

# Safety reliability optimal allocation of food cold chain

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## ABSTRACT

This paper applied the safety reliability of food cold chain logistics to establish reliability allocation model for cold chain systems, designed optimization algorithms, and made a case analysis. By applying system reliability allocation principle, this article firstly built safety reliability allocation model of food cold chain logistics system without cost constraint based on the safety reliability model of food cold chain logistics system, and then it set up optimal decision-making model of food cold chain logistics system with cost constraint using the functional relationship between the time, temperature of cold chain logistics and logistics costs. Next, according to the characteristics of the model, a heuristic algorithm was proposed to allocate safety reliability of the system to each cold chain unit so as to achieve the goal of operating costs optimization subject to assurance of overall safety reliability of the cold chain system. Taking the safety impact factor of food cold chain unit as a weight, the article also deduced the equation of reallocation of safety reliability of food cold chain system. In the end, these models were used to optimize the allocation of safety reliability in an example of Sushi cold chain process. It provided a new thought and method to optimally plan the unit safety of food cold chain system as well as reduce the cost of food cold chain.

**Keywords:** Cold Chain; Safety Reliability; Food Logistics System; Allocation Optimization

## 1. INTRODUCTION

Food cold chain is a system engineering which can keep perishable or fresh foods under prescriptive temperature across whole process of logistics such as production, storage, transportation, delivery and sale, so that to keep the food safety, reduce loss and prevent pollution [1]. As a result of lack of index reflecting continuous

changes of food safety in logistics process, few of essays thus far quantitatively studied the safety in the process of food logistics from the system point of view, instead, most of them focused on food quality loss and risk management in food supply chain [2-6]. Although microbial kinetics model may be used to predict the state of food safety [7-9], to be viewed from the safety analysis and optimization of logistics system, it has three aspects of insufficiencies to represent food safety by total bacterial count.

1) It is not intuitive. The safety degree of cold chain can not be determined by means of total bacterial count directly. For example, knowing that the total bacterial count of certain food is 10,000 cfu/ml is not enough for logistics operators and consumers to make exact judgment of safety or not, one also has to understand whether it exceeds health standards before making conclusion.

2) It is not a linear relationship between pathogens number and degree of harm to human body. For such food that its total bacterial count not exceeding the health standards, even people can tell it is safe, they are not informed of the specific safety status and level, hence unable to determine its shelf life.

3) The microbial growth model is precisely in an exponential form. It is quite hard to solve an optimization model with exponential representation.

In view of the above-mentioned facts, [10] modified predictive microbiology model by applying system reliability theory, and established safety reliability model of cold chain that was intuitive and simple to reflect the continuing impact of temperature on the safety of the food cold chain. He also defined the term of the safety reliability of food logistics unit as the probability of food logistics unit controlling the safety of food in an intended scope for a stated period of time under specified operating conditions.

Reliability allocation is a procedure during planning of system that, according to the general requirements of system reliability, to gradually break it up from global to local and allocate to various sub-systems and facilities [11]. It is in fact to solve following basic inequalities:

$$R_s(R_1, R_2, \dots, R_i, \dots, R_n) \geq R_s^* \quad (1)$$

$$g_s(R_1, R_2, \dots, R_i, \dots, R_n) \leq g_s^* \quad (2)$$

where:  $R_s^*$  is system reliability output constraint,  $g_s^*$  is synthesis constraint conditions to system planning, including expenses, weights, power loss, etc.

For a cascade system, Eq.1 may be converted to

$$R_1(t) \cdot R_2(t) \cdots R_i(t) \cdots R_n(t) \geq R_s^*(t) \quad (3)$$

To achieve safety and high efficiency of food cold chain system, it shall take into account of two aspects of restraints when allocate safety reliability: First, the safety constraint, *i.e.* under the condition of given initial safety reliability, it must comply with the stipulated requirements after food passes through the cold chain system; Second, the cost restraint. Food cold chain system is also an economic system that seeks for minimum logistics cost while satisfying safety demands. Therefore, safety reliability allocation of cold logistics system is how to allocate the total safety reliability to each unit so as to minimize total logistics cost. Yet there is no related research at present. This article applies the safety reliability of food cold chain logistics to establish reliability allocation model for cold chain logistics systems, design optimization algorithms, and make a case analysis and discussion.

