INTELLIGENT COLD SUPPLY CHAIN MANAGEMENT SYSTEM WITH RADIO FREQUENCY IDENTIFICATION, GLOBAL POSITIONING SYSTEM, AND WIRELESS SENSOR NETWORK

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Intelligent Cold Supply Chain Management System with Radio Frequency

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The Supervisory Committee certifies that this ***disquisition*** complies with North Dakota State University's regulations and meets the accepted standards for the degree of

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ABSTRACT

Yang, Xiaomin, M.S., Department of Industrial and Manufacturing Engineering, College of Engineering and Architecture, North Dakota State University, December 2009. Intelligent Cold Supply Chain Management System with Radio Frequency Identification, Global Positioning System, and Wireless Sensor Network. Major Professors: Dr. Jing Shi, and Dr. Kambiz Farahmand.

This thesis establishes an intelligent cold supply chain management system which consists of two parts: one is the intelligent tracking system integrated with Radio Frequency Identification (RFID), Global Positioning System (GPS), and Wireless Sensor Network (WSN); the other is the cold supply chain model.

This tracking system is mainly designed to monitor the food products during the transport, including two parts, a data terminal and a data server. The data terminal is installed inside a container, comprised of GPS, Bluetooth, industrial computer, WSN, RFID reader, RFID antenna, and Code Division Multiple Access (CDMA) modem. The data server is a computer which is able to access internet and has one Structured Query Language (SQL) database. Related application programs are developed with JAVA language. The whole system is successfully tested and meets the expectations we desired at the beginning. In this study, a refrigerator is used to simulate the environment of the container. The data terminal collects all information, including temperature inside the container, GPS location, Product's Identification, and current time in five minute intervals (customers will be asked to set this time interval at the beginning). CDMA cellular network provides the communication between the data server and the data terminal. The data server receives all information and saves the information in the SQL database, which can be used to predict the food safety. Advantages of this tracking system include the ability: 1) to trace and track the products starting from the suppliers to retailers; 2) to monitor and store

important parameters during the processing and distribution of food products, such as temperature; 3) to communicate in real time for prompt response; and 4) to quantify food safety prediction.

The objective of the model developed in this study is to maximize the profit of the cold supply chain. There are one distribution center, multiple retailers and suppliers involved in the cold supply chain. Since the real-time quality situations of products are available even during the transport, retailers can set prices of products based on the real quality situation. The company is able to dynamically plan the quantity of distribution from the distribution or suppliers' site. In addition, retailers are able to manage the inventory based on the real shelf life of products. This thesis also concludes all different inventory results for retailers under different scenarios which can help retailers to predict and manage the inventory. The optimization software, Lindo, is used to demonstrate that this model is capable to dynamically plan the distribution quantity. The sensitivity analysis for prices, transportation costs, and holding costs is discussed to simulate different situations during the transportation and distribution.

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CHAPTER 1. INTRODUCTION

From the statistics of food industry overview, shown in Table 1.1, in the United States consumers spend approximately one trillion dollars annually on food, which is nearly 10 percent of the Gross Domestic Product, and over 16.5 million people are employed in the food industry.

Table 1.1. Food industry overview in United States [1]

	Quantity	Unit	Date	Source
Total food sales, U.S.	1537	Bil. US$	2008	Plunkett Research Estimate
Supermarket and store food sales	527	Bil. US$	2008	U.S. Department of the Census
Restaurant food sales	566	Bil. US$	2009	National Restaurant Association
Red meat consumption per person	112.9	Lbs./Person	2009	United States Department of Agriculture
Fruit production, Citrus & Non-Citrus	30277	Thous. Tons	2008	Plunkett Research Estimate

Our food, before we eat it, travels through the mixmaster known as the food industry. Food processors and manufacturers are the key components in the food industry. The cold supply chain is one of the most important parts within the food industry because of the special features and storage requirements of perishable food. Food safety is always a primary consideration of the public, moreover, the constantly occurred food spoilage problems force manufacturers, logistics, providers and the government to address existing issues.

Food quality is related to the acceptability of the food to consumers, which depends on various subjective factors as taste, palatability, aroma, and appearance [2]. The need for having safe foods in the food supply around the world is of paramount importance. A recent food safety incident in the U.S. is the *E. coli* O157:H7 outbreak from spinach in September 2006, which sickened nearly 300 people and killed three in 26 U.S. states and Canada. The economic cost was clearly large, but the illness and loss of life was devastating. According to the World Health Organization (WHO), about 33% of the population suffer a food borne disease even in industrialized countries. In the United States, the U.S. Centers for Disease Control and Prevention (CDC) estimates that about 25% of the population will suffer, at some time in their life, an illness associated with a food borne pathogen. Regulations have been established to protect the safety of foods during the distribution process. For instance, the U.S. Food and Drug Administration (FDA) demands the establishment and maintenance of records, which must identify the previous source and subsequent recipient of foods in the U.S. supply chain. This is also called the "one up and one down" rule. In United States FDA regulated $417 billion worth of domestic food and $49 billion imported food each year to ensure the food American consumers eat is safe. Many food regulations are issued by U. S. Department of Agriculture (USDA), and (Food and Drug Administration) FDA.

