A MODEL TO PREDICT SHELF-LIFE LOSS OF HORTICULTURAL PRODUCE DURING DISTRIBUTION WITH FLUCTUATED TEMPERATURE AND VEHICLE VIBRATION

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Abstract: Fresh fruits and vegetables has become a public concern from the food security aspect. And the prediction of shelf-life loss under the fluctuated temperature becomes one of the key problems in food supply chain operation. So this paper identifies the impact aspects of produce decaying during distribution. For the key temperature factor, the process is divided into three phases: sorting, traveling and door-opening. Based on time-temperature function, a model of shelf-life loss of horticultural produce during distribution is developed by evaluating respiration rate of vegetables and fruits considering both the environment fluctuated temperature and vehicle vibration during traveling. Taking eggplant as an example, the numerical experiment result demonstrates that the average cost for ambient distribution is 2.8 times of the insulation way.

Keywords: shelf-life, horticultural produce, distribution, respiration rate

1. INTRODUCTION

Food is vital to human being which plays an important and fundamental part in sustaining life. Nowadays, consumers' increasing awareness of food safety and quality has become the major internal drivers for the government to play an efficient and effective security role of produce safety. "Special provisions on strengthening food safety supervision and management by State Council","2008 Beijing Olympic Food Safety Action Program" have been promulgated which indicate the Chinese Government has paid high attention to the national physical fitness. On another side, food business today is operating in a complex and changeable commercial environment. If companies want to survive, they must remain ahead of food security surveillance to keep perishable food fresh. So, the prediction of shelf-life loss naturally becomes one of the key problems in food logistics operation.

The unique characteristics of fresh food which differs form other processed items is the high rate of spoilage. The product moves along the "from farm to table" supply chain network going with sharp chemical and biochemical changes any time. In the last two decades many papers have been devoted to research on application and modeling for the food quality. (Johanne Rønnow Olsen, 2008) proposed that quality is a main determinant of consumer food choice and they investigate managerial quality goals and how these may be linked to product development competences. For animal produce such as meat, poultry and fish, Lynette(M. Johnston, 2006) pointed out that the loss of produce quality is the result of bacterial growth. (Fanbin Kong, 2007, Tomas Skoglund and Petr Dejmek, 2008) explained the relationship between food quality transformation by predictive microbiology and kinetics. For the horticultural produce, Uchino, (Nei,2004) develop a respiration model for time and temperature dependence to simulate the respiration rate for fresh produce during transport, retailing and storage. Roy, Nei et al. (2008) had done the life cycle inventory analysis of fresh tomato distribution systems in Japan considering the quality aspect. The result of (Li Guo,2008) demonstrated that the speed of green bean quality loss is influence by storage temperature and strength of CO_2 with the characters of respiration rate, weight loss, change in titrable acidity and sugar. (G. Urrutia-Benet etc 2007) showed at laboratory and pilot scale that potatoes' decaying speed was not increased after freezing and thawing processes when pressure was applied, being even slightly reduced in the metastable region. In the distribution process, the main quality affecting factors are environment temperature and vehicle-shake. Bogataj, (Bogataj,2005) forecasted the temperature evolution in cold logistic chain, and analysis the sensitivity of its fluctuation. (Van Zeebroeck, Tijskens ,2006) and (Van Zeebroeck,2007) used discrete element method to simulate the apples' damage during transportation. However, during the distribution process, the temperature is not constant but changeable and the vibration has to be considered at the same time. But there are few models on it up to now. That is the reason why we present this paper.

The rest of paper is organized as follows. First, impact factors of produce decaying during distribution are identified. And based on time-temperature function, a model of shelf-life loss of horticultural produce during distribution is developed by evaluating respiration rate. And computational results and discussion are presented later. Finally conclusions are drawn.

2. IMPACT FACTORS

Perishability arises mainly in agri-product such as fruits and vegetables, meat and poultry, fish and shellfish, milk etc. All of them deteriorate at a high speed as well as their semi-processed foods. In accordance with the composition of the food itself, they can be divided into two groups: animal produce and horticultural one. Raw materials can be strictly divided into these two categories, fruits and vegetables for the horticultural produce, meat and poultry for the animal produce of which decaying rate is easy to measure. But if the food is processed by both types of raw produce, take quick-frozen dumpling and bento as an example, the prediction of quality decreasing rate is much more complex.

