# Development of multi-criteria analysis approach considering food quality and energy consumption: Application to production process of puff pastry

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Manuscript ID: 250
DOI: 10.18462/iir.icr.2019.0250

# Development of multi-criteria analysis approach considering food quality and energy consumption: Application to production process of puff pastry

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## ABSTRACT

The preservation of perishable food *via* cold supply chain is essential to extend shelf life and ensure food safety. However, the use of refrigeration processes involves energy consumption with economic and environmental impact. Increasing the temperature set point in cold equipment could save energy, but the global cost may increase due to food waste or safety issues.

This study focuses on the modeling of the energy consumption of cold facilities, food temperature and bacterial growth in a puff pastry plant. Main components of production line (kneader, cooling spiral and cold room) were considered. Different scenarios were tested to evaluate the impact of operating conditions (setting temperature and duration) on energy consumption, food waste and food safety.

This methodology helps manufacturers in decision making to optimize operating conditions and reduce energy consumption with a limited impact on food waste and safety.

Key words: Multi-criteria analysis, energy consumption, temperature, food quality, refrigeration process

## 1. INTRODUCTION

Refrigeration is crucial to ensure optimal preservation of perishable food products, extend shelf life and provide consumers with safe food of high organoleptic quality. The use of refrigeration for food is in constant growth in developed and developing countries and this requires important energy consumption to cool down and to maintain food product at desired temperatures. In EU states, cooling and freezing represent about 30 % of electricity consumption in the food industry, a relatively high rate compared to other industrial sectors.

Public authorities and industrials are looking for solutions to reduce the impact of the refrigeration facilities such as implementing new regulation to limit the use of high GWP (Global Warming Power) fluids (Anonymous 2014), installation of doors on opened display cabinet in supermarkets (Anonymous 2015), developing more efficient new technologies.

Another solution to reduce the impact of refrigeration process consists in modifying the operating conditions, for example, by increasing the thermostat setting temperature of refrigerated equipment (Duret et al. 2019). However, because of accelerated product quality alteration caused by higher temperatures, the global cost due to food waste or safety issues may increase (Zanoni and Zavanella 2012). While numerous experimental and numerical studies were conducted on food product temperature and energy consumption in cold chain facilities: refrigerated transport (Merai et al. 2018), storage cold room (Duret et al. 2014, Gruyters et al. 2018), display cabinet (Chaomuang et al. 2017, Ben-abdallah et al. 2018) and domestic refrigerator (Laguerre and Flick 2010), few studies were conducted on food plants (Lecoq et al. 2017, Parpas et al. 2017, Parpas et al. 2018). Moreover, these studies focused on surface drying or on air distribution in food facilities but do not address the relationship between food plant operating conditions, energy consumption, food temperature and food quality.

The objective of this study is to propose an original multidisciplinary approach linking prediction of food temperature, food quality and energy consumption of refrigeration processes in a food plant. The proposed methodology was applied to a puff pastry plant. The daily-recorded temperatures and energy consumption provided by an industrial manufacturer and the data measured on site by our team were used in model development and validation. The developed models were used to study the influence of operating conditions on the product temperature, quality and energy consumption of cold facilities. In such a way, the potential efficient measures to reduce energy consumption with a limited impact on food quality can be identified.

## 2. MATERIALS AND METHODS

### 2.1 Product, production line and plant description

The studied product is a puff pastry of 0.23 kg per unit. The thermal heat capacity is 2760 J.kg$^{-1}$°C$^{-1}$. The production line described in Fig. 1 includes kneading, folding and lamination, cutting, wrapping, cooling spiral, packing and storage in a cold room. A pending step between packing and storage in the cold room is also included. The product flows through the different steps by conveying line. Rooms' dimensions, volume, operating conditions are presented in Table 1. The air is distributed in the process room by blowing through textile ducts. Cold air is provided in the cooling spiral and in the cold room by direct expansion coils.

