_n X_n \tag{7}$$

where X_n is the ratio of i_{th} of surimi lot adjusted to the target moisture content, α_n is the breaking force of i_{th} surimi lot at the target moisture content which were calculated from equation (4), β_n is the penetration distance of i_{th} surimi lot at the target moisture content which were calculated from equation (5a) and (5b). The equation (6) and (7) can be incorporated into the LP model as constraint functions.

The objective function which represents the cost of surimi blend is expressed by a linear canonical function (Eq. (8)) and the coefficient of each term indicating the unit cost of surimi lot at the target moisture content.

$$\text{Cost of surimi blend} = C_1 X_1 + C_2 X_2 + \cdots + C_n X_n \tag{8}$$

where C_n = the unit cost of i_{th} surimi lot at the target moisture content which were determined from equation (3).

The least cost linear programming (LCLP) model for surimi blending includes an objective function (Eq. (8)), decision variables (X_i, the ratio of each surimi lot), and constraint functions (Eq. (6) and (7)). The objective function of LCLP was set to be minimized, while the constraint functions and X_i are greater than constraint values and 0, respectively. In this study, the constraint values of the breaking force and the penetration distance were set at 250 g and 0.5, respectively, according to the target value of commercial surimi seafood product at 78% of target moisture content. The algorithm of the optimization procedure developed in this study was shown in Fig. 1. The optimization procedure of the LCLP for surimi blending was executed using both MS-Excel 2013.

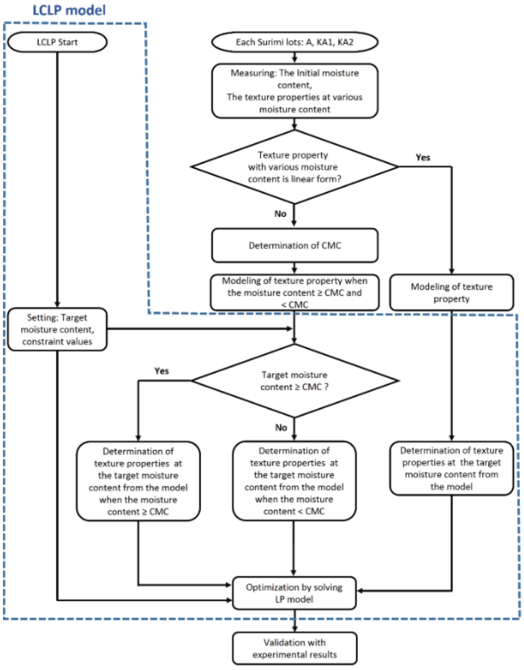

Figure 1: Algorithm of the Optimization Procedure for Surimi Blending Using Least Cost Linear Programming (LCLP).

Experimental values of the breaking force and the penetration distance of a surimi blend formulated based on the LCLP solution were compared with those values predicted from LCLP simulation for validation. In addition, the solutions from two different methods, such as the conventional algorithm and the novel linearization algorithm were compared.

2.5. Sensitivity analysis

Sensitivity analysis is commonly used to compute the sensitivity of performance measures with respect to design variables (Borgonovo and Plischke 2016, Deif, 2014, Sidhu et al. 2014). Sensitivity analysis was conducted according to Saltelli et al. (2008):

$$V = f(X, Y) \tag{9}$$

V is the measure of the value of the decision that is made, X is the variable which are subject to control by X_i, Y is the constraints, which affect the performance but which are not subject to control by X_i within the scope of the problem as defined, and f is the functional relationship between $\mathrm{X_i}$ and performance factors, and the dependent variable V. A detailed description of the methods applied to analyze the sensitivity result can be found in Saltelli et al. (2008).

2.6. Statistical analysis

All experiments were triplicated and the ANOVA in MS-Excel-2013 was used for the analysis at the statistical significance of $p < 0.05$.