Food deteriorates and spoils in a very complicated way with many chemical and biochemical reactions taking place at the same time. However, the main activities are microbial growth of meat and enzymes activity of plant. Fig.1 describes the primary factors affecting the perishable food during delivery. For animal food, the life is end without energy absorption from the environment to maintain its basic metabolism. The food corruption causes mainly by different types of microbial growth whose concentration impact by temperature greatly. Moreover the wind speed, solar radiation, air temperature and the times of door opening will cause the change of temperature. The temperature of perishable food distribution by cold chain in the urban area is different from the long-distance transportation's. For transportation, the period between one door opening and another is longer and less frequently with light temperature change. On the contrary, the travel time is shorter between two delivering customers and the door has to be opened more often for distribution. This is why the distribution temperature is fluctuated dramatically. For the plant food, the produce is still alive after harvest. They are breathing all the time in the supply chain. As they can not absorb nutrition from the nature, the respiration decomposes the food body itself then get rotten. That is the reason why the total amount of exhaled carbon dioxide is used to measure the waste quality of vegetables and fruits. In this paper we ignore the influence to respiration rate by water activity and gas composition but only temperature and vehicle vibration. The road condition, vehicle acceleration and position on the compartment will affect the intensity of vibration. Generally, items at the rear suffer greater vibration than ones on the front and the intensity at the bottom is less then the top.

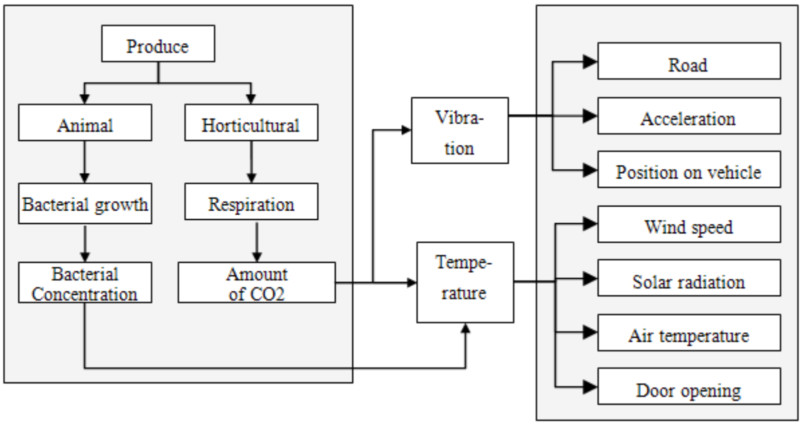

Fig.1: Primary factors affecting the perishable food during delivery

3. TIME-TEMPERATURE MODEL

Temperature plays a key role in the food quality decision in distribution the same as warehousing and transportation. So cold chain research today focuses on temperature control. Although the International Institute of Refrigeration recommended the fresh produce transport temperature, each country has its own regulation. For example, the temperature can not exceed 7℃ for meat product distribution in Australia. However, because of the high frequency switching doors and oxygen contact, the outside world impacts the food dramatically. Even with the refrigerator, the temperature inside will keep on fluctuating. According to it, the temperature variety is divided into three stages stage:

Sorting: Goods are sorted based on the food type and customer requirement artificially or by equipment and taken from the shelf to the handling area. Then they are ready for distribution. According to the plan all produce will be loaded into the trucks. In this process, the fresh suddenly get exposed in the air making the food hot with heavy breathing.

Traveling: The quality is influenced by the vehicle type and acceleration, outside temperature, wind speed, solar radiation and road condition with temperature increases.

Door opening: the door switching is an inevitable operation in discharging loads. After the door is opened, the air outside will flush into the compartment which results in the heat exchange leading to the food temperature increases.

