Mixed nonlinear modelling in food engineering: determination of the salting time of boneless dry-cured Cerretan hams

Xavier Espuña[1], Lesly Acosta[1], Josep A. Sanchez-Espigares[1], Xavier Tort-Martorell[1]

[1] Department of Statistics and Operations Research, Polytechnic University of Catalonia, Barcelona, Spain

E-mail for correspondence: `lesly.acosta@upc.edu`

Abstract: A great challenge in producing a good cured ham is to reduce the variability of the salt content between pieces of ham and to obtain homogeneity in terms of flavour and quality in general. This reduction in variability would imply a reduction in salt content, a recommendation of the World Health Organisation (WHO, 2007). This work focuses on the salting process of boneless Cerretan hams and our aim is two-fold: 1) to build a mathematical model that enables —through predictions— the reduction of the variability of salt between pieces, and 2) to determine an 'appropriate' salting time for each ham.

We propose a novel strategy within the ham industry to determine appropriate hams extraction time from the salting pile and we postulate that it is statistically and practically advantageous to the habitual hams extraction strategy (removal based on fat and weight classification and all at the same time).

We build a non-linear mixed (NLM) model that, according to the final salt uptake target of 1.7%, would allow to decide each ham extraction time depending on the initial weight and fat, plus the weight decrease on day one. This model has to be applicable in industrial production, albeit in an approximate form. To account better for the salting-time estimated uncertainty, we run a nonparametric bootstrap. A further aim is to extrapolate the use of the NLM modelling methodology and proposed novel extraction strategy to other boneless hams industrial production systems in Europe.

Keywords: NLM model; Bootstrap; Cured-ham; Salt content; Extraction time.

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1 Introduction

Various European countries have specialities of cured hams that are salted, dried and matured off the bone, such as Speck Alto Adige, Schwarzwälder Schinken, Tyrolean Speck, Culatello di Zibello from Italy as well as the Cerretan ham in Spain.

A great challenge in producing a good cured ham is to reduce the variability of the salt content between pieces of ham and to obtain homogeneity in terms of flavour. This reduction in variability would imply a reduction in salt content, a recommendation of the World Health Organisation (WHO, 2007), although a too low salt content could also increase pastiness defects in the texture of the ham that usually occurs at a low threshold of 1.4%; see, e.g., Toldrá et al (1997), Coll-Brasas et al. (2019), and Martín-Gómez et al. (2022).

This work focuses on the salting process of boneless Cerretan hams and our final goal is to propose a NLM model that, according to the average salt uptake target of 1.7%, would allow us to decide on the appropriate date of removal of the hams from the salting pile depending on the initial fat and weight, plus the weight decrease on day one. This model has to be applicable in industrial production, albeit in an approximate form, to estimate the salt pile removal time. We also run a nonparametric bootstrap study, to account better for the estimated salting-time uncertainty.

2 Materials and methods

2.1 Ham samples and Salting process

Twenty-seven lean Cerretan hams were selected from a nearby slaughterhouse with an initial pH between 5.8–6 (García-Rey et al., 2004). The hams had a fat percentage, as measured by the Multiscan X-ray technology, of 15% to 24%. Each ham was weighed, and measured for fat. In the salting phase, first, a specific seasoning mixture is used (Gratacos et al., 2013). The hams are left to stand for a day to absorb the salt and then covered with recycled, moist (4%-5%) salt (T-3 sea salt) at a temperature of 2ºC to 4ºC, and at a humidity of 85% to 95%. Lastly, they are placed on a flat surface in a container that lets the exudate run off.

The time starts counting when the hams were covered with the recycled salt and after 24 hours, the salt content is measured and also the weight to determine its decrease on day one. The hams continue to be measured in terms of salt uptake over time during seven days, since we study the salt acquisition curve up to the moment of saturation. Note that hams are normally salted for 0.5 days per kg of initial weight, which would mean that they are salted for around 4 days. In this study, however, they were left in the salting pile for 7 days, since it is of interest to study the salt acquisition curve up to the moment of saturation.

2.2 Nonlinear mixed modelling

To study the daily evolution of the salt content of each of the 27 sampled Cerretan hams pieces, which would allow to model the expected value of salt content and characterize its variability, the NLM modelling statistical methodology is used (Pinheiro and Bates, 2000). Specifically, we built a NLM model of logistic-type to predict the amount of salt that each ham will have at each point in time. A general expression of the logistic NLM model that, apart from time (days), depends on three fixed parameters $(\beta_1, \beta_2, \beta_3)$' and three random effects b_{1i}, b_{2i} and b_{3i} on each parameter is given by:

$$\begin{aligned} Y_i &= f(t, \phi_i) + \epsilon_i, \\ &= \mu_i(t) + \epsilon_i \quad \epsilon_i \sim N(0, \sigma^2 I) \quad i = 1, \ldots, k \end{aligned}$$

where

$$\mu_i(t) = \frac{\Phi_{1i}}{1 + \exp(-\frac{t - \Phi_{2i}}{\Phi_{3i}})}.$$

and

$$\phi_i = \begin{pmatrix} \Phi_{1i} \\ \Phi_{2i} \\ \Phi_{3i} \end{pmatrix} = \begin{pmatrix} \beta_1 \\ \beta_2 \\ \beta_3 \end{pmatrix} + \begin{pmatrix} b_{1i} \\ b_{2i} \\ b_{3i} \end{pmatrix}.$$

The parameter Φ_{1i} represents the salt saturation and the parameter Φ_{2i} the time it takes to reach half of the saturation value. The parameter Φ_{3i} tells us how steep is the central part of the logistic S-shaped function, i.e. the instantaneous speed at which the salt is absorbed.

