EVALUATION OF FOOD SAFETY ALONG THE COLD CHAIN BY DETERMINISTIC AND STOCHASTIC APPROACHES

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ABSTRACT

Several surveys have shown temperature abuses in the last 3 steps of the cold chain: display cabinet, transport by consumer and domestic refrigerator. To evaluate the food safety, this work was carried out to predict the product temperature and microbial load evolutions in these steps.

Deterministic models were used to take into account the heat transfer by convection, conduction and radiation inside the equipments. They were combined with stochastic models to take into account different sources of randomness: ambient temperature, thermostat setting, product position and residence time in the equipments etc. Distribution laws were developed to fit the survey data of these random parameters. The sampling values were used as input parameters of the heat transfer model to predict the temperature evolutions of a large number of products along the cold chain. Then, these temperature evolutions were applied to a growth model of *Listeria monocytogenes* to predict the bacterial contamination.

1. INTRODUCTION

The evolution of food products along the cold chain in term of quality and safety is of major importance. The objective of this study is to develop a modelling methodology to predict the evolution of food products and its variability all along the cold chain. This methodology, taking into account various sources of randomness such as ambient temperature, product residence time etc., was applied to the 3 steps of the cold chain during which temperature abuses are often observed: refrigerated display cabinet, consumer shopping basket and domestic refrigerator. Indeed, according to a survey carried out by our team, the product temperature is often too high to ensure the food safety in these equipments (30% in the display cabinet and 40% in domestic refrigerators, Cemagref and ANIA, 2004).

2. METHODOLOGY

The methodology will be illustrated for a part of the cold chain: from the display cabinet to the domestic refrigerator but the same approach could be used for the other steps of the cold chain (storage in cold room, transport…). The product of interest is pre-packaged meat. For this kind of product, survey data are available (Cemagref and ANIA, 2004). The product evolution will be here characterized only by the temperature and the bacterial load. The same approach could also be used to follow other parameters such as moisture loss, vitamin degradation for other types of product.

The methodology is composed of:

- a stochastic description of the logistic chain
- a semi-deterministic description of the cold chain equipments
- a deterministic description of the product evolution (temperature, bacterial load)

A large number of products are introduced at $t=0$ in the logistic chain (in the current study only the part of the logistic beginning in the display cabinet is considered). Each product is characterized at each time t by several state variables which are the mean product temperature and the bacterial load. The initial values of the product state variables can be considered either as constant for all product items or as random variables.

To avoid long calculation time to predict the evolution of all product items present in the equipments all over the time, this approach distinguishes the individual product of interest and the other products present in the equipment. These other products, called ‘load’, will not be followed individually but lumped together for each typical location.

The load temperature at each position of an equipment depends on some random parameters (ambient temperature, thermostat setting, thermal insulation of the shopping basket…). The load temperatures are estimated by a deterministic thermal model for each equipment taking into account conductive, radiative and convective heat exchanges.

In each equipment, the temperature evolution of the product of interest is predicted from its initial value (when the product is introduced in the equipment) and from the mean surrounding temperature which is the temperature of the load at the corresponding position.
Finally, the bacterial load evolution is predicted from the temperature evolution.

3. STOCHASTIC DESCRIPTION OF THE LOGISTIC CHAIN

This study considers the logistic chain of three equipments:

- display cabinet (DC)
- shopping basket (SB)
- domestic refrigerator (Ref)

When the products are loaded in the display cabinet, they are placed preferentially in the rear part and the older products are moved to the front. In this way, the products with the closest best-before date have more chance to be taken by the consumers. To take into account this manipulation, two indexes k=1 and k=2 are used for the display cabinet, as shown in Figure 1. Only one type of display cabinet is considered here: open vertical type, which is the most common for pre-packaged meat.

Index k=3, is used for the shopping basket, even if this step is not really a refrigeration equipment.

Two kinds of domestic refrigerators are considered: static refrigerator (free convection) which is indexed by k=4 and ventilated refrigerator which is indexed by k=5.