## 2. ALLOCATION OF SAFETY RELIABILITY WITHOUT COST CONSTRAINT

For a cold chain logistics system composed of  $m$  cold chain units, according to [10], its safety reliability  $R_i$  after food continuously passes through the  $i$ th ( $i \leq m$ ) unit can be expressed as

$$R_i = R_0 - d \sum_{j=1}^i \Delta T_j^2 t_j \quad (0 \leq R_i \leq 1), \quad (4)$$

where:  $R_0$  is initial safety reliability of food cold chain system,  $\Delta T_j = T_j - T_{\min}$  ( $T_j$  is the temperature of cold chain unit  $j$ ,  $T_{\min}$  is the temperature at which no growth of microbial),  $t_j$  is logistics time of cold chain unit  $j$ ,  $d$  is a parameter related to food variety).

As  $\Delta T_j^2 t_j \geq 0$ ,  $R_i$  is non-increasing function which means in food cold chain system, safety reliability gradually decreases from initial point to destination. Normally lower temperature has higher demand for equipment conditions. Yet it is impossible for facilities to reach infinite low temperature, there have to be certain low limits (for instance, some refrigerated trucks' lowest temperature can only reach down to  $0^\circ\text{C}$ ), which we indicate by  $T_j^*$ . Moreover, it usually has restrictions on the processing time of logistics unit. For example, the quickest forwarding time under existing conditions of food transportation and distribution; the shortest time for producing and handling. Here let  $t_j^*$  represent the time-limiting

requirement. We now have safety reliability optimization allocation model of cold chain system as follows:

$$\text{Max} R_m = R_0 - d \sum_{j=1}^m \Delta T_j^2 t_j \quad (5)$$

$$s.t. \quad \sum_{j=1}^m \Delta T_j^2 t_j \leq \frac{1}{d} R_0 \quad (6)$$

$$\Delta T_j \geq T_j^* \geq 0 \quad (j = 1, 2, \dots, m) \quad (7)$$

$$t_j \geq t_j^* \geq 0 \quad (j = 1, 2, \dots, m) \quad (8)$$

Obviously when  $T_j^*$  and  $t_j^*$ , the lower limits of both the temperature and time of each cold chain unit are applied to the above equations,  $\sum_{j=1}^m \Delta T_j^2 t_j$  is the smallest and the objective function reaches its maximum. Mean-time, the cold chain system has highest safety reliability.

## 3. ALLOCATION OF SAFETY RELIABILITY WITH COST CONSTRAINT

### 3.1. Model Establishing

Suppose a cold chain system composed of  $m$  cold chain units, after food passed unit  $j$  ( $j=1, 2, \dots, m$ ), its logistics cost is  $C_j$ , logistics service volume provided is  $V_j$  and safety reliability is  $R_j$ , then the function of cost of the unit is

$$C_j = C_j(V_j, R_j) \quad (9)$$

Logistics service provided by food cold chain unit has typical scale effect (e.g. the higher inventory level in cold store, the lower unit operation cost is; the bigger delivery amount of refrigerated truck, the lower unit distribution cost), that is to say, logistics cost and logistics service volume has the relation of

$$\frac{\partial C_j}{\partial V_j} > 0 \quad \text{and} \quad \frac{\partial^2 C_j}{\partial V_j^2} < 0.$$

Given that cold chain system is a cascade system whose processing capacity is determined by the unit of least processing capacity, when system processing capacity is fixed, it can be represented by the processing time of the logistics system, *i.e.* for food logistics of certain quantity, processing time shortens as processing capacity increases. Therefore under the condition of fixed processing capacity of the system, the processing volume of food cold chain system is proportional to its processing time, while the above equation can be written as

$$\frac{\partial C_j}{\partial t_j} > 0 \quad \text{and} \quad \frac{\partial^2 C_j}{\partial t_j^2} < 0 \quad (10)$$

To maintain low temperature in the process of food cold chain, it needs special refrigerate equipment and consumes energy. Moreover, along with the cold chain

unit temperature drops, much more energy is consumed and equipment of higher technical conditions is required. Consequently, logistics cost increases quickly [12]. Thereupon, cold chain logistics cost and temperature has following relationship:

$$\frac{\partial C_j}{\partial \Delta T_j} > 0 \quad \text{and} \quad \frac{\partial^2 C_j}{\partial \Delta T_j^2} < 0 \quad (11)$$