There are two ways to facilitate better cold chain management, logistical and monitoring solutions [3]. Due to the pressing need, we have seen research efforts in combating the threats of unsafe foods – quality control and warning mechanisms have been developed based on sensor technologies, tracking techniques such as radio frequency identification (RFID), and global positioning system (GPS). Studman surveys the applications of sensor technology for post-harvest applications of sensors [4]. It shows that the sensors are used in monitoring the storage conditions of food products, inventory controls, sorting and weighing of various food and produce, transportation, and further handling at the distributor and/or the grocery stores and supermarkets. Wang et al. investigate the effects of wireless sensor technology in agriculture and food industry, introducing some examples of applications of wireless sensors and networks in agriculture and food production, including environment monitoring, precision agriculture, machine and process control, building and facility automation and traceability systems [5]. It is estimated that once the sector reaches critical mass, wireless sensor networks expects to grow by 200% per year till the market is saturated. Frisby et al. develop an autonomous, wireless pH and temperature sensing system for monitoring pig quality [6]. By collecting real time pH and temperature data of the carcass during the first 24 hours after the slaughter, it is possible to identify the non-normal carcass from the normal one. Tan et al. employ a gas sensor for freeze damage detection in oranges [7]. By measuring the ethanol and carbon dioxide levels, a classification for sound and non-sound oranges can be made.

The use of Radio Frequency Identification (RFID) technology in cold chain industry has been increasing. It can provide the minute information on the inventory, logistics and the freshness. In the meantime, it helps to reduce manual labor activities as well as theft and misplacement incidents of the food products. Prate et al. evaluate the impact of RFID on supply chains [8]. International Institute of Refrigeration (IIR) summarized the application of RFID technologies to improve the performance of perishable supply chains, first, tracking the geographical position of individual packages, pallets, shipping containers, or trucks, stationary or in movement; second, identifying items through a unique electronic product code (EPC) or other barcode alternatives; third, storing real time environmental data, such as temperature, and transmitting this information in near real time, allowing corrective actions to be taken in advance before products get damaged [9]. Due to the improved visibility of supply chain, the inventory levels can be decreased, and the retailer can have more shelf space to provide additional products with more variety.

Smith et al. discuss the traceability of food products from a US perspective [10]. Many of the traceability requirements for food products in US are voluntary rather than mandatory. They point out that the link between the farms, ranches, finishing facilities and packer/processor is weak, and additional measures are required to strengthen the link and provide a comprehensive traceability and accountability. What's more, it is believed that sensors coupled with RFID technology carry tremendous potential for food industry [5]. The food products can be tracked and traced, and, at the same time, important parameters during the processing and distribution of food products can be closely monitored, stored and evaluated. Research on integration of sensor and RFID technology for cold chain application is in early stage. Jedermann et al. discuss applying sensor networks, RFID technology and software agents for monitoring the fruit conditions for the transportation [11]. The ethylene sensors are deployed to monitor the levels of ethylene gas during transportation of fruits. Even one overripe fruit can spoil hundreds of tones if they are connected to the same closed loop air stream. Sensor data can be logged during transportation and downloaded later.

On the other hand, the existing technical solutions to our knowledge are not able to address the special requirements on monitoring of foods during transportation, which is critical for cold chain because the potential threats can grow with poor environment control on carrier vehicles, and they will be spread out geographically. To tackle the challenge, a new solution needs to be developed. This not only requires the basic tracking and sensing, but also calls for the real-time communication capability for prompt response and the capability of quantitative prediction of food safety.

In this research, we also suggest a model to optimize the total supply chain, based on the real data from tracing and tracking system. Traditionally, people consider two classifications of perishability: fixed lifetime and random lifetime; the former category includes those cases where the lifetime is known a priori to be a specified number of periods or a length of time independent of all other parameters of the system. The latter category will include exponential decay as a special case and will also include those cases where the product lifetime is a random variable with a specified probability distribution [12]. In our model, the life time will be predicted with the real quality situation of the products during the whole supply chain, from the suppliers to the retailers, even including the transit time. The model in this thesis could dynamically make planning the whole supply chain, and provide quality status of products from suppliers to retailers, meeting the requirement of regulations of food and ensuring the customer's safety.