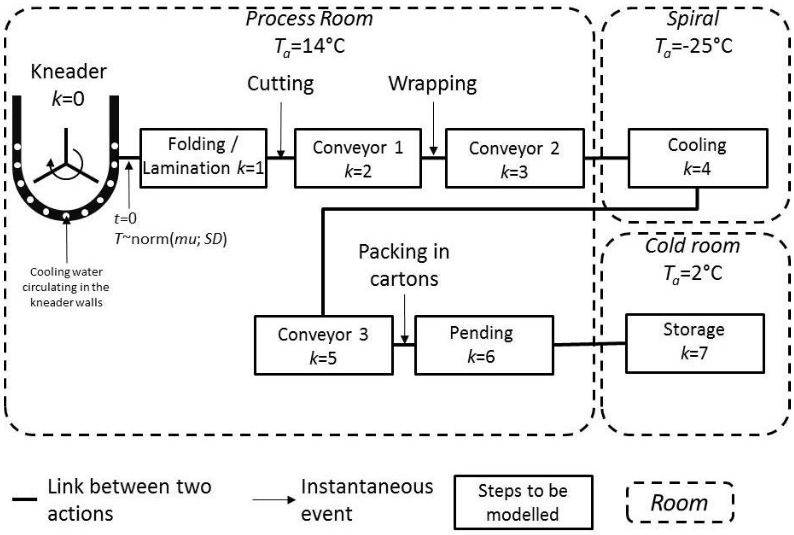


**Figure 1: Overview of the food plant**

**Table 1. Dimensions (estimated from site plan) and current operating conditions (data provided by the manufacturer)**

| Room | Floor Surface Area (m²) | Wall Surface Area (m²) (including floor and ceiling) | Volume ($m^3$) | Setting temperature (°C) | Air distribution system |
|---|---|---|---|---|---|
| Process | 2325 | 5600 | 10460 | 14°C | textile ducts |
| Spiral | NE* | NE* | NE* | -25°C | Direct expansion coils |
| Cold room | 320 | 970 | 1450 | 2°C | Direct expansion coils |

* (NE) Non Estimated

## 2.2. Model development

Products were modeled individually for each production step from the kneader (*k*=0) to the cold room (*k*=7). The product temperature was assumed uniform at each step. Because of a short duration at each step, water transfer was considered as negligible. A discrete event framework was used to describe the consecutive element of the processing line (i.e. kneader, conveyor, cooling spiral...). In such a manner, the inclusion of additional events or the modification of event sequences is possible, for example, refrigeration process breakdown or periods of standstill which are difficult to manage. A first-order Monte Carlo simulation was implemented to describe the variability of the operating conditions such as product initial temperature, product cooling rates in the storage cold room. The model was implemented in the Matlab software R2016b (MathWorks Inc., Natick, MA, USA) and is available on request to the corresponding author.

### 2.2.1. Product temperature

#### *2.2.1.1. Product initial temperature.*

According to the manufacturer, dough temperature during and after the kneading (*k*=0) is highly heterogeneous and depends on many parameters such as the external temperature $T_{ext}$, the process room temperature $T_{a,p}$ and the temperature of the cooling water flowing in the double envelope of kneader walls $T_{water}$. These operating condition temperatures were recorded every 10 minutes over 1 year (manufacturer data, 51408 measurements) while one temperature per batch over 1 year was recorded (manufacturer data, 20899 measurements). Because of the difficulty to develop heat transfer model to predict the product temperature due to the complexity of the kneader (mixing of several ingredients of different initial temperature, heat generation because of reactions between ingredients and mechanical energy during mixing with variable speeds), a statistical approach was used assuming a normal distribution of the dough temperature of one batch after the kneading (*k*=0). Considering that conduction and convection are the main heat transfer modes while radiation is negligible in the kneader, a linear correlation was considered between the batch average temperature after kneading $\overline{T}_0$ and the other known temperatures $(T_{ext}, T_{a,p}, T_{water})$. For these reason, the three known temperatures were considered as fixed effects while the batch was considered as a random effect to predict the initial dough temperature after the kneading (*k*=0).