At present food cold chain usually extends to selling section only. For the sake of consumption safety, it is necessary to reserve certain safety reliability at selling unit. Suppose the requisite final safety reliability of logistics system is no less than  $R_E$ , then we obtain from **Eq.6** that

$$\sum_{j=1}^m \Delta T_j^2 t_j \leq \frac{1}{d} [R_0 - R_E]. \quad (12)$$

In summary, for food cold chain system having constraints of processing capability and safety reliability, its cost optimal decision-making model is as below:

$$\text{Min} C = \sum_{j=1}^m C_j(V_j, R_j) = \sum_{j=1}^m C_j(\Delta T_j, t_j) \quad (13)$$

$$\text{s.t.} \quad \sum_{j=1}^m \Delta T_j^2 t_j \leq \frac{1}{d} [R_0 - R_E]$$

$$\frac{\partial C_j}{\partial t_j} > 0 \quad \text{and} \quad \frac{\partial^2 C_j}{\partial t_j^2} < 0$$

$$\frac{\partial C_j}{\partial \Delta T_j} > 0 \quad \text{and} \quad \frac{\partial^2 C_j}{\partial \Delta T_j^2} < 0$$

$$\Delta T_j \geq T_j^* \geq 0$$

$$t_j \geq t_j^* \geq 0.$$

### 3.2. Heuristic Algorithm

Considering that every cold chain unit has different cost function, plus the expression is complicated, it is rather difficult to solve the model directly. However, we can derive a quite straightforward heuristic algorithm from the special relationship of cold chain cost with temperature and time.

Note from **Eq.4** that the decrease of safety reliability is proportional to logistics time whereas it has a square relation with temperature in logistics unit. Hence it is more effective to regulate the temperature in logistics unit rather than logistic time for acquiring specific safety reliability. And the smaller temperature difference between the various aspects of cold chains, it is more favorable for food quality maintenance [13,14]. That is to say, under the premise of system's overall safety reliability being no less than end-point safety reliability  $R_E$ ,

starting from the logistics unit of lowest temperature, advance its temperature to the same value of the unit of most adjacent temperature; If there are a number of logistics units of the same temperature, then give priority to the unit with longest logistics time; Thus keep adjusting until system's overall safety reliability reaches the requirement  $R_E$ . Following is the algorithm.

Step 1: Arrange  $T_j^*$  in ascending order to obtain a set  $S(s_1, s_2, \dots, s_m)$ .

Step 2: Let  $t_j = t_j^*$ ,  $\Delta T_j = T_j^*$  ( $j=1, 2, \dots, m$ ).

Step 3: If  $\sum_{j=1}^m \Delta T_j^2 t_j > \frac{1}{d} [R_0 - R_E]$ , then no solution and stop; Otherwise go to step 4.

Step 4: Take the smallest element  $s_i$  from the remainder of set  $S$ , its corresponding logistics unit  $j$ , if there are more than one element of the lowest value, then take the one with greatest  $t_j^*$ .

Let  $\Delta T_j = \Delta T_j + (s_{i+1} - s_i)$ , and temperatures of the rest units remain invariable.

If  $\sum_{j=1}^m \Delta T_j^2 t_j = \frac{1}{d} [R_0 - R_E]$ , the optimal solution declared.

If  $\sum_{j=1}^m \Delta T_j^2 t_j > \frac{1}{d} [R_0 - R_E]$ , then gradually narrow down  $\Delta T_j$  till it satisfies  $\sum_{j=1}^m \Delta T_j^2 t_j = \frac{1}{d} [R_0 - R_E]$ , and we obtain the optimal solution.

Step5: If  $\sum_{j=1}^m \Delta T_j^2 t_j < \frac{1}{d} [R_0 - R_E]$ , then remove  $s_i$  from the set  $S$ , rearrange set  $S$  per non-descending order of  $T_j^*$  and return to Step 4.

### 4. REALLOCATION OF SAFETY RELIABILITY

As aforementioned, there is no solution to the optimization model if  $\sum_{j=1}^m \Delta T_j^2 t_j > \frac{1}{d} [R_0 - R_E]$ . Such situation indicates that the existing food cold chain system can not meet the minimum safety reliability requirements and further modification of original planning is necessary to enhance its safety reliability, *i.e.* need to reallocate safety reliability to each logistics unit.

