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Association d'approches déterministes et stochastiques appliquée à la chaîne du froid des produits alimentaires

Combined deterministic and stochastic approaches applied to the food cold chain

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Résumé

Plusieurs enquêtes ont montré que la température de produits dans les 3 dernières étapes de la chaîne du froid est problématique: meuble frigorifique de vente, transport par les consommateurs après l'achat et réfrigérateur domestique. Cette étude a été effectuée pour proposer une méthodologie de prédiction de l'évolution de la température du produit et de la charge microbienne tout au long de la chaîne du froid. Les modèles déterministes développés prennent en compte le transfert de chaleur par convection, conduction et rayonnement. Ceux-ci ont été combinés avec des modèles stochastiques pour tenir compte de différents paramètres aléatoires: la température ambiante, le réglage du thermostat, la position et le temps de séjour du produit dans les équipements etc. Des lois de distribution ont été développées pour ces paramètres aléatoires par ajustement sur des données d'enquête. Les valeurs échantillonnées de ces lois ont été utilisées comme paramètres d'entrée du modèle de transfert de chaleur permettant de prédire les évolutions de température d'un grand nombre de produits le long de la chaîne du froid. Ces évolutions de température ont été utilisées dans un modèle de croissance microbienne pour prédire les évolutions de la charge de *Listeria monocytogenes*. Des analyses statistiques des résultats ont été réalisées permettant de connaître le pourcentage de produits ayant différents niveaux de contamination.

Mots-clés : chaîne du froid, sécurité des aliments, température, charge microbienne, prédiction.

Abstract

Several surveys have shown temperature abuses in the last 3 links of the cold chain: display cabinet, transport by consumer and domestic refrigerator. 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 models 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. Statistical analysis of

simulation results was carried out enabling the distribution of product at various contamination levels.

Keywords : cold chain, food safety, temperature, microbial load, prediction

1. Introduction

In refrigeration of food products, temperature control along the cold chain is essential to maintain the product quality. To provide safe food products of high organoleptic quality, attention must be paid to every aspect of the cold-chain from the production until the consumption. As the product is present in several equipments during the supply-chain, it is difficult to control and maintain the temperature all along the cold chain.

The objective of this study is to develop a prediction methodology for the product time-temperature history and the evolution of microbial load along the cold chain. This methodology takes into account different sources of randomness in the cold chain: ambient temperature (may vary due to the seasons, presence/absence of air conditioning system), thermostat setting (may vary due to the behaviour of operator/consumer), product position and residence time in the equipments (may vary due to the strategy of logistic management) etc. In the present paper, the methodology was applied to the 3 last links of the cold chain: refrigerated display cabinet, transport by consumer after purchase, domestic refrigerator where temperature abuse was often observed (Figure 1).

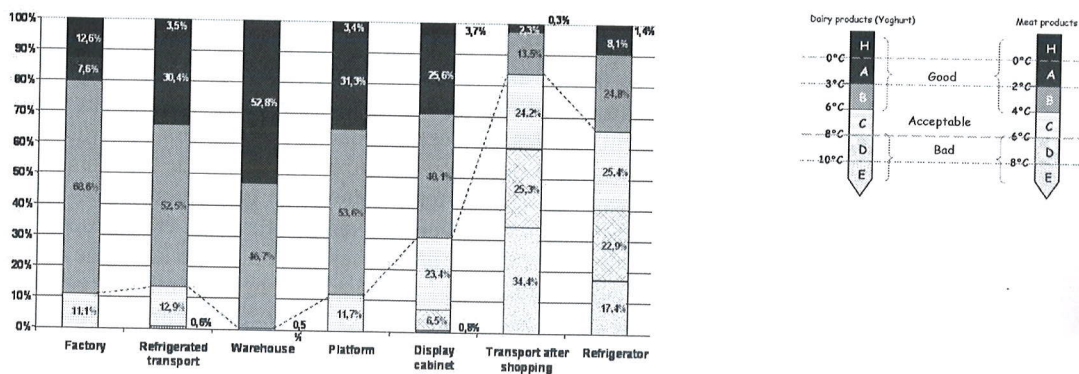


Figure 1: Percentage of dairy and meat products in different temperature ranges according to the Cemagref and Ania survey (2004).