The last step (k=K=6) corresponds to eating of the product. It is assumed that once a product is removed from the refrigerator, it is consumed (it does not return in refrigerator).

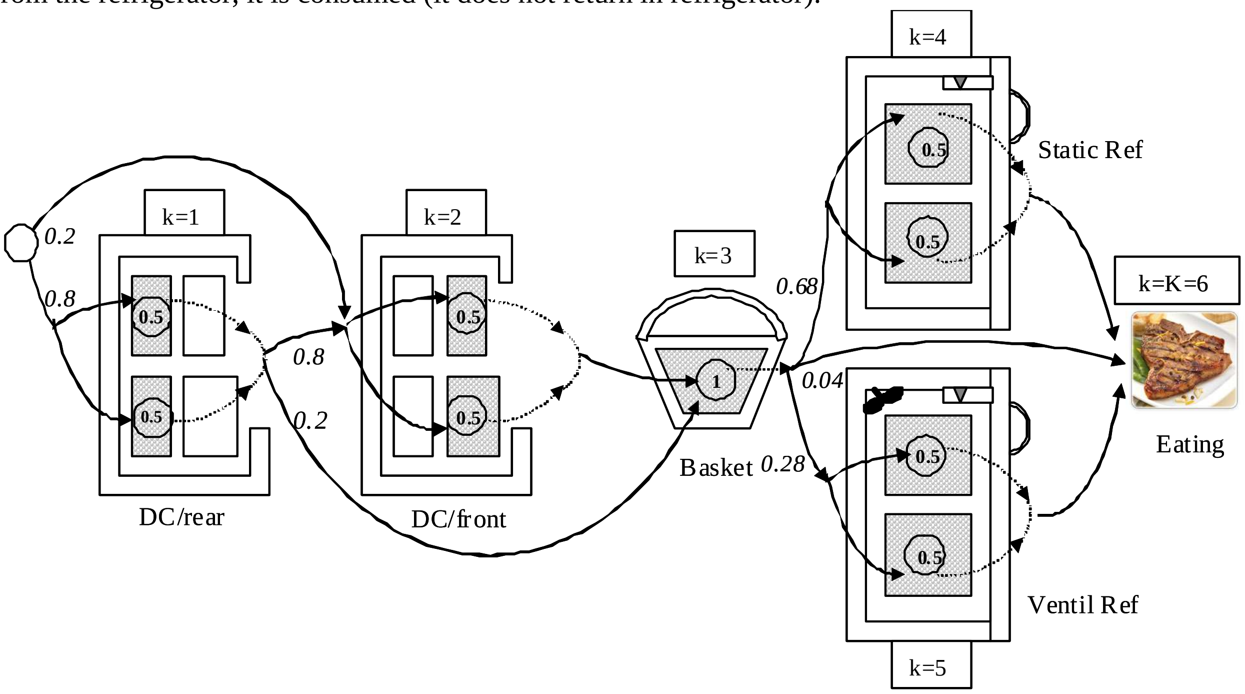


Figure 1**:** Logistic chain: probability of product transfer from an equipment to another (*italic*), probability of product position (**bold** in circle)