3. RESULTS AND DISCUSSION

3.1. Effect of moisture on the breaking force of surimi gel

The addition of water to surimi seafood is necessary to maintain acceptable texture and to minimize cost of raw materials. Generally, in surimi seafood industry, the first step to evaluate the quality of surimi lots are 1) to measure the moisture content of surimi lots and 2) to measure the texture properties at various moisture contents. The moisture contents of grade A, KA1, and KA2 used in this study were determined to be 75.0 (±0.1), 77.1 (±0.4), and 76.6% (±0.5), respectively. Changes of breaking force of each surimi lot at varied moisture content (74.4 to 82%) were shown in Fig. 2. The lowest moisture content applied to KA1 and KA2 were 77 and 76%, respectively, since the initial moisture content of KA1 and KA2 were 77.1 and 76.6%, respectively. The highest moisture content applied to KA2 was 81.1%, because gels were not formed when the moisture content was higher than 81.1%. The breaking force of A, KA1, and KA2 linearly decreased from ~503.1 to ~78.9 g (r^2=0.99), from ~225.7 to ~59.9 g (r^2 =0.99), and from ~86.5 to ~33.85 g (r^2 =0.95), respectively, as moisture content increased. The breaking force or texture properties related to the hardness, such as failure shear stress and failure compressive force, indicate the quantity of protein networks in the gel. As moisture content increased, the concentration of protein in the gel decreased, so that the probability to form 3 dimensional networks from the myofibrillar protein decreased. Such moisture content dependence of surimi gel can be explained based on the classic rubber elastic theory (Treloar 1975, Yoon et al. 2004a, Yoon et al. 2004b).

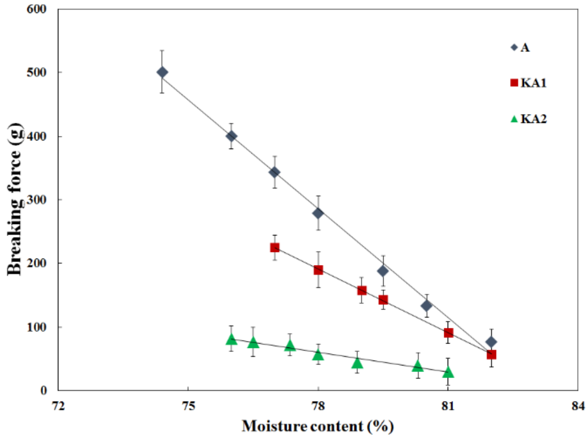

Figure 2: Effect of Moisture Content on the Breaking Force of Threadfin Bream Surimi Gels. Markers Indicate the Experimental Data and the Lines Were Drawn Based on the Values Calculated from the Model Equations Developed by Equation (4).

It is worth to mention that the breaking force values of KA2 were lower than those of KA1 even though the initial moisture content of KA2 was lower than that of KA1. It might be because KA2 included more solid contents, such as sorbitol and sugar, than KA1. It implies that the quality of surimi should be evaluated by measuring not only the moisture content but also the texture properties at varied moisture content. Linear models to describe the moisture content dependence of the breaking force of each surimi lot were developed by linear regression analysis. The coefficients, intercept, and R^2 values of each model were summarized in Table. 1, and the lines shown in Fig. 2 were drawn based on the data calculated from model equations. Measuring texture properties at various moisture content is one of the most important procedures to inspect the quality of surimi lots, and the texture behavior and the models might provide useful insights to develop final product formula with surimi lots for the manufacturers.

3.2. Effect of moisture on penetration distance of surimi gel

Penetration distance or texture properties related to the deformation, such as failure shear strain or failure strain, of surimi gels commonly refers to as an indicator of protein quality (Park 2005). In general, such deformation ability was not affected within a certain range of moisture content (Park 2005, Yoon et al. 1997). Changes of penetration distance at varied moisture content were shown in Fig. 3.

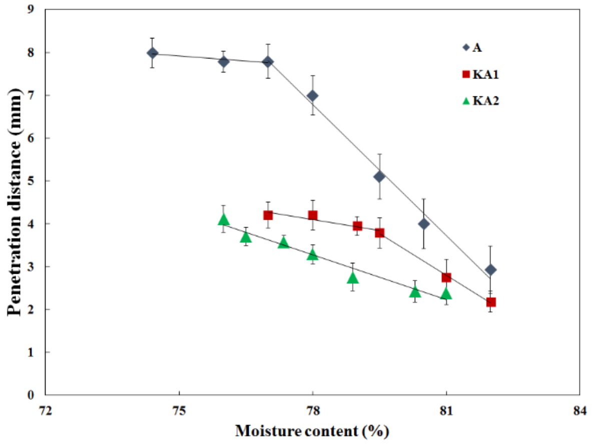

Figure 3: Effect of Moisture Content on the Penetration Distance of Threadfin Bream Surimi Gels. Markers Indicate the Experimental Data and the Lines Were Drawn Based on the Values Calculated from the Model Equations Developed by Equation (5a) and (5b).