CHAPTER 2. LITERATURE REVIEW

2.1. Food safety and quality

This section provides a literature review for food safety, regulations, and predictive microbiology. The Centers for Disease Control and Prevention (CDC) estimated that Escherichia coli O157 (O157 STEC) infections cause 73,000 illnesses annually in the United States, causing more than 2,000 hospitalizations and 60 deaths [13]. The impact of food regulations on the food supply chain is discussed by a lot of researches. In addition, if we could predict the bacterial growth in food, we can prevent the consequences of the deteriorated food in advance. Predictive microbiology in an area of food microbiology is wildly used in the last two decades. Food microbiologists have been working on models of microbial growth which might predict the microbiological consequences of food storage.

2.1.1. Food safety and regulations

The study that Food Net conducted is based on the seven categories of annual O157 STEC cases, from person who not hospitalized and survived to patients who died, and the total cost of those separately estimated cost for each of the seven severity categories includes the costs from medical care, lost productivity, and premature deaths and are reported 405 million in 2003 dollars [13].

The Centers for Disease Control and Prevention (CDC) also monitors food borne microorganisms under its Food Net program, Figure 2.1 shows the relative rates compared with 1996 – 1998 baseline period of laboratory – diagnosed cases of infection with Campylobacter, O157 STEC, Listeria, Salmonella and Vibrio. We can see although the incidence of illnesses associated with these food borne microorganisms has mostly remained steady or gone down since the late 1990s, Vibrio and Escherichia coli (STEC) O157 increase recently, and further progress is needed [14].

The Food Protection Plan addressed by FDA presents a robust strategy to protect the nation's food supply from both unintentional contamination and deliberate attack is based on three integrated elements of protection: Preventing food borne illnesses in the first place; Intervening with risk based FDA actions at critical points in the food supply chain; and Responding rapidly when contaminated food or feed is detected.

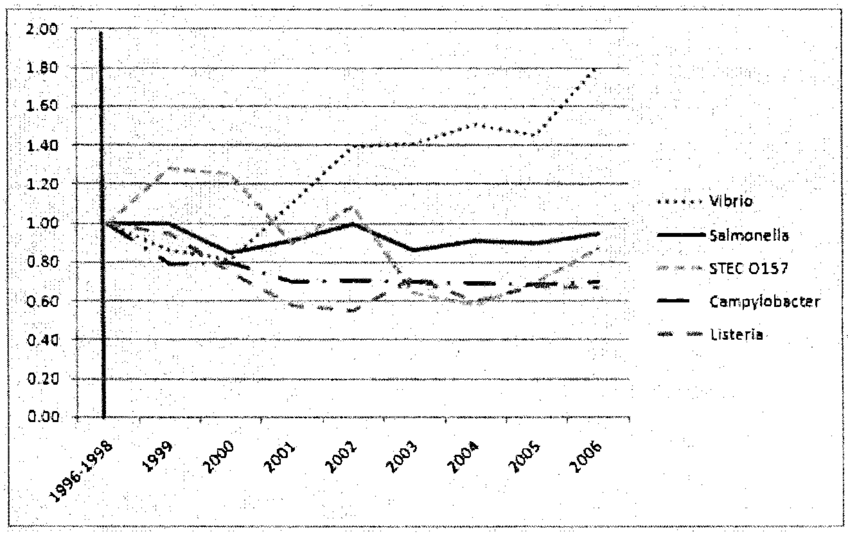

Figure 2.1. Relative rates compared with 1996-1998 baseline cases of infection [14]

Aruoma thought the main aim of food regulation is at protecting the consumer's health, increasing economic viability, harmonizing well being and engendering fair trade on foods within and between nations [15].

M. reviewed a literature about regulatory impact assessment, the United States government has taken the lead in making regulations impact assessment, based on benefit cost analysis, a part of policy formation process. US policy requires an assessment of all major regulations, likely to have an impact of at least $100 million. The benefits of food safety regulation are reductions in risks of morbidity and mortality associated with consuming foods that could be contaminated with microbial pathogens and other hazards. There are some economic approaches to analyze the benefits of food safety regulations. Theoretical models can be used to derive expressions for willingness to pay (WTP) for reduced risk of morbidity and mortality. The costs of food safety regulation include the industry's cost of compliance, borne by both industry and the consumers of their products, as well as administrative costs borne by taxpayers and the deadweight loss associated with taxation. The overall efficiency of either a design standard or a performance standard depends on what level of food safety a regulation is attempting to achieve except the performance and process standards in the plant.

The Food Safety Inspection Service (FSIS) conducted a regulatory impact assessment and concluded that over a 20-year time period the benefits of implementing HACCP and pathogen reduction regulations would range from $0.99 to $3.69 billion annually (1995 dollars) if the regulations were completely effective in eliminating the risk of illness and death from four major pathogens. The costs of sanitation procedures, pathogen sampling, and HACCP plan development and operation were estimated to be in the range of $1-1.2 billion over a 20-year period [16]. Nesve compared the legal system of the food safety between U.S. and U.K. in the aftermath of the food scares in 2007, noticing that U.S. food safety is unique, transferring broad based direct regulatory regimes from Europe will be very inefficient [17].