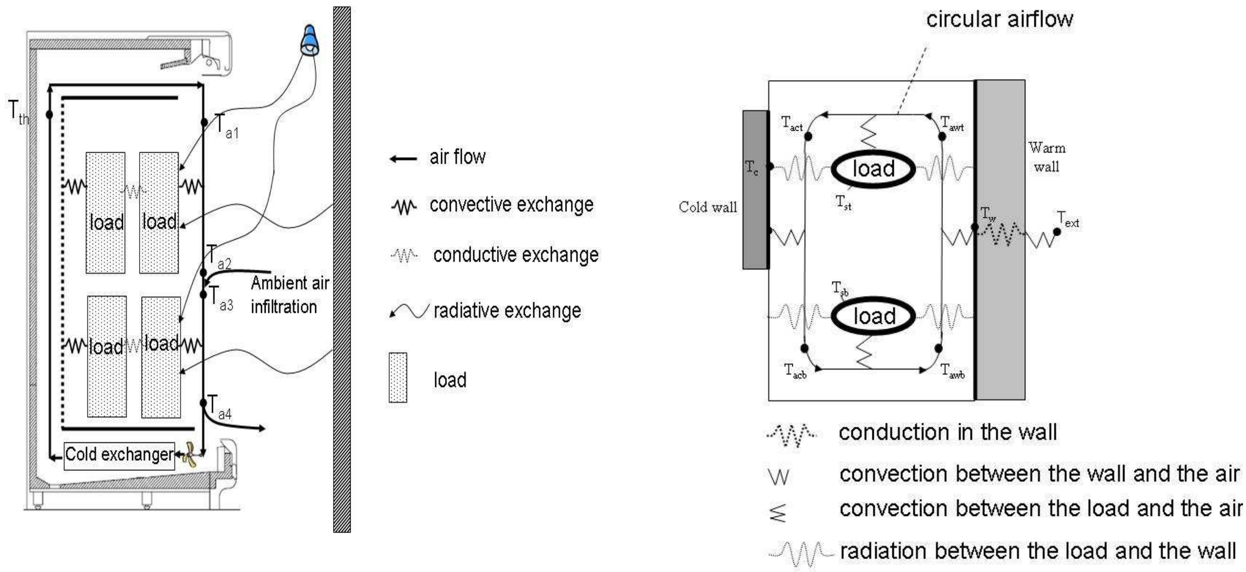
From the literature (Evans et al, 2007) it appears that the products placed in the front part of the display cabinets are submitted to higher temperatures than the one placed in the rear and that product placed in the bottom part are often warmer than the ones placed in the top part. Therefore, 4 characteristic positions were considered in the display cabinet. In the same way (Laguerre and Flick, 2010), two characteristic positions were considered in the domestic refrigerator, the temperature being generally higher at the top than at the bottom especially for static refrigerators.

The logistic chain with probabilities of transition from one to another equipment and of position inside equipments is presented schematically in Figure 1. Equal probability was assumed for position. Probability for a product to be firstly placed at the rear of the display cabinet was estimated to be 80%. Probability for a product to be placed in a static or a ventilated refrigerator was estimated from the observed percentage in France (Diouris and Mahé, 2007). The distribution of residence time of pre-package meat in the display cabinet, shopping basket and domestic refrigerator was fitted by an exponential Probability Density Function (PDF) (Cemagref and ANIA, 2004).

4. SEMI-DETERMINISTIC DESCRIPTION OF THE COLD CHAIN EQUIPMENTS

4.1 Display cabinets (DC)

In this case study, only the open front vertical display cabinet is considered because it is mostly used for keeping chilled food in supermarket (Gac and Gautherin, 1987) especially pre-packaged meat. In order to take into account the non-uniformity of product temperature, 4 loads are considered: rear top, rear bottom, front top and front bottom (Figure 2a). The details of the development and validation of the thermal model were presented in Laguerre *et al.*, 2010a.



(a) (b)

Figure 2. Heat transfer model considering (a) 4 load positions in an open vertical display cabinet (b) 2 loads positions in domestic refrigerator.

The load temperatures depend on the position and two random parameters: the air temperature in the store T_{ext} and the radiation temperature T_{rad}. The distribution of T_{ext} is assumed to follow Gaussian PDF with a mean value of 16.5°C and a standard deviation of 1.8°C (Lindberg *et al.*, 2010). According to Gac and Gautherin (1987), it appears that the radiation temperature is correlated to the ambient air temperature. When grocery shelves are placed oppositely to the refrigerated display cabinet, the radiation temperature is close to that of air. When other display cabinets are placed oppositely, the radiation temperature is averagely 6°C lower than the air temperature. Therefore, two equally probable values of $T_{rad} - T_{ext}$ of $0°C$ and $-6°C$ are chosen.