As shown in Fig. 3, it is very clear that there were specific moisture contents at which the penetration distance was not affected by increasing moisture content. In this study, the moisture content where the penetration distance begins to decrease as increase of moisture content was defined as the critical moisture content (CMC) of each surimi lot. In this study, the purpose of determining CMC was to develop empirical models to describe changes of penetration distance on the moisture contents. The penetration distance of A was not affected until the moisture content was 77%, but at 78% of moisture content the breaking force began to decrease dramatically as increase of moisture content. For KA1, the maximum values were maintained up to 79% and, at 79.5% of moisture content, the values dropped as the moisture content increased. However, the KA2 did not show the CMC in the given range of moisture content. To describe the moisture content dependence of penetration distance, eqn. 5a and 5b were applied with CMC of each surimi lot. The unit cost, the initial moisture content, the CMC, the coefficient, and the intercept used in the LCLP model were summarized in Table 1. The lines shown in Fig. 3 were drawn based on the data calculated from eqn. 5a and 5b, and showed good fittings of experimental results. This modeling approach could be the first time ever challenged before. The empirical equations to predict the penetration distance value will greatly contribute to develop surimi seafood products, because the deformation ability is a unique texture property reflecting the protein quality and could not be improved by adding other ingredients, such as wheat flour, unlike the breaking force or texture properties related to the hardness.

Table 1: The Properties of Each Surimi Lot, such as the Unit Cost, Breaking Force, the Penetration Distance, IMC and CMC Used in the LCLP Model.

		A			KA1			KA2	
Unit cost ($/kg)		2.80			1.30			1.35	
IMC (%)		75.0			77.1			76.6	
CMC (%)		77			79			N.D.	
	Coef.	Int.	R^2	Coef.	Int.	R^2	Coef.	Int.	R^2
B.F. (g)	-55.97	4656.2	0.99	-33.18	2780.9	0.99	-10.52	885.7	0.96
P.D. (mm) (MC ≤ CMC)	-0.24	26.1	0.70	-0.15	15.6	0.82	-0.35	30.5	0.95
P.D. (mm) (MC > CMC)	-1.01	85.9	0.98	-0.63	54.0	0.99	N.D.	N.D.	N.D.

(IMC = initial moisture content, CMC = critical moisture content, MC = moisture content, Coef. = coefficient, Int. = intercept, B.F. = breaking force, P.D. = penetration distance, N.D. = not detected)

3.3. Optimization using LCLP model

The constraint functions and objective function to be incorporated in the LCLP model were developed according to equation (3), (4), (5a) and (5b) (Table 2). The coefficient of each function indicated the properties, such as the breaking force, the penetration distance, and the cost of surimi gel, at the target moisture content set at 78% for this study.

Table 2: Summary of the Least Cost Linear Programming (LCLP) Model.

LCLP Model					
Surimi type		**A**	**KA1**	**KA2**	
Objective function	**Unit price ($/kg) (adjusted at target moisture content)**	2.46	1.25	1.27	**Minimizing Σ unit cost**
Constraint function					**Constraints**
	B.F. (g)	290.5	192.9	65.1	≥ 250.0
	P.D. (mm)	7.1	3.9	3.2	≥ 5.0

(B.F. = breaking force, P.D. = penetration distance)

The coefficients of each term used in the constraint function for the breaking force and the penetration distance were calculated from the model equations to describe the changes of breaking force and penetration distance at varied moisture contents (Table 1). Solving the LP model is basically finding a solution of a system of simultaneous of inequality equations (Eppen et al 1993, Hiller and Frederick 2010). In this study, the system of simultaneous inequality equations incorporated in the LCLP model summarized in Table 2 was:

Objective function:

$$\text{Cost of surimi blend} = 2.24 \times (\%\text{ of A}) + 1.13 \times (\%\text{ of KA1}) + 1.15 \times (\%\text{ of KA2}) \qquad (10a)$$

Constraint functions:

$$\text{Breaking force} = 290.5 \times (\%\text{ of A}) + 192.9 \times (\%\text{ of KA1}) + 65.1 \times (\%\text{ of KA2}) \geq 250 \qquad (10b)$$

$$\text{Penetration distance} = 7.1 \times (\%\text{ of A}) + 3.9 \times (\%\text{ of KA1}) + 3.2 \times (\%\text{ of KA2}) \geq 5 \qquad (10c)$$

Nonreactivity constraint:

$$X_A, X_{KA1}, X_{KA2} \geq 0 \qquad (10d)$$

where X_i = the ratio of each surimi lot adjusted to the target moisture content.