The principle of reliability reallocation is that the unit of lower reliability is easier to improve, otherwise, more difficult. This is actually to reallocate reliability according to the weight of unit in the system. In food cold chain system, the cold chain unit of bigger  $\Delta T^2 t$  has lower safety reliability whereas the one with smaller  $\Delta T^2 t$  has bigger safety reliability. Therefore, reallocation of safety reliability of food cold chain system can be carried on in accordance with  $\Delta T^2 t$  of cold chain unit.

Define  $\Delta T^2 t$  of food cold chain unit  $j$  as its safety impact factor  $f_j$ .

$$f_j = \Delta T_j^2 t_j \tag{14}$$

Assume food cold chain system has  $m$  units, then  $w_j$ , the weight of unit  $j$  in the system is:

$$w_j = \frac{f_j}{\sum_{j=1}^m f_j} \tag{15}$$

Safety reliability of system before optimization is:

$$R_m = R_0 - d \sum_{j=1}^m f_j \tag{16}$$

Let  $R_m^s$  ( $R_m^s > R_m$ ) the optimized safety reliability of cold chain system,  $f_j^*$  the safety impact factor of each cold chain unit. Apply to **Eq.4** to obtain

$$R_m^s = R_0 - d \sum_{j=1}^m f_j^* \tag{17}$$

Thus, according to the principle of reliability reallocation, the equation of optimized safety reliability of each cold chain unit  $R_j^*$  can be written as follows:

$$R_j^* = R_j + w_j (R_m^s - R_m) \tag{18}$$

### 5. CASE ANALYSIS

As made by hand, Sushi is apt to be infected by *Staphylococcus aureus* to cause food safety problem. **Table 1** shows the data of temperature and time restrictions in the process of Sushi cold chain. Suppose the initial safety reliability is 1.0, expected safety reliability is 0.8 so as to ensure edibility after consumer purchased sushi for a period of time; moreover,  $d$  is 0.0003 and no-microbial-growth temperature is 5°C [9].

According to **Eq.4**, we apply the lower limits of both the temperature and time of each cold chain unit to the

equation, and obtain the end-point safety reliability 0.851 (refer to **Table 1** for solving details) which is higher than the expectation of 0.8. From a cost perspective, the logistics system still needs to be optimized under the premise of ensuring safety.

In the light of solution method, first is to optimize the unit of the lowest temperature. It is selling unit (11°C) in this system. Use previous heuristic algorithm to advance the temperature of selling unit to the most adjacent value 13°C of delivering unit, and solve again to acquire safety reliability of the system, which is by then still higher than the expectation of 0.8. Thus after several loops of solving steps, the algorithm finds optimal solution to the temperature and time of each cold chain unit (as shown in **Table 2**), *i.e.* under the premise of full assurance of food safety, it can save logistics cost as far as possible by an appropriate increase in the temperature of delivering unit and selling unit (2°C and 2.5°C respectively).

If the end-point safety reliability requirement is raised to 0.9, when choosing the lower limits of both the temperature and time of each cold chain unit, the end-point safety reliability is 0.851 (see **Table 1**) which is lower than the expectation, the system cannot satisfy the requirement and must reallocate the safety reliability.

The results of safety weight of each cold chain unit  $w_j$  are shown in **Table 3**, wherein the delivering unit has the highest degree of weight that reaches 0.353, and then followed by the selling unit, 0.221, the loading unit is the least, only 0.044.

After reallocation, the system output of safety reliability is 0.901 that satisfies the safety reliability requirement of no less than 0.9. By comparing  $R_j$  and  $R_j^*$  we can find that the safety reliability of delivering unit, the one with highest degree of weight needs to be improved

**Table 1.** Data of Cold chain Units before Optimization.

No. $j$	Cold Chain Unit	Temperature $T_j$ (°C)	Time $t_j$ (h)	$\Delta T_j^2 t_j$	$\sum_{j=1}^i \Delta T_j^2 t_j$	$d \sum_{j=1}^i \Delta T_j^2 t_j$	$R_i$
1	Producing	15.0	0.8	80.0	80.0	0.024	0.976
2	Packing	17.0	0.5	72.0	152.0	0.046	0.954
3	Loading	22.0	0.1	28.9	180.9	0.054	0.946
4	Delivering	13.0	2.3	147.2	328.1	0.098	0.902
5	Unloading	21.0	0.2	51.2	379.3	0.114	0.886
6	Handling	20.0	0.2	45.0	424.3	0.127	0.873
7	Selling	11.0	2.0	72.0	496.3	0.149	0.851