The load temperature can be calculated from the equipment parameters by linear relations (Laguerre *et al.*, 2010a):

- for k=1 : display cabinet - product placed in rear part (DC/rear)
  with two load positions : *l*=1 - top, *l*=2 - bottom

$$T_{load.1} = 0.0027T_{ext} + 0.0430T_{rad} + 1.4655$$
$$T_{load.2} = 0.0244T_{ext} + 0.0435T_{rad} + 1.4814 \quad (1)$$

- for k=2 : display cabinet - product placed in front part (DC/front)
  with two load positions : *l*=1 - top, *l*=2 - bottom

$$T_{load.1} = 0.0117T_{ext} + 0.1831T_{rad} + 1.3534$$
$$T_{load.2} = 0.1040T_{ext} + 0.1889T_{rad} + 1.4178 \quad (2)$$

4.2. Shopping basket

From the display cabinet to the domestic refrigerator, the product is transported in a shopping basket which is more or less thermally insulated (only one load position is considered).

Two random parameters are considered: the mean temperature of the air surrounding the basket $T_{ext}\left(°C\right)$ and the heat transfer conductance $H\ (W.K^{-1})$ which depends on the basket insulation. The distribution of T_{ext} is Gaussian PDF: mean value 17.2°C and standard deviation 5.8°C (Cemagref and ANIA, 2004). Investigations in different countries showed that the majority of people did not use any food protection during transportation: 87.3% in the UK (Evans, 1992); 84.5% in Slovenia (Jevsnik *et al.*, 2008) and 81.4% in New Zealand (Gilbert *et al.*, 2007). So, it is assumed that there is 84% (mean of these 3 values) of the shopping basket having no insulation and 16% being thermally insulated. The heat transfer conductance was measured in our study for a non insulated basket: $H = 0.15W.K^{-1}$ and an insulated one: $H = 0.09W.K^{-1}$.

4.3. Domestic refrigerators (Ref)

The domestic refrigerators are of two different types: static (without a fan, free convection) and ventilated (forced convection). Inside a static refrigerator, there is about 4°C temperature difference between top and bottom (Laguerre and Flick, 2004) while this difference is lower in a ventilated appliance.

The load temperatures depend on the position and on two random parameters: the air temperature in the kitchen T_{ext} and the thermostat setting T_{th} which depends on consumer habits. In order to take into account the non uniformity of product temperature, 2 load positions are considered: top and bottom (Figure 2b). T_{ext} and T_{th} can be fitted by normal distributions (Laguerre and Flick, 2010b):

- for T_{ext} : mean value 16.7°C and standard deviation value 3.1°C

- for T_{th} : mean value 6.0°C and standard deviation value 2.3°C

The load temperatures can be calculated from the equipment parameters by following relations (Laguerre and Flick, 2010b):

- For k=4: static refrigerator (Static Ref)

  with two load positions : *l*=1 top, *l*=2 bottom

$$T_{load.1} = 0.0723T_{ext} + 0.9277T_{th}$$
$$T_{load.2} = 0.0077T_{ext} + 0.9923T_{th} \quad (3)$$

- For k=5: ventilated refrigerator (Ventil Ref) with two load positions : l=1 top, l=2 bottom

$$T_{load.1} = 0.0343T_{ext} + 0.9657T_{th}$$
$$T_{load.2} = 0.0147T_{ext} + 0.9853T_{th} \tag{4}$$

Figure 3 summarizes the involved equipment and product state variables and parameters

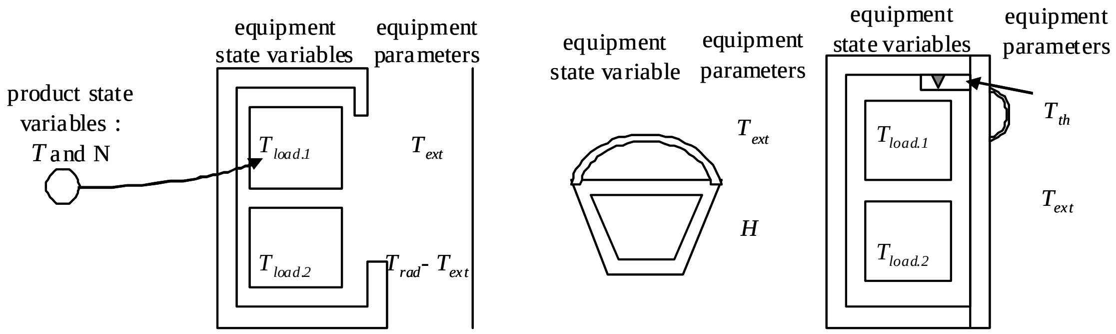


Figure 3. Equipment and product state variables and parameters.