2. Deterministic models

2.1 Simplified steady state heat transfer models for load

Simplified steady state heat transfer models were developed to predict the temperature of the load (T_{load}) located at different positions in the display cabinet and domestic refrigerator. The models take into account the heat transfer by convection, conduction and radiation.

2.1.1 Domestic refrigerator (Ref)

The proposed simplified heat transfer model of loaded refrigerator represents the main phenomena observed by CFD simulation (Laguerre et al., 2007): circular airflow in the cavity, temperature

stratification along the height. Figure 2 presents a diagram of simplified airflow and heat transfer in steady state (Laguerre et al., 2010). During the flow, air exchanges heat with cold wall, with bottom load, with warm wall and with top load, simultaneously. There is also radiation between cold wall and load and between warm wall and load. Finally, there is conduction in the door and the side walls and convection with the external air.

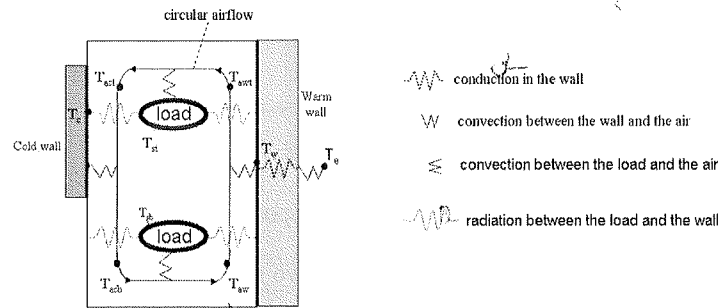


Figure 2: Simplified model of heat transfer and airflow in loaded refrigerator.

The static domestic (without a fan, free convection) and ventilated refrigerators (forced convection) are studied in this work. In the static type, 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.

The load temperatures can be calculated from T_{ext} and T_{th} by following relations (Laguerre and Flick, 2010):

- For static refrigerator with two load positions : $l=1$ top, $l=2$ bottom

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

$$T_{load.2} = 0.0077T_{ext} + 0.9923T_{th}$$

- For ventilated refrigerator with two load positions : $l=1$ top, $l=2$ bottom

$$T_{load.1} = 0.0343T_{ext} + 0.9657T_{th} \quad (2)$$

$$T_{load.2} = 0.0147T_{ext} + 0.9853T_{th}$$

2.1.2 Display cabinets (DC)

In this work, only the open front vertical display cabinet is studied because it is mostly used for keeping chilled food in supermarket (Gac and Gautherin, 1987). In order to take into account the non-uniformity of product temperature, 4 load positions are considered: rear top, rear bottom, front top and front bottom (Figure 3). The details of the development and validation of the thermal model were presented in Laguerre *et al.*, 2012.

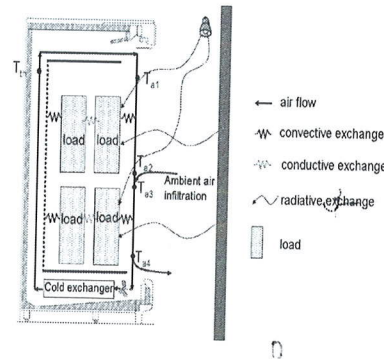


Figure 3. Heat transfer model considering 4 load positions in an open vertical display cabinet.

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 load temperature can be calculated from the equipment parameters by linear relations (Laguerre *et al.*, 2011):

- product placed in rear part (DC/rear), $l=top, 2=bottom$

$$T_{load,1} = 0.0027T_{ext} + 0.0430T_{rad} + 1.4655$$

$$T_{load,2} = 0.0244T_{ext} + 0.0435T_{rad} + 1.4814 \quad (3)$$

- product placed in front part (DC/front), $l=top, 2=bottom$

$$T_{load,1} = 0.0117T_{ext} + 0.1831T_{rad} + 1.3534$$

$$T_{load,2} = 0.1040T_{ext} + 0.1889T_{rad} + 1.4178 \quad (4)$$

2.2 Simplified transient heat transfer model for product of interest

A simplified transient heat transfer model was developed to predict the temperature evolution of the product $T(t)$ which circulates along different links of the cold chain (called product of interest). This model takes into account the temperature of the load located near the product of interest (T_{load}), product properties: weight (m), surface area (A) and specific heat (C), the product initial temperature (T_0), and the heat transfer coefficient between the products and surrounding air (by natural or forced convection).