**Table 2.** Data of cold chain units after optimization.

No. $j$	Cold Chain Unit	Temperature $T_j$ (°C)	Time $t_j$ (h)	$\Delta T_j^2 t_j$	$\sum_{j=1}^i \Delta T_j^2 t_j$	$d \sum_{j=1}^i \Delta T_j^2 t_j$	$R_i$
1	Producing	15.0	0.8	80.0	80.0	0.024	0.976
2	Packing	17.0	0.5	72.0	152.0	0.046	0.954
3	Loading	22.0	0.1	28.9	180.9	0.054	0.946
4	Delivering	15.0	2.3	230.0	410.9	0.123	0.877
5	Unloading	21.0	0.2	51.2	462.1	0.138	0.862
6	Handling	20.0	0.2	45.0	507.1	0.152	0.848
7	Selling	13.5	2.0	144.5	651.6	0.196	0.804

the most by 0.048; while handling unit of the least weight needs to be improved the least by only 0.005.

## 6. CONCLUSION AND DISCUSSION

Safety reliability provides a new quantitative method for the analysis and optimization of food cold chain system. For food cold chain system, once knowing ambient temperatures and logistics time, it is convenient to calculate the safety reliability of any cold chain unit and cold chain system, which effectively solves the problem of lack of quantitative tools in the study of cold chain system. However as a new indicator, the validity and scope of application is naturally an issue of concern. We re-calculated the shelf life in some literature according to the safety reliability model and then compared with the original data. The results indicated that the deviation fell in acceptable range (see **Table 4**). That proves that safety reliability model can be applied to reliability optimally allocate of food cold chain system under certain conditions.

Certainly any model has its applicable conditions. Safety reliability model of food cold chain is built on the basis of kinetics model of microbial growth whose applicable conditions also apply to safety reliability model. To be specific, there are following three aspects:

1) Sealed package. The sealed package is mainly to avoid secondary or multiple infections by microorganisms in food logistics process; it also prevents the physical and chemical hazards. Without sealed packaging, safety reliability model is unable to calculate and assess the final result because of uncertainty of the infected microbe species and their initial values, plus possible conti-

nuous new pathogenic invasion in logistics process.

2) Protein-rich food. Protein-rich food (milk, meat and poultry, etc.) is suitable for microbial growth and microbe hazard is the most important factor affecting its logistics safety, which can be expressed by safety reliability model. Yet for low-protein-content food such as fruits and vegetables, microbe hazards are not the main safety factors; moreover, if not to be eaten as it is (e.g. fruits, vegetables, etc.), instead, cleaned and even cooked for consumption, then the propagation of pathogenic bacteria may not cause actual harm to the human body. Thus the model has better effect for the safety assessment of fresh milk, chilled meat, frozen food and cooked food, etc.

3) Minimum logistics ambient temperature. When food logistics ambient temperature is below the minimum microbial growth temperature, the number of microbes will not increase, food safety remains unchanged. Meanwhile in safety reliability model,  $(T_i - T_{\min})^2 t \geq 0$  indicates that safety reliability is reduced. Therefore safety reliability is only suitable for the situation when logistics ambient temperature is higher than the minimum microbial growth temperature. For the case of logistics ambient temperature being lower than the minimum microbial growth temperature, as the microbes in a dormant state, pathogenic bacteria number in the logistics process will not increase, consequently at this moment there is no need to consider the safety changes in logistics process.

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**Table 3.** Safety Reliability of Each Cold Chain Unit after Relocation.

No. <i>j</i>	Cold Chain Unit	$f_j$	$w_j$	$f_j^*$	$R_j^*$
1	Producing	80.0	0.123	59.9	0.982
2	Packing	72.0	0.110	54.0	0.965
3	Loading	28.9	0.044	21.7	0.959
4	Delivering	230.0	0.353	172.4	0.938
5	Unloading	51.2	0.078	38.5	0.926
6	Handling	45.0	0.069	33.7	0.916
7	Selling	144.5	0.221	36.1	0.901

**Table 4.** Comparison of shelf life results predicted by safety reliability model and original data in literature.

Food Type	$T$ (°C)	Shelf Life (h)	Reference	Model Calculation (h)	Deviation
Sushi	17.4	4.7	[9]	4.26	9.3%
Sushi	21.8	3.1	[9]	3.49	12.6%
Chicken	8.0	168	[15]	187	11.3%
Pork	4.0	116	[16]	124	6.9%
Pork	10.0	60	[16]	55	9.2%

(NO.71172077) and “The study on control mechanism and key parameters optimization of perishable food multi-temperature refrigerated transport” (NO. 51008087).