5. DETERMINISTIC DESCRIPTION OF THE PRODUCT EVOLUTION

Two product state variables are considered: the mean product temperature and the microbial load.

5.1 Evolution of the mean product temperature *T*

Inside display cabinet or refrigerator (k=1, 2, 4, 5), using a lumped thermal model, the mean temperature of the product of interest tends to the load temperature at its position $T_{load,l,k}$:

$$mC\frac{dT}{dt} = H_{l.k}\left(T_{load,l,k} - T\right) \tag{5}$$

- The load temperature $T_{load,l,k}$ can be calculated by linear relations (equations 1, 2, 3 & 4).

- The mass m and the thermal capacity of the product C are considered to be constant. For this case study of pre-packaged meat, m=0.250kg and C=3500 J.kg^{-1}K^{-1}.

In the shopping basket, a similar model is applied:

$$mC\frac{dT}{dt} = H_{k=3}\left(T_{ext} - T\right) \tag{6}$$

The heat transfer conductance $H_{l.k}$ was measured for each position l of each equipment: display cabinet (k=1 and 2) and refrigerator (k=4 and 5). For this purpose, the product (initial temperature T_0) was placed at position l of equipment k at time $t_0=0$. A thermocouple was placed at the product's centre to measure the evolution of product temperature T. The expected temperature evolution can be presented by the equations 7 and 8:

$$T = T_0 + \left(T_{load.l.k} - T_0\right)\exp\left(-\frac{H_{l.k}t}{mc}\right) \tag{7}$$

$$\Rightarrow \ln\left(T^*\right) = -\frac{t}{\tau_{l.k}} \tag{8}$$

where $\tau_{l.k} = \frac{mc}{H_{l.k}}$ and $T^* = \frac{T - T_{load.l.k}}{T_0 - T_{load.l.k}}$.

An example of the temporal evolution of the product temperature T and $\ln(T^*)$ is presented in Figure 4. Figure 4b illustrates how the characteristic time $\tau_{l,k}$ can be calculated.

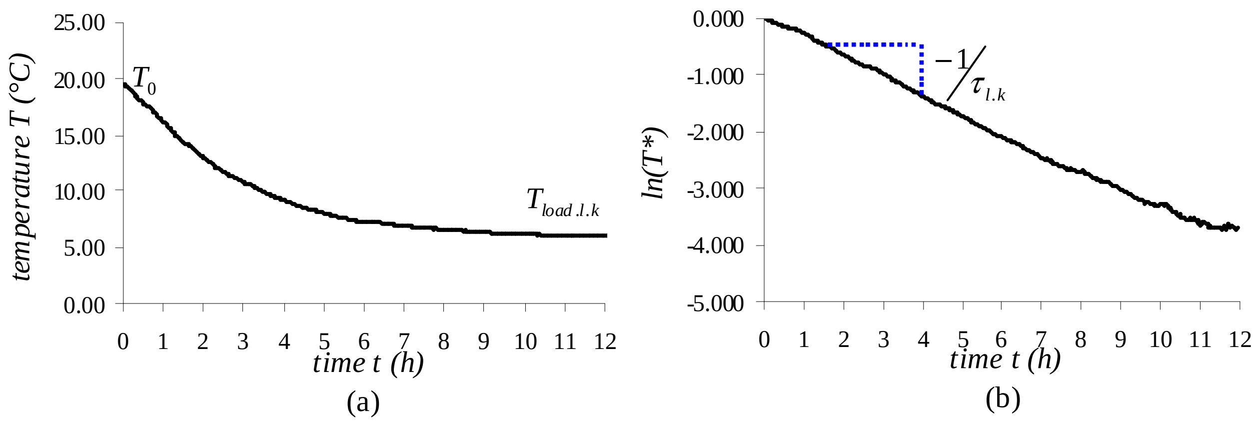


Figure 4. Temporal evolution of product temperature:
(a) temperature T vs time t - (b) $ln(T^*)$ vs time t