Inside display cabinet, shopping basket and domestic refrigerator, using a lumped thermal model, the mean temperature of the product of interest tends to the neighbouring load temperature (Figure 4). The temperature evolution of the product of interest can be expressed by exponential equation below:

$$T(t) = T_0 + (T_{load,l,k} - T_0) \exp\left(-\frac{H_{l,k}t}{mc}\right) \quad (5)$$

$$\Rightarrow \ln(T^*) = -\left(\frac{t}{\tau_{l,k}}\right) \quad (6)$$

where $\tau_{l,k} = \frac{mc}{H_{l,k}}$, $T^* = \frac{T(t) - T_{load,l,k}}{T_0 - T_{load,l,k}}$, $H_{l,k}$ = heat transfer conductance

l =position index, $l=1$ (top), $l=2$ (bottom),
 k = link index, $k=1$ display cabinet with rear load, $k=2$ display cabinet with front load, $k=3$ shopping basket, $k=4$ static domestic refrigerator, $k=5$ ventilated domestic refrigerator.

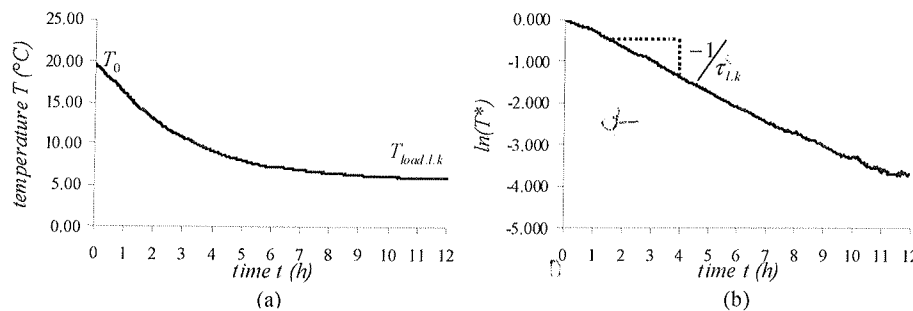


Figure 4. Temperature evolution of product of interest
 (a) temperature T vs time t - (b) $\ln(T^*)$ vs time t

The heat transfer conductance, $H_{l,k}$ was measured experimentally for each position l of each link k . Packaged meat ($m=0.250$ kg and $C=3500$ J.kg⁻¹K⁻¹) was used to determine $H_{l,k}$. During experiment, the product was placed at a position l of a link k and a thermocouple was placed at the product's centre to monitor the evolution of product temperature. Using the eq.6, $\ln(T^*)$ versus t was traced (Figure 4b) and the slope was used to calculate $H_{l,k}$ for each link (Table 1).

$H_{l,k}$ ($W.K^{-1}$)	$k=1$ DC/rear	$k=2$ DC/front	$k=3$ Shopping basket*	$k=4$ Static Ref	$k=5$ Ventil Ref
$l=1$	0.26	0.35	0.15 (non insulated basket) 0.09 (insulated basket):	0.12	0.13
$l=2$	0.30	0.26	-	0.13	0.13

* one product position is considered in shopping basket

Table 1: Heat transfer conductance $H_{l,k}$ ($W.K^{-1}$) of pre-packaged meat (0.250 kg) in display cabinet, shopping basket and domestic refrigerator.

2.3 Evolution of microbial load N

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

$$\frac{dN(t)}{dt} = \mu N(t) \tag{7}$$

$$\Rightarrow \ln\left(\frac{N(t)}{N_0}\right) = \int_0^t \mu \cdot dt' \quad (8)$$

where $N(t)$ is the microbial load at time instant t , N_0 is the initial load (CFU/g) and μ is the 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):

$$\sqrt{\mu} = b(T - T_{\min}) \quad (9)$$

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 $T_{\min}=0^{\circ}\text{C}$ and $b=0.00035 \text{ s}^{-1/2}\text{K}^{-1}$. More sophisticated model proposed by Baranyi *et al.* (1993) and Zwietering *et al.* (1996) could also be used with the same approach.