A non-profit consumer advocacy organization, Center for Science in the Public Interest (CSPI), presented a paper in 2002 from a consumer perspective. The CSPI has been working to improve the public's health, through its work on nutrition and food safety issues since 1971. They are supported primarily by over 800,000 subscribers to its Nutrition

Action Health Letter, the largest circulation health newsletter in North America. HACCP focuses on preventing food borne-illnesses by applying science-based controls to food production and has been endorsed by many scientific groups. However, HACCP implementation in the seafood, meat and poultry industries has graphically highlighted the weakness in the fragmented regulatory system in the US. They discussed the inconsistent of implementation of HACCP between USDA and FDA. The example is from seafood industry. FDA required all seafood processors, both large and small, to develop and implement HACCP plans in December 1997 [18].

C. E. thought the laws, regulations, and organizations comprising the food safety system frequently lag behind current scientific knowledge of the risks posed by food-borne pathogens. Three federal agencies shared regulatory responsibilities for the safety of food: the Environmental Protection Agency (EPA), the Food Safety and Inspection Service (FSIS), and the Food and Drug Administration (FDA). The EPA is responsible for protecting the public and environment from risks posed by pesticides and for promoting safer means of pest management. FSIS is responsible for ensuring that meat, poultry, and egg products are safe, wholesome, and accurately labeled. The author also pointed out four approaches to reducing illness, population surveillance and better outbreak detection; prevention based regulatory approaches; information and education; toward a more risk based system [19].

Rafik described a model for temperature controlled management with end to end transparent control. He mentioned the current gaps and problems when shipping temperature controlled products although global regulations and pharmacopeia standards for those kinds of products are established for a long time. The key of temperature controlled logistics is the mapping and seamless integration of defined logistics processes between the shipper, forwarder, ground carrier, airline and ground handling agents. And all of the details information should be included as documented in quality agreement, such as condition setting of temperature controlled trucks, temperature monitoring device management, real time temperature monitoring, quality management, pick up time, handling and loading time [20].

2.1.2. Predictive microbiology

In the United States, E. coli O157:H7 causes an estimated 73,480 illnesses, 2,168 hospitalizations, and 61 acute illness deaths, of which 85 percent are considered to be from food borne sources [21].

Baranyi presented a review paper about those models in 1994. Some models estimating the effects on microbial growth of single "controlling factors" such as temperature, PH or water activity have been available for a long time, and some scientists recognized that there are a lot of other factors contributing the growth, food structure, the composition of the atmosphere above the food. Temperature is the most important environmental factor determining growth, however, other not controllable factors during the storage of the food can affect each other, pH and water activity, so the dynamic models are necessary, based on the currently used logistic type models [22]. For a model of bacterial growth, the lag time, specific growth rate and growth yield are essential as a function of temperature [23].

Van Impe proposed a novel class of microbial growth models [24] "this novel model prototype constitutes an elementary building block to be extended in a natural way towards, e.g., microbial interactions in co-cultures (mediated by metabolic products) and microbial growth in structured foods (influenced by, e.g., local substrate concentrations)." "A phenomenon inherent to microbial kinetics is lag, which is typically observed as a delayed response" [25], purely mechanistic models are very rare in practical applications. Models in daily use are between two, using mechanistic elements when possible and completing them with empirical approaches when only observations are available. A review paper of predictive food microbiology for the meat industry was given in 1999 by McDonald. It summarized a table of some intrinsic and extrinsic factors affecting microbial growth in Table 2.1. Some models of predictive food microbiology are listed in Table 2.2.

Table 2.1. Some intrinsic and extrinsic factors affecting microbial growth [26]

Intrinsic factors	**Extrinsic factors**
pH, acidity, acidulant identity, % buffering power	Temperature
Water activity and content, humectant identity	Relative humidity
Redox potential	Light intensity and wavelength
Presence of antimicrobials	Atmospheric gas composition and ratio
Identity and distribution of natural microbial flora	Packaging characteristics and interactions
Presence of physical structures	Processing characteristics and interactions
Presence of biological structures	Storage, distribution and display considerations
Availability of nutrients	
Colloidal form	
Substrate surface to volume ratio	

Table 2.2. Main models of predictive food microbiology [26]

	Description	Model
1	Gompertz function	$y = A + C\exp\{-\exp[-B(T-M)]\}$
2	A dynamic model for predictive microbial growth	$y(t) = y_{\max} - \ln[1 + (e^{-y_{\max}-y_0} - 1)e^{\mu_m A_n(t)}]$
3	Empirical non-linear regression model	$\sqrt{k} = b(T - T_{\min})\{1 - \exp[c(T - T_{\max})]\}$
4	Combined effects of pH and temperature	$\sqrt{k} = b(T - T_{\min})\sqrt{(pH - pH_{\min})}$

Where y is logarithm of relative population size, A is asymptotic log count as t decreases indefinitely $(CFU)^{-1}$, C is asymptotic amount of growth that occurs as t increases indefinitely log $(CFU)^{-1}$, B is relative growth rate at time M (s^{-1}), T is temperature (K), M is time at which absolute growth rate at maximum (s), k is growth rate constant (s^{-1}), T_{min} is notional minimum growth temperature, pH_{min} is minimum pH for growth [26].