After solving the system of equation (10a), (10b), (10c) and (10d), the results of simulation of the LCLP model (Table 3) indicated that, when 58.5% of A and 41.5% of KA1 are mixed together, the surimi blend will have the least cost ($1.96/kg) with 250 g of the breaking force and 5.78 mm of the penetration distance. Because the coefficients of each term in the objective function and the constraint functions were adjusted at the target moisture content, the solution of LCLP model can have more feasibility to be applied in the surimi seafood industry. The long time limit of use of LP model, since proposed by Yoon and et al. (1997a), was overcome and now the LCLP can be practically used in the surimi seafood industry.

Table 3: The Results of LCLP Simulation.

Optimum solution					
Results of simulation	**Unit price ($/kg)**		1.96		
	B.F. (g)		250.0		
	P.D. (mm)		5.78		
		Surimi type	**A**	**KA1**	**KA2**
	Ratio of surimi (%)		58.5	41.5	0

(B.F. = breaking force, P.D. = penetration distance)

Conventional simulation, which is a linearization method without CMC, was also conducted to compare with the result of simulation of the LCLP model. The results of conventional simulation indicated the surimi blend will have the least cost ($1.96/kg) with 250g of the breaking force and 5.40 mm of the penetration distance. The breaking force and the penetration distance values of the surimi blend formulated according to the simulation result (A = 58.5%, KA1=41.5%, moisture content 78%) were compared with those of simulation results (Fig. 4a & b). The experimental values of breaking force and the penetration distance were 241.8 g (±9.05) and 6.18 mm (±0.77), respectively. There were no significant differences between the experimental values and the results of simulation of the LCLP model ($p < 0.05$), in contrast to the results of conventional simulation.

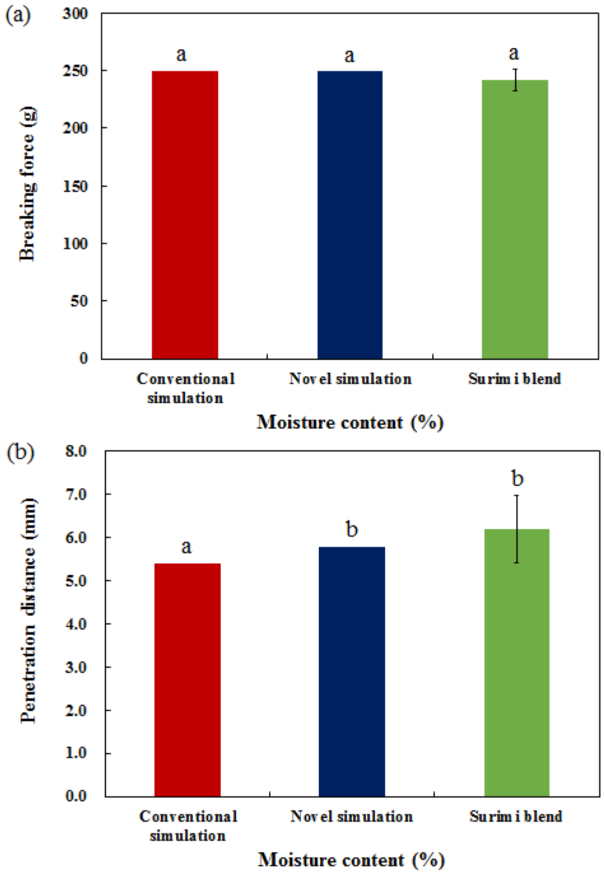

Figure 4: Comparison of the Breaking Force (5a) and the Penetration Distance (5b) Values between Simulation Result and Experimental Results of Surimi Blend. The Surimi Gel Was Blended Based on the Ratio Calculated by the LCLP.

Since the failure shear strain or any texture properties related to the deformation ability of surimi gels showed a nonlinear function upon the moisture content (Park and Yoon 2015, Park 2013, Yoon et al. 1997a), linear programming for surimi gels could not be used with various moisture contents. Novel algorithm was successfully applied to linearize the function of the penetration distance of surimi gels on the moisture contents.