3. Stochastic models

The distribution laws of the random input parameters of each link were developed to fit the survey data (Table 2). The normal law was used to represent the temperature distributions, the exponential law for residence time distributions. According to Gac and Gautherin (1987), it appears that the radiation temperature is correlated to the ambient air temperature. In supermarkets, 2 cases are generally presented. First case: the radiation temperature is close to that of air when grocery shelves are placed oppositely to the refrigerated display cabinet. Second case, the radiation temperature is averagely 6°C lower than the air temperature when 2 display cabinets are placed oppositely. Therefore, Bernoulli law was chosen with two equally probable values of $T_{\text{rad}} - T_{\text{ext}}$: 0°C and -6°C . Investigations in different countries showed that the vast majority of people did not use any means of food protection during transportation: 87.3% in the UK (Evans, 1992); 84.5% in Slovenia (Jevnik *et al.*, 2008) and 81.4% in New Zealand (Gilbert *et al.*, 2007). So, it is assumed that 84% (mean of these 3 values) of the shopping baskets do not have insulation and 16% are thermally insulated. Bernoulli law was chosen to represent the possibility for the consumer to use the insulated/non insulated basket.

4. Simulations

The logistic chain of meat is shown in Figure 5. The probability of product to be placed at the front (0.2) and the rear (0.8) of a display cabinet was obtained using expert data. The probability of product to be placed in a static (0.68), ventilated refrigerator (0.28) and directly consumed (0.04) was obtained by Diouris and Mahé (2007). There is an equal probability (0.5) to be at the top and the bottom of display cabinet and domestic refrigerator.

The sampling values (by Monte Carlo) of the input random parameters were applied to the steady state heat transfer model enabling the calculation of the load temperature, T_{load} and to the transient heat transfer model enabling the calculation of the product of interest temperature, $T(t)$.

The simulation was repeated for numerous product items (10^5) to predict the temperature evolutions in different cold chain equipments until domestic refrigerator. The time-temperature history of the products was applied to a growth model of *Listeria monocytogenes* to predict the bacterial load evolution until consumption. The analysis of the numerical results was carried out and shown in paragraph 5 (Results and discussion).

Link	Random input parameter	Distribution law	Reference
Display cabinet	T_{ext}	$N(16.5^{\circ}\text{C}; 1.8^{\circ}\text{C})$	Lindberg <i>et al.</i> (2010)
	$T_{rad} - T_{ext}$	Bernoulli p(0°C)=0.5 p(-6°C)=0.5	Gac and Gautherin (1987)
	Residence time (Δt_{DC} , days)	Exp(3.8)	Cemagref and ANIA (2004)
Shopping basket	T_{ext}	$N(17.2^{\circ}\text{C}, 5.8^{\circ}\text{C})$	Cemagref and ANIA (2000)
	H	Bernoulli p(0.15)=0.84 p(0.09)=0.16	Evans, (1992) UK survey Jevsnik <i>et al.</i> (2008) Slovenia survey Gilbert <i>et al.</i> (2007) New Zealand survey.
	Residence time (Δt_{SB} , days)	Exp(0.05)	Cemagref and ANIA (2004)
Domestic refrigerator	T_{ext}	$N(16.7^{\circ}\text{C}, 3.1^{\circ}\text{C})$	Hunt and Gidman (1982)
	T_{th}	$N(6.0^{\circ}\text{C}, 2.3^{\circ}\text{C})$	Laguerre <i>et al.</i> (2002)
	Residence time (Δt_{Refs} , days)	Exp(2.8)	Cemagref and ANIA (2004)

Table 2: Distribution law of random input parameters

Normal distribution: $N(\text{mean}, \text{standard deviation})$

Exponential distribution: Exp(mean)

Bernoulli distribution: probability of a random parameter, p(random parameter)

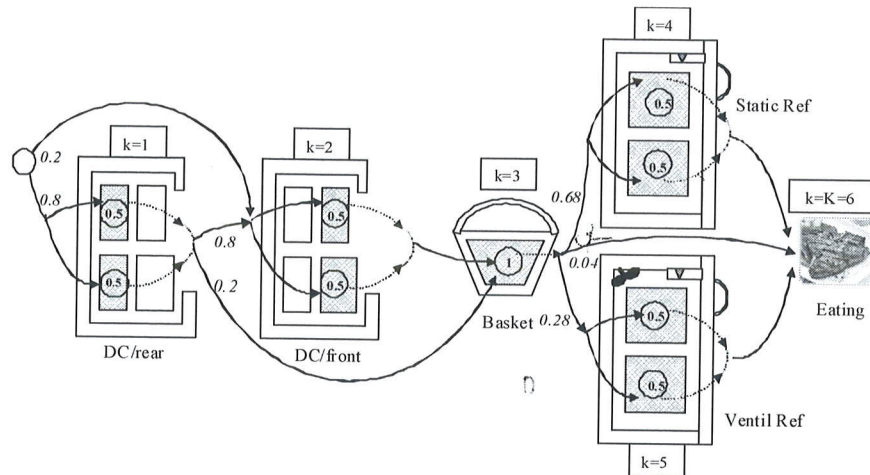


Figure 5. Logistic chain: probability of product transfer from an equipment to another (*italic*), probability of product position (**bold in circle**).