$$T_0 \sim N\left(\overline{T}_0\left(T_{a,p}, T_{ext}, T_{water}\right), SD\right) \qquad \text{Eq. (1)}$$

Where $\overline{T}_0$ is the batch average temperature (Eq. 2) and SD the standard deviation (*SD*=1.2).

$$\bar{T}_0 = 16.82 + 0.12 \times T_{ext} + 0.20 \times T_{a,p} + 0.10 \times T_{water} \quad \text{Eq. (2)}$$

*2.2.1.2. Product temperature change along the production line.*

For each step of the production line from *k*=1 to *k*=7, the product temperature $T_k(t)$ tends to reach the ambient temperature $T_{air,k}$. The product temperature evolution can be represented by Eq. 3.

$$T_k(t) = T_{air,k} + \left(T_{0,k} - T_{air,k}\right) \times e^{-t/\tau_k} \quad \text{Eq. (3)}$$

where $T_{0,k}$ the product initial temperature at the step *k*, *t* the time and $\tau_k$ the characteristic time of the product in the step *k*. The characteristic time $\tau_k$ is defined as:

$$\tau_k = {}^{m \times C}\!/_{h_k \times A_k} \quad \text{Eq. (4)}$$

With *m* product mass (kg), *C* product heat capacity ($J.kg^{-1}.°C^{-1}$), $h_k$ convective heat transfer coefficient between product and air at step *k* ($W.m^{-2}.°C^{-1}$), $A_k$, exchange surface area between product and air at step *k*.

For certain steps where the experimental product temperature change was available (Fig. 2a), the characteristic times of the product $\tau_k$ was determined from the slope of the dimensionless temperature (T*, $T^* = \frac{T_{p,k}(t) - T_{0,k}}{T_{air,k} - T_{0,k}}$) as a function of time (Fig. 2b).

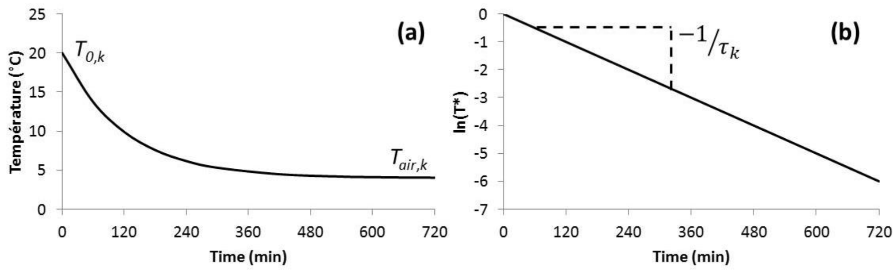


**Figure 2: Illustration of the method to calculate the characteristic time. (a) Temporal evolution of product temperature. (b) The characteristic time $\tau_k$ can be calculated from the slope of the curve (Hoang et al., 2012)**

Calculated $\tau_k$ values of the products at the different steps are presented in Table 2.

**Table 2. Calculated $\tau_k$ values of the products at the different steps**

| Step | $\tau$ (min) | Determination method |
|---|---|---|
| Lamination and folding | $+\infty$ | No temperature variation |
| Conveyor 1 | 15 min | Calculation (Eq. 4) |
| Conveyor 2 | 54 min | Experimental temperature (Fig. 2) |
| Cooling spiral | 55 min | Experimental temperature (Fig. 2) |
| Conveyor 3 | 54 min | Experimental temperature (Fig. 2) |
| Pending | [202; 299] min | Experimental temperature (Fig. 2) |
| Cold room | [275; 805] min | Experimental temperature (Fig. 2) |