The vector of random effects $(b_{1i}, b_{2i}, b_{3i})'$ has a normal distribution with $b_i \sim N(0, \Sigma_b)$. The fixed effects vector of the parameters could be expressed as a linear function of other variables.

The general procedure, using the data of the 27 sampled ham pieces, for building a valid model to predict the salt average amount that each ham will have at each time point, and later to estimate when to remove the ham from the salting pile is:

1. Describe the time evolution of the 7-day salt measurements for each of the 27 sampled hams; in this case the observed S-shaped behaviour suggested the fit of a logistic NLM model.

2. Fit the logistic NLM model with salt-uptake as an outcome and only time as an independent variable. In this case, a strong correlation between the parameters Φ_{2i} and Φ_{3i} was observed and to avoid over-parameterization we get a reduced model by expressing Φ_{2i} in terms of the the parameter Φ_{3i}.

3. Fit an NLM model considering, apart from time as an independent variable, the covariates initial fat and weight, plus the weight decrease on day one. This model should be simplified to obtain a final model including only significant terms.

4. Validate the model and report the estimation results. In this case, the fitted model was properly validated (results not shown).

5. With the final model, predict the salt uptake per ham and also determine the extraction time from the salting pile required to reach the fixed target salt average content of 1.70%. A limitation, however arises, because it would not be industrially feasible to extract the hams at every predicted time of day; it would involve excessive labour costs.

6. Propose as a solution the strategy of considering five possible predefined extraction points in time (days: 1, 1.5, 2, 2.5 and 3) at which hams (as a percentage per day) could be removed from the salting pile. With this strategy, we improved the habitual hams extraction strategy (removal based on weight and fat similarities, and all at the same time) in terms of bias and uncertainty.

2.3 Nonparametric bootstrap

To better quantify the uncertainty of the salting time of extraction, we run a nonparametric bootstrap (Davison, A. C. and Hinkley, 1997). The idea is that the 1000 simulated data would have similar characteristics to our 27 experimental units and based on these trajectories, the time at which the target 1.7% salt content is reached can be estimated, and also the empirical distribution of those extraction salting times. This distribution, being per se continuous, is discretized using the five predefined extraction points in order to plan the removal of hams from the salting pile based on a feasible industrial production plan. This discretization will produce a small increase in the variability of the measured salt in removed hams, but despite that, the obtained uncertainty will be lower than the one obtained with the habitual hams extraction strategy.

References

Coll-Brasas, E., Arnau, J., Gou, P., Lorenzo, J.M., García-Pérez, J.V., and Fulladosa, E. (2019). Effect of high pressure processing temperature on dry-cured hams with different textural characteristics. *Meat Science*, **152**, 127–133.

Davison, A. C. and Hinkley, D. V. (1997). Bootstrap Methods and their Application. *Cambridge Series in Statistical and Probabilistic Mathematics*. Cambridge University Press.

García-Rey, R.M., García-Garrido, J.A., Quiles-Zafra, R., Tapiador, J., and Luque-de-Castro, M.D. (2004). Relationship between pH before salting and dry-cured ham quality. *Meat Science*, **67(4)**, 625 – 632.

Gratacós-Cubarsí, M., Sárraga, C., Castellari, M., Valero, A., García Regueiro, J., and Arnau, J. (2013). Effect of ph24h, curing salts and muscle types on the oxidative stability, free amino acids profile and vitamin b2, b3 and b6 content of dry-cured ham. *Food Chemistry*, **141(3)**, 3207 – 3214.

Martín-Gómez, A., Segura-Borrego, M.P., Ríos-Reina, R., José Cardador, M., Callejón, R.M., Morales, M.L., Rodríguez-Estévez, V., and Arce, L. (2022). Discrimination of defective dry-cured Iberian ham determining volatile compounds by non-destructive sampling and gas chromatography. *LWT*, **154**, article no. 112785.

Pinheiro, J. and Bates, D.M. (2000). Nonlinear mixed-effects models: basic concepts and motivating examples. *Mixed-effects models in S and S-Plus.* Springer.

Toldrá, F., Flores, M., and Sanz, Y. (1997). Dry-cured ham flavour: enzymatic generation and process influence. *Food Chemistry*, **59(4)**, 523 – 530.

WHO. (2007). Reducing salt intake in populations: Report of a WHO forum and technical meeting. *World Health Organization Geneva, Switzerland.*