5. Results and discussion

The total residence time, t_s , is the sum of Δt_{link} of the 3 links. It is interesting to compare t_s with the shelf life of the product. For pre-packaged meat, the shelf life of a product at the end of production is 21 days (Legrand et al., 2010). According to the ANIA investigation, the mean residence time of the product in the upstream links (factory, refrigerated transport and platform) is 3 days. Thus, the shelf life of the product for the final 3 links (display cabinet, shopping basket and refrigerator) is 18 days on the average. Figure 6 presents the cumulative distribution of t_s obtained from the simulation and the survey. The residence time of 50% of the products is less than 5.5 days and it is less than 18 days for 97% of products.

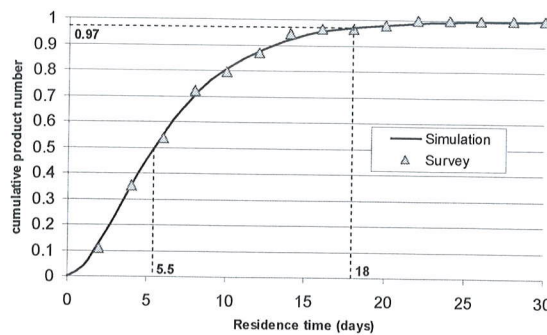


Figure 6. Cumulative distribution of total residence time, t_s , at the end of the cold chain (display cabinet, shopping basket and domestic refrigerator)
 $t_s \leq 5.5$ days for 50% of product items
 ≤ 18 days for 97% of product items
(number of product items $I=100\ 000$)

Figure 7 presents the cumulative distribution of the overall Decimal Increase: $DI = \log(N_F/N_I)$; $F = \text{final}$; $I = \text{initial}$ in the microbial load of the cold chain for 10^5 product items. It can be observed that for 50% of the products, the microbial load is multiplied by less than 3.31, which is reasonable. The microbial load increases over 200-fold for 5% of products, and this can be critical for consumers. An overall relative increase in the microbial load (N_F/N_I) of more than 10^4 is obtained for 1% of products, which may lead to food poisoning. These products are statistically representative because they represent 1000 items.

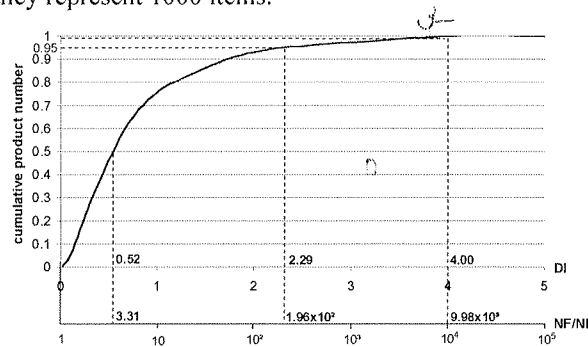


Figure 7. Cumulative distribution of the overall decimal increase in the microbial load of the cold chain DI (display cabinet, shopping basket and domestic refrigerator)
 $DI = \log(N_F/N_I) \leq 0.52$ or $N_F/N_I \leq 3.31$ for 50% of product items
 ≤ 2.29 or $N_F/N_I \leq 1.96 \times 10^2$ for 95% of product items
 ≤ 4.00 or $N_F/N_I \leq 9.98 \times 10^3$ for 99% of product items
(number of product items $I = 100\ 000$).

6. Conclusion

A methodology combining deterministic heat transfer models for the refrigeration equipments and stochastic models taking into account various sources of randomness in the cold chain was proposed. It enables the prediction of the temperature evolution of a large number of products. These temperature evolutions can then be used to estimate microbial growth. Thus, this approach can contribute to evaluate food safety along the cold chain. It can also be used as a complementary approach of survey which is of high cost and time consumption.

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