The time-temperature function is described by a sub-linear relationship:

$$T(t) = \begin{cases} a_s t + b_s & , \quad t \in [s_{tart}, s_{end}] \\ a_c(i)t + b_c(i) & , \quad t \in [c_{start}(i), tc_{end}(i)] \\ a_t(i)t + b_t(i) & , \quad t \in [t_{start}(i), t_{end}(i)] \\ a_o(i)t + b_o(i) & , \quad t \in [o_{start}(i), o_{end}(i)] \end{cases} \quad (1)$$

Where: a(i) is the temperature evolution rate of period i, b(i) denotes the temperature adjustment of period i, s denotes sorting period, c cooling period while traveling, t is only traveling period, o is door opening period, T is temperature, t is time, i denotes the period i.

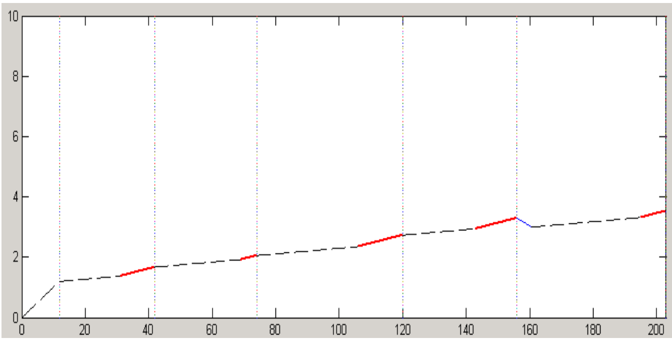

Fig.2: Time-temperature evolution

The vertical dashed separate time-temperature evolution into six periods that is to say the vehicle serves six customers (see fig.2). The first period is for sorting. Form the second to the fifth the dashed line is for traveling and the real line is for door opening which has a stronger temperature shift. In the last one, there are three sub-lines, first one is for cooling with decreased temperature and then the other is for traveling and door-opening.

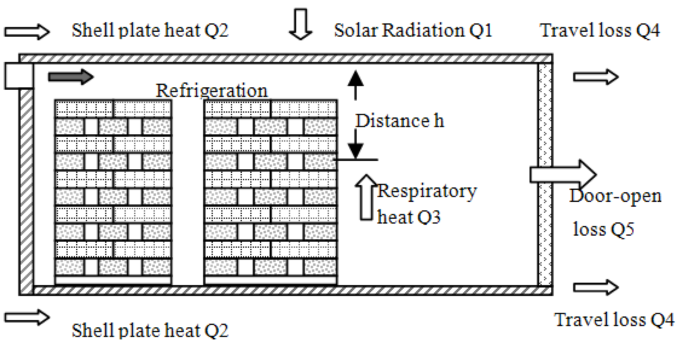

Fig.4: Cold consumption id the delivery process

In real life, there are many factors change the temperature inside the delivery vehicle, food's breath will produce heat and conduct the thermal by both conductivity and radiation with the environment which is a very complicated process. To simplify the calculation, only the main factors are considered. As shown in Fig. 4, the refrigeration vents is usually installed in the upper front of the compartment with refrigeration Q0; the impact from air temperature and solar radiation is Q1; cold consumption from the shell is Q2; respiration hot is Q3; cold loss because of internal and external pressure is travel loss Q4; the loss by opening the door and loading cargo is Q5. The total consumption of cold Q to influence the temperature is:

$$Q=Q1+Q2+Q3+Q4+Q5-Q0 \tag{2}$$

4. SELF-LIFE LOSS PREDICTION MODEL

Horticultural produce is different from meat because life still continues. The respiration of fruits and vegetables is the symbol of continuity of living. In the cultivation process, the individual can obtain nutrients form the natural world. However, in the circulation process, it can not, so it decomposes to maintain the life of its normal activities. There is a correlation between the corruption velocity and respiration rate with temperature as a major factor. Therefore, the self-life loss is evaluated by the amount of CO_2 caused by reparation which is affected by fluctuated temperature and truck vibration.