### 2.2.2. Energy consumption

The energy consumption model was developed to evaluate the energy required for the refrigeration of the food plant in function of the operating conditions (i.e. setting temperature, external temperature, production throughput…). The total heat generation $P_T$ (W) is composed of heat generation from the walls ($P_w$), product ($P_p$), air renewal ($P_{air}$), lights ($P_f$), machines ($P_m$), fans ($P_f$) and doors ($P_d$) (Evans et al. (2014) :

$$P_T = P_w + P_p + P_{air} + P_l + P_m + P_f + P_d \qquad \text{Eq. (5)}$$

The electrical consumption $Q_T$ (J) of the equipment was calculated using Eq. 5:

$$Q_T = \frac{P_T \times dt}{\eta \times COP} \qquad \text{Eq. (6)}$$

With $\eta$ the global performance coefficient of the cooling unit ($\eta$ is considered to be 0.5) and COP the coefficient of performance of Carnot. The COP corresponds to the ratio of the provided cooling to the work required (not including thermodynamic irreversibility in the refrigerating machine) and can be calculated as below:

$$COP = \frac{T_{cold}}{T_{hot} - T_{cold}} \qquad \text{Eq. (7)}$$

with $T_{cold}$ and $T_{hot}$ the temperatures of the cold and hot sources, respectively. These temperatures can be estimated from the thermostat temperature ($T_{th}$), and the ambient temperature ($T_a$) considering a temperature pinch of 10°C (temperature difference between the air and the refrigerant in the evaporator), i.e. $T_{cold} = T_{th}$-10 and $T_{hot}$=$T_{ext}$+10. For the majority of the cold production system, the air temperature at the evaporator outlet is close to the thermostat temperature $T_{th}$.

### 2.2.3. *Microbiological quality change along the production line*

A generic microbial growth without lag time is proposed to evaluate the log increase of the bacterial population in function of the product temperature is proposed as below.

$$\frac{dQ}{dt} = \mu_{Ref} \times \left(\frac{T - T_{min}}{T_{ref} - T_{min}}\right) \qquad \text{Eq. (8)}$$

with $\mu_{ref}$ the reference growth rate (=0.3 $h^{-1}$), $T_{ref}$ and $T_{min}$ the reference and minimal growth temperatures, respectively set at 25°C and 0°C. Validated growth models for *Listeria monocytogenes* and lactic acid bacteria will be integrated in further study.

## 2.3. Description of studied scenarios

Six scenarios are proposed to evaluate the impact of the operating conditions on the energy consumption and products quality (Table 3). Results were expressed relatively to the reference scenario (#1). Results of each scenario were normalized to the scenario 1 (Reference of this study), to provide a relative measure (Table 4).

**Table 3. Studied scenarios**

| Scenario number | T° ext | T° process room | T° air in spiral | T° air in cold room | Description |
|---|---|---|---|---|---|
| Ref (#1) | 20°C | 14°C | -25°C | 2°C | Reference condition |
| #2 | 20°C | 14°C | -25°C | <u>4°C</u> | Increased air temperature in cold room |
| #3 | 20°C | <u>16°C</u> | -25°C | <u>4°C</u> | Increased air temperature in cold room and in process room |
| #4 | 20°C | 14°C | <u>14°C</u> | 2°C | Cooling spiral outage |
| #5 | <u>40°C</u> | 14°C | -25°C | 2°C | Hot day without technical issue |
| #6 | <u>40°C</u> | <u>20°C</u> | <u>-20°C</u> | <u>4°C</u> | Hot day with limited power of refrigeration processes |

## 3. RESULTS AND DISCUSSION

### 3.1. Product temperature change along the production line.

The reference scenario (**#1,** Table 3) was used for the simulation and the results are reported in Fig. 3 for six random initial product temperatures (after kneading). These temperatures were obtained by Eq. 1 considering normal distribution of the known temperatures ($T_{ext}, T_{a,p}, T_{water}$). As expected the cooling spiral (k=4) can easily be identified on the temperature profiles. The temperature tends to increase after the spiral (k=5) and in the pending zone, with a slow decrease in the cold room. Precautions on the duration of the pending during product packing have to be made by the manufacturer to avoid product temperature increase.