2.2. Technologies and solutions used for cold chain management

2.2.1. Technologies used for cold chain management

Wang in 2006 published a review paper about wireless sensor technologies and standards for wireless communications. M2M, communications from machine to machine, from machine to mobile or from mobile to machine, which integrates discrete assets within the system with an IT system, could be used for data communication between host system and local station [5]. There are several ways to complete wireless communications for intermodal transport, shown in Figure 2.2, GSM (Global System for Mobile Communication), CDMA (Code Division Multiple Access), GPRS (General Packet Radio Service) and UMTS (3G) (Universal Mobile Telecommunications System) are the implementations of WWAN (Wireless Wide Area Network) in our life.

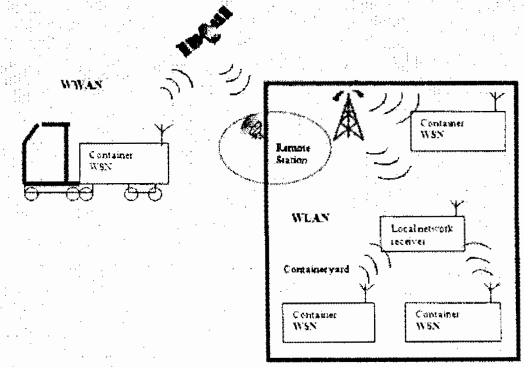

Figure 2.2. WWANs, WLANs and WSNs in intermodal transport [27]

IIR also pointed out the new development of RFID in the future for cold chain applications, shown in Table 2.3, including the combination of RFID technology and time temperature indicators (TTI), wireless technologies that allow gathering of data and exchange of real time information with supply chain partners, multi-sensing RFID nanosensors, temperature sensors integrated to RFID tags [9].

Table 2.3. Summary of ICT applications in transport [27]

Category	Subject
GPS, GSM	Monitoring animals during transport
WSN, GPS	Tracking and monitoring nuclear materials
WorldFIP	Remote monitoring of nuclear materials
Bluetooth	Link between truck and trailer
RFID	Automatic identification in rail transport
GPS	Intermodal movement status monitoring systems
GPS, WLAN	Container tracking systems
RFID	Automation container identification
RFID	Tracking containers
RFID	Electronic seals
WWAN, GPS, GIS	Tracking and monitoring containers worldwide
GPS, WSN	Securing and/or tracking cargo containers
Zigbee	WSNs in refrigerated vehicles
WSN	Tracking system for containers in ports
WLAN, WWAN, RFID	System and method for asset tracking and monitoring
RFID	RFID tags in container depots
RFID, GPS, Sensors	Integrated tracking, seal and sensor systems
WLAN, WSN	Smart container monitoring systems
RFID	Monitoring electronic container seals
Zigbee	Mesh-network in cargo containers
RFID, WSN	Smart Packing, improve traceability
RFID, WSN	Autonomous sensor systems in logistics

2.2.2. Solutions developed for cold chain management

Jedermann presented an automated quality tracing way in food chain with semi-passive RFID, data logger, which can measure temperature, relative humidity, light intensity, voltage, pressure, shock and the list goes on. The following picture is the process how suppliers trace the temperature conditions during transport with smart container and intelligent RFID data loggers [28].

In the first step, manufacturer configures the intelligent RFID tag for the shipping products. In the step two, the intelligent RFID measures and stores temperature values without external communications. In step three, the light signal will indicate the quality state of the passing products. Worker could pick out the problematic freight items. From this system, the supply chain manager could make the decision about how to deal with the freight before they arrive in the warehouse. In Figure 2.3, the author discussed the obstacles in food tracing of temperature, the first is automatically collecting the spatial temperature data, and second is the current RFID data loggers only are available in high quantities and require manual handling with their low reading range [28].