3.4. Sensitivity analysis

Sensitivity analysis based on the simulation results using the LCLP model was conducted to evaluate the optimum solutions (Table 4). Critical price indicated the maximum price of each surimi type to be included in the surimi blend. Surimi lots, such as A and KA1, maintain the ratio of surimi blend within the allowable range of each surimi. In order to include KA2 in surimi blend, the price of KA2 should be lower than \$0.93. To estimate the cost variation of surimi blend depending on the constraints, the sensitivity of constraints was also analyzed as shown in Table 4. As the constraint of breaking force decreases by 1g, the price of surimi blend can decrease by \$0.012 within 226.2 to 290.5 g of breaking force, whereas the price of surimi blend do not depend on the constraint of penetration distance when it is lower than 5.78mm. The information from the sensitivity analysis provides a quantitative estimate for desirable design changes, although a systematic experimental design is not carried out. Based on the sensitivity results, the formula developer can decide the amount of variable changed to improve the performance. In addition, sensitivity information can provide answers to “what if” questions by predicting performance measure perturbations when the perturbations of design variables are provided (Choi and Kim 2006).

Table 4: The Sensitivity Analysis of LCLP Simulation.

Sensitivity analysis			
Surimi type	**A**	**KA1**	**KA2**
Optimized ratio of surimi (%)	58.5	41.5	0
Critical price (\$/kg)	-	-	0.93
Allowable range (\$/kg)	> 1.88	< 1.64	< 0.93
Constraint	**B.F. (g)**		**P.D. (mm)**
Optimized value	250.0		5.78
Cost variation per unit (\$/g or mm)	0.012		0
Allowable range (\$/g or mm)	226.2-290.5		< 5.78

(Critical price = Maximum price of each surimi type to be included in surimi blend)

3.5. Texture map from breaking force and penetration distance

The texture map of surimi gel was first time developed and published by Park (2002), based on the failure shear stress and failure shear strain values of surimi gels, and widely used for surimi industry and surimi seafood industry to control the quality of surimi lots as well as to develop a new product by blending of surimi lots and adding ingredients. Fig. 5A was drawn from experimental values used in this study. The size of bubble indicates the unit cost of each surimi gel at various moisture content and optimized surimi blend. The box located at the upper left side referred to the cost of surimi gel in the bubble. As shown in Fig. 5, as the moisture content increased, each surimi gel moved to the south-west direction on the texture map and the bubble size became smaller.

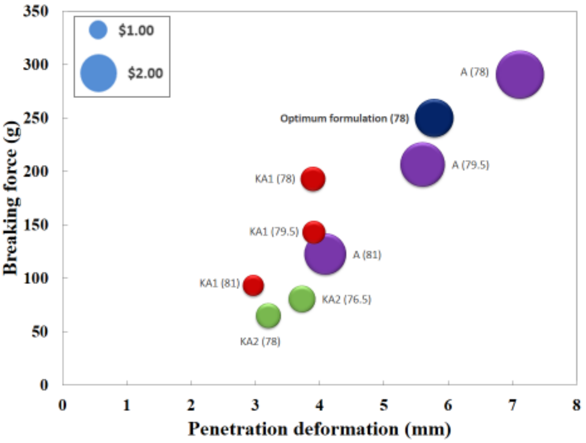

Figure 5: Texture Map Created from the Unit Cost, the Breaking Force and the Penetration Distance. The Location of the Bubbles Indicates the Texture Property of Surimi Gels with Various Moisture Content Described in the Parenthesis. The Size of Bubbles Indicates the Unit Cost of Each Surimi Gel.

The texture map developed in this study is distinguished from that created by Park (2002) in terms of followings: 1) using breaking force and penetration distance instead of failure shear stress and failure shear strain for practical use for surimi and surimi seafood industry, and 2) using a bubble chart which can be created in the commercial spread sheet software to compare the change of cost as well as the texture properties of surimi blend simultaneously. The texture map incorporated with the LCLP developed in this study might provide full of information of using surimi lots at various moisture content to control the texture properties as well as the cost of surimi gels.

4. CONCLUSION

Optimization technique using LCLP model was successfully applied to determine the least cost blending of surimi types. The limit of practical use of LP for surimi blending had existed because the unit cost and texture properties of surimi blend at various moisture contents were unsure to be incorporated into the LP model due to the non-linearity of deformation related property, such as the penetration distance. Empirical models developed in this study showed a good fitness of the changes of texture properties of surimi lot at various moisture content, and these models enabled to use the optimization technique to determine the optimum ratio of surimi blend as well as to predict the texture properties of surimi blend at the lowest cost. Sensitivity analysis was used to provide an additional information when the perturbations of design variables are provided. The systematic procedure to use LCLP model and the texture map introduced in this study will be very practical tools for surimi seafood industry to maintain the consistency of product quality in fluctuation of surimi price and unstable supplying of specific species of fish at the least cost and to make a decision for surimi purchasing.

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