Toshitaka Uchino(2004) simulate the respiration rate of fresh produce with a model based on the enzyme kinetics. They respiration rate is presented as follows:

$$R_c = A \cdot \exp\left(\frac{-Ea}{RT}\right)\left\{\frac{k_s}{k_d} - \left(\frac{k_s}{k_d} - [E]_0\right)\cdot \exp(-k_d \cdot t)\right\} \tag{3}$$

Where: R_c is the respiration rate (mmolkg^{-1}h^{-1}), A is pre-exponential factor(h^{-1}), Ea shows the apparent activation energy(J mol^{-1})，R is ideal gas constant(J mol^{-1}K^{-1}），T absolute temperature(K), k_s denotes rate constant of synthesis of enzyme(mmolkg^{-1}h^{-1}) and k_d is rate constant of decomposition(h^{-1}),[E] is the enzyme concentration (mmolkg^{-1}), $[E]_0$ is the initial concentration, t is time(h).

Based on Toshitaka's Eq.(3), substitute time-temperature Eq.(1) into Eq.(3) transforming the respiration rate Rc(T , t) to Rc(t) with only one variable time t:

$$R_c = A \cdot \exp\left(\frac{-Ea}{R(a \cdot t + b)}\right)\left\{\frac{k_s}{k_d} - \left(\frac{k_s}{k_d} - [E]_0\right)\cdot \exp(-k_d \cdot t)\right\} \tag{4}$$

As the distribution food has to be transported to overcome space distance, the produce will get a certain degree of injury which will lead to the respiration increase during the sorting and delivering operations. Japanese scholar proposed a quantitative model to evaluate the traffic injury according to Palmgren-Miner linear cumulative rule (Heye Chengfu, 1999). The model described as follows:

First, suppose the injury is D caused by the harmonic vibration while the acceleration amplitude vibration Gi for the frequency n_i ($n_i = 1,2,\dots$), then:

$$D = \frac{1}{\beta}\sum n_i G_i^{\alpha} \tag{5}$$

α、β denote constant of food characteristics. The injury caused by random vibration:

$$D = \frac{f_0 t}{\beta}(\sqrt{2\sigma})^3 \Gamma(1+\frac{\alpha}{2}) \tag{6}$$

f_0 is the average frequency of vibration, σ is transient stress probability density standard deviation, Γ represents the gamma function(Heye Chengfu, 1999).

Suppose there is a positive correlation between the degree of injury and respiration rate then:

$$R_c = m \cdot D \cdot A \cdot \exp(\frac{-Ea}{RT})\left\{\frac{k_s}{k_d} - (\frac{k_s}{k_d} - [E]_0) \cdot \exp(-k_d \cdot t)\right\} \tag{7}$$

m denotes the injury adjustment factor. Integral the respiration rate to compute the amount of CO2 (TCO2):

$$TCO_2(t) = \int_{t_0}^{t} R_c(t)dt \tag{8}$$

Then, substitute respiration rate Eq.(7) into Eq.(8)

$$TCO_2(t) = \int_{t_0}^{t} m \cdot D \cdot A \cdot \exp(\frac{-Ea}{R(a \cdot t + b)})\left\{\frac{k_s}{k_d} - (\frac{k_s}{k_d} - [E]_0) \cdot \exp(-k_d \cdot t)\right\} \tag{9}$$

Let $K_1 = \frac{K_s}{K_d}A$, $K_2 = \frac{K_d}{K_s}[E]_0 - 1$, then

$$TCO^2(t) = \int_{t_0}^{t} m \cdot D \cdot K_1 \cdot \exp(\frac{-Ea}{R(a \cdot t + b)})\{1 + K_2 \cdot \exp(-k_d \cdot t)\} \tag{10}$$

Don W. Brash(1995) discovered that a similar strong negative correlation obtained between shelf-life and a accumulated heat units and CO2 is linearly related to accumulated heat units. So the shelf-life of customer (SLP) can be presented as：

$$SLP = b_{co2} - a_{co2} \times TCO_2 \tag{11}$$

b_{co2} and a_{co2} is shelf-life constant.