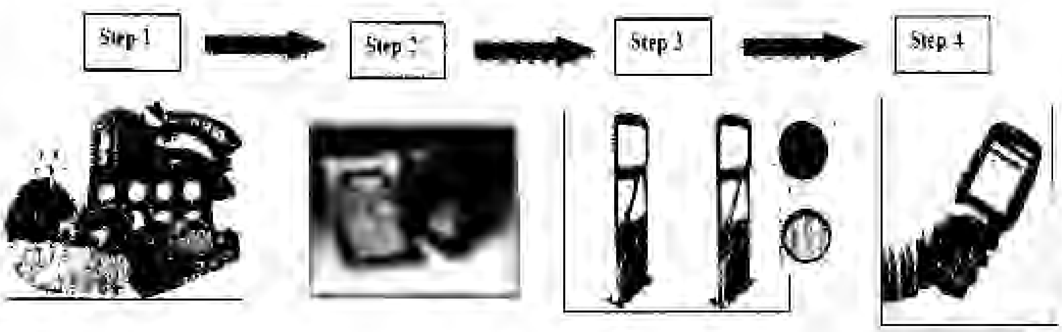

Figure 2.3. Supervision process based on intelligent RFID [28]

A prototype of the intelligent container is showed in Figure 2.4, Jedermann developed an intelligent container as autonomous supervision system, the inside processor provides a platform for local interpretation and preprocessing of sensor information to continuous monitor the inside environment of the container. WSN will also be used for local data collection and transmission [11].

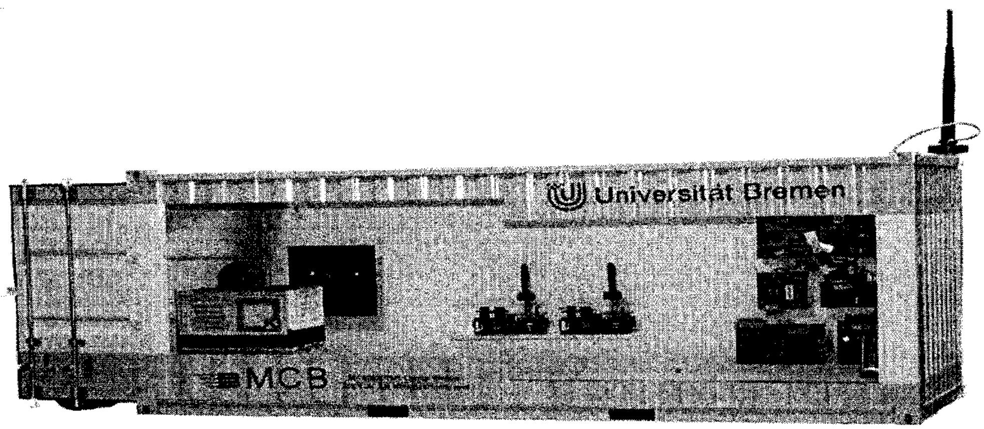

Figure 2.4. Prototype of the intelligent container [11]

2.3. Models for the cold supply chain

There are two basic inventory models, the EOQ (Economic Order Quantity) model and the newsvendor model. The first is the simplest model of cycle stocks, which arise when there are repeated cycles in which stocks are built up and then drawn down, both in a predictable, deterministic fashion. The second is the simplest model of safety stocks, which are held owing to unpredictable variability.

In EOQ model, a single product is used (for demanded) at a continuous fixed and known rate over time, continuing indefinitely into the future. Shortages or delayed deliveries are not allowed. Replenishments are received as soon as they are requested. In the Newsvendor model, an unknown quantity D of a single product will be demanded (requested for use) during a single period. While the probability distribution of demand is known, the actual number demanded will not be known until after a decision y, how many to order (or make), is made. In short, order y first, observes the stochastic demand D second. The amount sold/delivered will be min (D, y): You cannot sell more than you have or than are demanded. Under some demand distributions, such as the normal distribution, it is impossible to always meet all demand, so the prospect of unmet demands must be accepted. The ordering cost consists of a proportional cost incurred for each item ordered. Units are sold for more than they cost. Units purchased but not sold become obsolete by the end of the period and have no salvage value [29].

Ganeshan developed a model to manage supply chain inventories with a multiple retailer, one warehouse, and multiple suppliers, providing a near optimal reorder point, order quantity (s, Q) type inventory policy for the retailers and the warehouse that minimizes the total logistics costs, subject to customer service constraints. Ganeshan analyzed the whole supply chain with three sub systems, the inventory at each of the retailers, the demand process at the warehouse, and the inventory at the warehouse. The expected total annual cost for the system is developed as:

$$ETAC(Q_w, s_w, Q_r, s_r) = c_o + c_h + c_s \tag{2-1}$$

Where c_o is the ordering cost, c_h is holding costs, and c_s is transportation cost, and the problem is to find Q_w, Q_r, order quantity at each retailer and at the warehousing, s_r, s_w, reorder point at the retailer and at the warehouse, which minimize ETAC subject to constrains, such as customer service constraints, the warehouse orders from suppliers probability constrains. In the case study part, this paper assumes all suppliers and retailers are identical, and suppliers are always in stock.