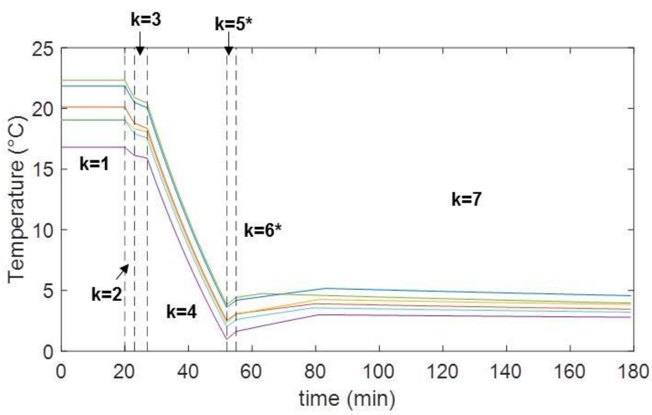


**Figure 3: Temperature evolution along the chain of six random products of one batch; time = 0 min corresponds to step *k*=0 (after kneading). *Products in pending zone (*k*=6) have different durations, e.g. if a palette loading is starting or about to end, duration of products varies**

### 3.2. Influence of operating temperatures on energy consumption and quality loss

The six scenarios (Table 3) were used for the simulation and the results are reported in Table 4 in terms of daily energy consumption relative to the reference scenario, % of products with temperature < 6°C at the entrance and exit of the cold room and the microbiological quality loss compared with the reference scenario. It is to be emphasized that the recommended temperature is 6°C. The analysis of the scenario 6 shows that 42% of product with temperature < 6°C after 6h, 94.5% after 12h and all of them (100%) after 18h.

Increasing temperature in the process room and the cold room (scenarios 2 and 3, decreases energy consumption by 12 and 18% with a limited impact on food quality (<1%).

**Table 4. Results of simulation of scenarios**

| Scenario number | % Reference daily energy consumption (normalized) | % of products <6°C at the entrance of the cold room | % of products <6°C at the exit of the cold room (1 day) | % Reference microbiological quality loss (normalized) |
|---|---|---|---|---|
| Ref | | 98.5% | 100% | |
| #2 | -12% | 98.5% | 100% | -0.4% |
| #3 | -18% | 84.3% | 100% | -0.5% |
| #4 | * | 0% | 100% | -2.8% |
| #5 | +72% | 92.83% | 100% | -0.2% |
| #6 | +33% | 0.2% | 100% | -1.5% |

*Comparison is not relevant because of the outage of the cooling spiral.

### 3.3. Influence of season on energy consumption

Simulations were carried out by using the external air temperature ($T_{ext}$) recorded every 10 minutes by the manufacturer in summer, fall and winter. The results of the daily energy consumption of the production line room and cold room are presented in Table 5. Information on the energy consumption of the cooling spiral could not be retrieved. While differences can be observed between predicted and measured data, overall, the trend is acceptable with higher energy consumption during the summer and lower energy consumption during the winter. These differences might be explained by the uncertainty of the model and the difficulty to include all characteristics of the food plant (air infiltration, machines, deterioration of the isolation). For example, the model largely underestimates energy consumption in the cold room during the winter with a total of 56 kWh per day while a total of 215 kWh per day was measured. More detailed onsite investigation will be conducted to characterize these differences.

**Table 5: Influence of the external air temperature on the energy consumption of production line and cold room (comparison between predicted and measured results)**

| | Summer day 06/21/2017 (Average $T_{ext}$ = 27°C) | | Fall Day 10/02/2017 (Average $T_{ext}$ = 15°C) | | Winter Day 02/28/2018 (Average $T_{ext}$ = -1.8°C) | |
|---|---|---|---|---|---|---|
| | Predicted (kWh / day) | Measured (kWh / day) | Predicted (kWh / day) | Measured (kWh / day) | Predicted (kWh / day) | Measured (kWh / day) |
| Production line room | 1258 | 928 | 786 | 669 | 201 | 349 |
| Cold room | 699 | 803 | 531 | 547 | 56 | 215 |

## 4. CONCLUSION

This study proposes an original multidisciplinary approach linking prediction of food temperature, food quality and energy consumption of refrigeration processes in a food plant. More precisely, this study focuses on a production line of puff pastry including kneading, folding and lamination, cutting, wrapping, cooling spiral, packing and storage in a cold room. Temperature and energy consumption data provided by the manufacturer and measured by our team were used to develop and validate the model. Six scenarios simulating issues encountered by the manufacturer (hot days, equipment failures) and solution to reduce energy consumption were tested. The impact of these scenarios on the food quality was evaluated. The slight increase of temperature setting of the air in the process room and in the cold room could reduce energy consumption with a limited effect on food quality degradation.