Next we have to calculate the $Load_i$ which represents the truck load from customer i to customer i+1 (see fig.5):

$$Load_i = \sum_{k=i+1}^{M} g_k, \quad i = 0,1,\cdots M-1 \tag{12}$$

M is the number of customer, g_i denotes the request of customer i (i=1,2,⋯,M), i=0 is distribution center. The total shelf-life loss of plant food is described as:

$$TSLP = \sum_{k=0}^{i-1} load_i \times (SLP_i - SLP_{i+1}) \quad (13)$$

C_{PSLP} is the value for each unit. Then, we evaluate the total value loss C_{TSLP}:

$$C_{TSLP} = C_{PSLP} \times TSLP \quad (14)$$

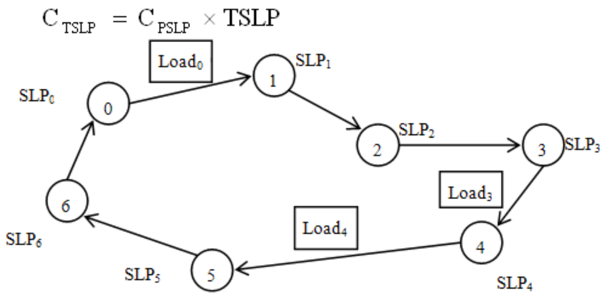

Fig.5: Shelf-life loss parameters during distribution

5. CASE STUDY

The model is coded in Matlab 7.0 on a computer with AMD Sempron(tm) Processor LE-1100 1.91GHz， 512M RAM， Windows XP. The temperature evolution rate, sorting time, traveling time from one customer to another, door opening time, loading time and customer requirement are generated by random number. The vehicle travel input parameters are in Table 1. The traveltimes, opentimes and loads are array generated by the size of amount of customers.

Table 3. Travel input data

Parameter	Meaning	Range	Unit
a_s	Evolution rate of sorting	[0.08,0.12]	℃/m
a_c	Evolution rate of cooling	[-0.03,-0.07]	℃/m
a_t	Evolution rate of traveling	[0.006,0.01]	℃/m
a_o	Evolution rate of door opening	[0.01,0.03]	℃/m
picktime	Sorting time	[10,30]	m
traveltimes	Traveling time	[15,45]	m
opentimes	Door opening time	[5,20]	m
loads	Customer requirements	[50,100]	kg
size	Amount of customers	[5,10]	-

The numerical experiment takes eggplant as an example and the respiration related input parameters are in Table 2.

Table2. Eggplant respiration data

Parameter	Value	Parameter	Value	Parameter	Value
m	1.00	Ea	193.00	α	3.00
K_1	2760.00	R	0.83	β	2.27×105
K_2	0.79	f_0	2.80	σ	0.12
k_d	0.29	a_{co2}	0.002	C_{PSLP}	0.1

Because the absolute value of result can not fully reflect the quality loss of agricultural products, in this paper we simulate two types of distribution respectively: ambient distribution of which the temperature evolution is the above curve in figure 6 and insulation distribution of which the temperature evolution is the below curve. The initial temperature of ambient distribution is a random number between [37K, 42K] and the insulation distribution is a constant 32K.

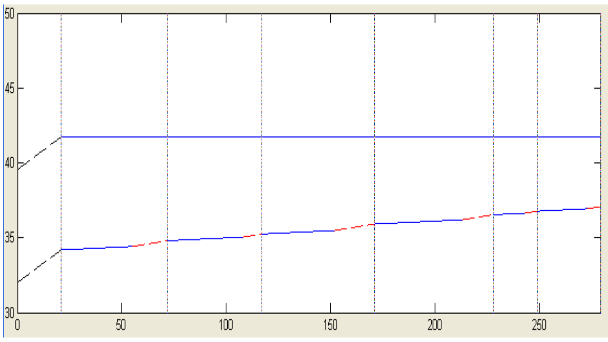

Fig.6: Time temperature evolution curves

According to the input parameters in Table 1 and 2, operate the Matlab procedure for 30 times. The average load is 415.82kg, the average cost for insulation distribution is 141.68 RMB, the average cost for ambient distribution is 397.45 RMB which is 2.8 times of insulation way.

6. CONCLUSION

Temperature and vibration are considered to be the most important factors in evaluating the shelf-life loss of horticultural produce during distribution. So, a model of the loss is developed by evaluating the respiration rate. In order to simulate the distribution process, the mathematical tool Matlab is used taking eggplant as an example. The numerical experiment result demonstrates that the average cost for ambient distribution is 2.8 times of the insulation way. It is concluded that this approach to predicting shelf-life loss of horticultural during distribution has considerable potential in real time food safety surveillance in food logistics.

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