Other parameters in the case study include daily demand at retailer with Poisson distribution; the warehouse to retailer transit time with Gamma distribution. Totally 32 unique test problems were constructed and got the conclusion that this inventory – logistics cost minimizing model for a production or distribution network with multiple suppliers supplying a distribution center is quite good, retailer backorders within 3.59%, and the warehouse backorder levels within 1.12% [30].

Li proposed a model to maximize the product values for customers instead of merely reducing costs [31]. This paper presented the food supply chain planning model based on the assumption that the perishable food supply chains are able to identify up to date product perishing status at all supply chain control points with RFID technology which could be applied to automatically collect product information.

Most of research on supply chain or inventory control about perishable food has been based on expected product shelf life, sales and relevant costs, this paper introduced using RFID technology to identify the actual impacts of the supply chain environment on food quality, so parameters, such as temperature will be used in model to estimate the value of products.

$$\text{Lost Value} = \text{Original Value} * [1 - \text{EXP}(-\alpha * \text{T})] \quad (2\text{-}2)$$

The objective of this model is to minimize loss of values and costs based on order quantities, shipping costs, losses of product value, and costs of re-allocating the products.

$$\text{Min Costs} = \text{Loss of product values in processing} + \text{Costs in transit} + \text{Penalty} \quad (2\text{-}3)$$

The paper considered a supply chain case in Figure 2.5, and the value tracking model is developed in equations below.

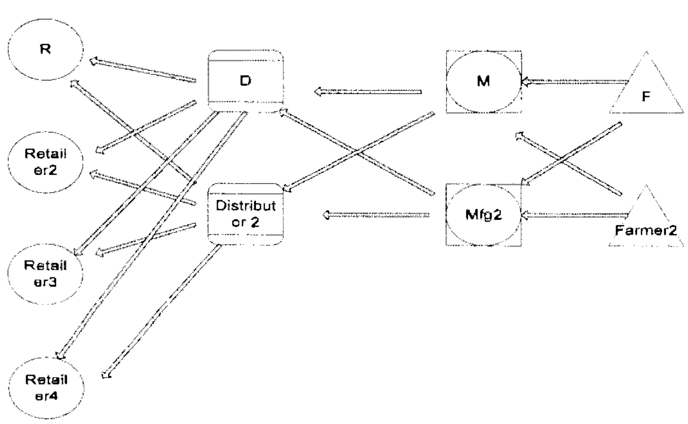

Figure 2.5. A case of dynamic product value tracing in a food supply chain [31]

In this model, farmers, manufacturers and distributors place orders to their suppliers, which can be determined either based on long term contracts with the supply chain members, or by the output results from model. Loss of product values can be calculated in following equations.

$$V_{m,k*g} = b_{k*g} \cdot V_{f-m,g} \cdot e^{-(\lambda_{f-m,k*g} \cdot t_{f-m,k*g})}$$

$$V_{m-d,k} = b_{k*g} \cdot V_{m,k*g} \cdot e^{-(\lambda_{m,k} \cdot t_{m,k})} \quad (2\text{-}4)$$

Where b indicates whether the delivery passed through the route or not, $V_{m,k*g}$ is the value of product which is at the time of entering to the manufacturer, $k*g$ is the route from farmers to manufacturer. $V_{m-d,k}$ is the value of product during the transit from manufacturing to distributor. The model supposed the quality of product changes is dynamically stored in the RFID system, including temperature data and the time of entering and leaving a process [31].

Liu also suggested using RFID technology to optimize the pricing and ordering decision for the perishable food in supermarket [32]. The model assumes that RFID systems are already in operation in the supermarket, and the product value can be estimated by the RFID systems according to automatically captured product properties and related environmental data, such as temperature and humidity. This paper formulated an equation about retailer's average profit per unit time.

$$\pi(p,\theta) = \frac{1}{\theta}\{\int_0^{\theta}[(p(t) - c - ht)D(p,t)]dt - K\} \quad (2\text{-}5)$$

Where K is the fixed ordering cost; c, the variable cost for each unit ordered; h, the unit inventory holding cost per unit time; p(t), the selling price per unit at time t; D(p, t), the price-dependent linear demand function; θ is the cycle length. The optimal order quantity and optimal price with the product value tracing could be solved from above equation. This paper also discussed the optimal pricing under uncertainty demand.

An inventory system of ameliorating items for price dependent demand rate is developed by Biswajit [33]. The inventory cycle is divided into two intervals considering the stock will be changed due to environmental effects. The mathematical model discussed the inventory system in three different cases based on deterioration effect.

$$I_t = R(p)\exp(\alpha t^{\beta} - \theta t)\int_t^T \exp(\theta t - \alpha t^{\beta})dt \qquad (2\text{-}6)$$

Where $R(p)$, the demand rate, is dependent on selling price per unit; and α , β are parameters of the Weibull distribution. These three cases are divided by the point when inventory reaches the zero level at t_2.