5.2. Evolution of microbial load N

As a primary model, a simple first order growth was assumed:

$$\frac{dN(t)}{dt} = \mu N(t) \tag{9}$$

where $N(t)$ is microbial load at time instant t, N_0 is initial load (CFU/g) and.μ is specific growth rate (s^{-1}).
The dependence of the specific growth rate μ on the temperature is described by the square root model of Ratkowsky *et al.* (1982):

$$\sqrt{\mu} = b(T - T_{\min}) \tag{10}$$

where T_{min} is the minimum temperature under which there is no bacterial growth and b is a coefficient. For *Listeria monocytogenes*, Duh and Schaffner (1993) reported that T_{min}=0°C *and* b=0.00035 $s^{-1/2}K^{-1}$

More sophisticated model proposed by Baranyi et al (1993) and Zwietering et al (1996) could also be used with the same approach. The aim of the present study is to illustrate the potentiality of the methodology, but not to predict accurately the microbial growth of specific species in a specific food product.

6. RESULTS AND DISCUSSION

For a simulation of 100000 product items, Figure 5 shows a cumulative distribution of final/initial ratio of bacterial load for the part of the cold chain (from the display cabinet to domestic refrigerator). It can be observed that for 50% of the product items, the bacteria multiplication is less than 3.31 which is very acceptable. However, the bacterial multiplication is higher than 200 for 5% of the product items, which can be dangerous for consumer. The estimated multiplication of more than 10^4 for 1% of the products could certainly lead to food poisoning. This fraction of the products is still statistically representative because it represents 1000 items. But it is to be reminded that a simple bacterial growth model was used. For this kind of extreme analysis, the microbial growth model should be improved to take into account influence of the initial load, the initial physiological state and the variability of the growth parameters.

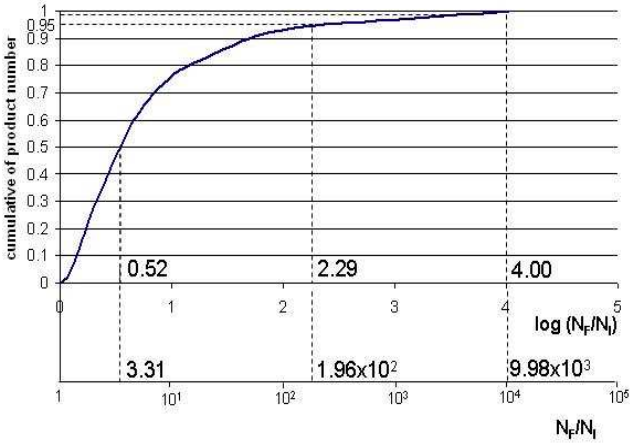


Figure 5. Cumulative distribution of final/initial ratio of bacterial load at the end of the cold chain (display cabinet, shopping basket and domestic refrigerator) for total product items of 100 000.

$\log (N_F/N_I) \leq 0.52$ or $N_F/N_I \leq 3.31$	for 50% of product
$\log (N_F/N_I) \leq 2.29$ or $N_F/N_I \leq 1.96\text{x}10^2$	for 95% of product
$\log (N_F/N_I) \leq 4.00$ or $N_F/N_I \leq 9.98\text{x}10^3$	for 99% of product

7. CONCLUSIONS

A methodology combining deterministic heat transfer models for the refrigeration equipments and stochastic models to take account of various sources of randomness in the cold chain was proposed. It enables the prediction of the temperature evolution of a large number of products. Theses temperature evolutions can then be used to estimate bacterial growth. Thus, this approach can contribute to evaluate food safety along the cold chain.

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