## REFERENCES


Anonymous, 2014. Regulation (EU) No 517/2014 of the European Parliament and of the Council of 16 April 2014 on fluorinated greenhouse gases.

Anonymous. (2015). "Fermeture des meubles frigorifiques de vente à température positive. BAT-EQ-124. Journal officiel de la république française - N°75 du 29 mars 2015." Retrieved April 04, 2018, from http://atee.fr/sites/default/files/bat-eq-124-fermeture_meubles_frigorifiq_de_vente_a_temperature_positive.pdf.

Ben-abdallah, R., D. Leducq, H. M. Hoang, O. Pateau, B. Ballot-Miguet, A. Delahaye and L. Fournaison, 2018. Modelling and experimental investigation for load temperature prediction at transient conditions of open refrigerated display cabinet using Modelica environment. Int. J. Refrigeration.

Chaomuang, N., D. Flick and O. Laguerre, 2017. Experimental and numerical investigation of the performance of retail refrigerated display cabinets. Trends Food Sci Technol, 70,(95-104.

Duret, S., H.-M. Hoang, E. Derens-Bertheau, A. Delahaye, O. Laguerre and L. Guillier, Combining Quantitative Risk Assessment of Human Health, Food Waste, and Energy Consumption: The Next Step in the Development of the Food Cold Chain? Risk Anal, 0,(0).

Duret, S., H. M. Hoang, D. Flick and O. Laguerre, 2014. Experimental characterization of airflow, heat and mass transfer in a cold room filled with food products. Int. J. Refrigeration, 46,17-25.

Evans, J. A., A. M. Foster, J. M. Huet, L. Reinholdt, K. Fikiin, C. Zilio, M. Houska, A. Landfeld, C. Bond, M. Scheurs and T. W. M. van Sambeeck, 2014. Specific energy consumption values for various refrigerated food cold stores. Energ Buildings, 74,(Supplement C), 141-151.

Gruyters, W., P. Verboven, M. Delele, S. G. Gwanpua, A. Schenk and B. Nicolaï, 2018. A numerical evaluation of adaptive on-off cooling strategies for energy savings during long-term storage of apples. Int. J. Refrigeration, 85,431-440.

Hoang, H. M., D. Flick, E. Derens, G. Alvarez and O. Laguerre, 2012. Combined deterministic and stochastic approaches for modelling the evolution of food products along the cold chain. Part II: A case study. Int. J. Refrigeration, 35,(4), 915-926.

Laguerre, O. and D. Flick, 2010. Temperature prediction in domestic refrigerators: Deterministic and stochastic approaches. Int. J. Refrigeration, 33,(1), 41-51.

Lecoq, L., E. Derens, D. Flick and O. Laguerre, 2017. Influence of air dehumidification on water evaporation in a food plant. Int. J. Refrigeration, 74,435-449.

Merai, M., D. Flick, L. Guillier, S. Duret and O. Laguerre, 2018. Experimental characterization of airflow inside a refrigerated trailer loaded with carcasses. Int. J. Refrigeration, 88,(337-346.

Parpas, D., C. Amaris and S. A. Tassou, 2017. Experimental investigation and modelling of thermal environment control of air distribution systems for chilled food manufacturing facilities. Appl. Therm. Eng, 127,1326-1339.

Parpas, D., C. Amaris and S. A. Tassou, 2018. Investigation into air distribution systems and thermal environment control in chilled food processing facilities. Int. J. Refrigeration, 87, 47-,64.

Zanoni, S. and L. Zavanella, 2012. Chilled or frozen? Decision strategies for sustainable food supply chains. Int. J. Prod. Econ, 140,(2), 731-736.