## REFERENCES

- [1] Liu, B.L. (2004) Food preservation and cold chain. Chemical Industry Publishers of China, 163.
- [2] Adrie J. (2005) Food safety and transparency in food chains and networks. *Food Control*, **16**, 481-486. <http://dx.doi.org/10.1016/j.foodcont.2003.10.010>
- [3] Fearne, A., Hornibrook, S. and Dedman, S. (2001) The management of perceived risk in the food supply chain: a comparative study of retailer-led beef quality assurance schemes in Germany and Italy. *The International Food and Agribusiness Management Review*, **4**, 19-36. [http://dx.doi.org/10.1016/S1096-7508\(01\)00068-4](http://dx.doi.org/10.1016/S1096-7508(01)00068-4)
- [4] Van der Gaag, M.A., Vos, F., Saatkamp, H.W., Van Boven, M., Van Beek, P. and Huirne, R.B.M. (2004) A state-transition simulation model for the spread of Salmonella in the pork supply chain. *European Journal of Operational Research*, **156**, 782-798. [http://dx.doi.org/10.1016/S0377-2217\(03\)00141-3](http://dx.doi.org/10.1016/S0377-2217(03)00141-3)
- [5] Aruoma, O.I. (2006) The impact of food regulation on the food supply Chain. *Toxicology*, **221**, 119-127. <http://dx.doi.org/10.1016/j.tox.2005.12.024>
- [6] Tijskens, L.M.M. and Polderdijk, J.J. (1996) A generic model for keeping quality of vegetable produce during storage and distribution. *Agricultural Systems*, **51**, 431-452. [http://dx.doi.org/10.1016/0308-521X\(95\)00058-D](http://dx.doi.org/10.1016/0308-521X(95)00058-D)
- [7] Zwietering, M.H., De Wit, J.C. and Notermans, S. (1996) Application of predictive microbiology to estimate the number of bacillus cereus in pasteurized milk at the point of consumption. *International Journal of Food Microbiology*, **30**, 55-70.
- [8] Zwietering, M.H. (2002) Quantification of microbial quality and safety in minimally processed foods. *International Dairy Journal*, **12**, 263-271.
- [9] Rho, M.-J. and Schaffner, D.W. (2007) Microbial risk assessment of staphylococcal food poisoning in Korean kimbab. *International Journal of Food Microbiology*, **116**, 332-338. <http://dx.doi.org/10.1016/j.ijfoodmicro.2007.02.006>
- [10] Zou, Y.F., Xie, R.H. and Lin C.P. (2010) Study on safety reliability of foods cold chain logistics. *Proceedings of the 3rd International Conference on Logistics and Supply Chain Management*, 2010, 425-443.
- [11] Zeng S.K., Zhao T.D., Zhang, J.G., Kang, R. and Shi, J.Y. (2001) Design and analysis textbook of system reliability. Beijing Aerospace University Publishers, Beijing, China, 52-66.
- [12] Liu, G.H. (2007) Study on analysis of energy consumption and optimization of refrigerated transportation equipment. Doctoral dissertation of Central South University, Changsha, China.
- [13] Chen, L., Shen, J. and Zou, T.H. (2002) The frequency analysis on the temperature fluctuation of the cold store. *Journal of Refrigeration*, **4**, 13-17.
- [14] Flores, S., Cleland, A.C. and Cleland, D.J. (2001) Prediction of the dynamic thermal behavior of walls for refrigerated rooms using lumped and distributed parameter models. *International Journal of Refrigeration*, **24**, 272-284. [http://dx.doi.org/10.1016/S0140-7007\(00\)00018-9](http://dx.doi.org/10.1016/S0140-7007(00)00018-9)
- [15] Betts, G. and Everis, L. (1996) Shelf-life determination and challenge. CCFRA Guideline No. 11, CCFRA, Chip-ping, Campden, UK, 1996.
- [16] Li, M.Y. (2006) Study on the analysis of microbial ecology in chilled pork and shelf life predictive mode. Dissertation of Nanjing Agricultural University, Nanjing, China, 91-104.