One model developed by Chande for inventory control of perishable products could determine optimal timing for discount offers and also optimal order quantity [34]. The most important aspect of supply chain management is inventory control, and the management of inventory of perishable products is more difficult than other products because of deterioration. In the analysis of fixed life perishability problem under price promotions in this paper, the objective is maximize total expected reward in period t to the end of horizon. This paper also give a conclusion of issues in implementation of RFID, including cost, level of identification, level of automation, integration, tangible benefits and intangible benefits.

Adachi [35] proposed a perishable inventory model with different selling prices of perishable products under stochastic demand. The model considers the discriminating sales prices by m stories' varying three different lifetimes for perishable products. The main equation is the profit per unit time, when k is selected under the state α :

$$\begin{aligned} q_\alpha(k) = & r_3 \min\{I_{(n,3)}, [D_n - (I_{(n,2)} + I_{(n,1)})]^+\} \\ & + r_2 \min\{I_{(n,2)}, [D_n - I_{(n,1)}]^+\} + r_1 \min\{I_{(n,1)}, D_n\} \\ & - h \max\{I_{(n,3)} + I_{(n,2)} + I_{(n,1)}, 0\} \\ & - a \max\{I_{(n,1)} - D_n, 0\} \\ & - b \max\{0, -I_{(n,3)}\} \\ & - o \cdot k \end{aligned} \tag{2-7}$$

Where $I_{(n,m)}$ is the stock quantity of goods whose lifetime is m th units period in the n th period, r_m is sales price of goods whose lifetime is m th units period, D_n is the demand in n th period, o is purchasing cost per unit, k is order quantity. The sales price in this model is decided by the degree of the remaining lifetime of goods. This paper used a Markov decision process model to determine an optimal inventory policy to maximize the expected average profit per period.

There are more models developed for perishable products supply chain, Wei presented one paper [36] about dynamic allocation of uncertain supply for the perishable commodity supply chain, establishing modeling groundwork for the Dynamic Allocation Problem with Uncertain Supply (DAP/US) problem for the Perishable Commodity Supply Chain (PC-SC), and developing an optimal control mechanism for the allocation of orders and distribution quantities to prioritized suppliers and retailers respectively. This paper designs the model under these assumptions: the strategic alliance of the PC-SC consists of suppliers, retailers, a distribution center, and a coordination center, responsible for quick response mechanism, generating optimal strategies and maximizing the total net profit of the alliance; the suppliers and retailers in the strategic alliance of the PC-SC both agree to set up a long term delivering quantity, so any resultant deviations from the agreement will cause penalties or loss to the alliance; there are two flows within a PC-SC, information flow and logistic flows in an ordering cycle. The main equation is:

$$\begin{aligned}\max Z &= \max(\text{total net profit of the strategic alliance of PC - SC}) \\ &= \max(\text{total sales - total costs - total penalties})\end{aligned} \tag{2-8}$$

The structure of the model developed by this author is the most similar research to the model developed in the thesis. The total costs included total commodity cost, total shortage loss, total disposal cost and total holding cost. And also consider the penalties incurred at both retailers and suppliers. Since the assumption used for this model is the supply chain with uncertain demand and uncertain suppliers, two stage control routines, order control routine (OCR) and commodity allocation routine (CAR) are introduced and solved by eGA (extended-Genetic Algorithm).

CHAPTER 3. PROBLEM STATEMENT

The cold chain refers to the transportation of temperature sensitive products along a supply chain through thermal and refrigerated packaging methods and logistical planning to protect the integrity of these shipments [37].

We know maintaining the proper temperature in the cold supply chain is the key point in ensuring the quality of perishable products. Perishable food will be spoiled or lose freshness due to exposures over and under safe temperature limits. In addition, the products handled inappropriately can result in product disposal, customer dissatisfaction, illness, and even loss of life.

To ensure food safety, the FDA (Food and Drug Administration) issued regulations to control food processing. However, from the previous chapter, we can see there are still some gaps and problems currently in the cold supply chain management. Food-safety experts believe that contaminated food causes up to 76,000,000 illnesses, 325,000 hospitalizations and 5,000 deaths each year in the US alone [15]. Although there are some solutions or models designed to improve the safety of food, in the literature review part, we can see there are still no methods which can track and trace all relevant information of the perishable food during the whole supply chain, from suppliers, to distribution centers, to retailers. After workers receive products, they do not know what the quality situation of the products in containers is, what kind of environment is inside the container during the transport, and how to figure out the shelf life based on the actual number of bacteria inside the products.

In an economic context, the profitability of the perishable food supply chain is highly reliant on the quality of products. In the US, the food industry annually discards 35 billion dollars worth of spoiled goods [38]. Preventing food spoilage will benefit all partners involved in the food cold supply chain.

Based on the system we developed in this paper, companies will minimize the cost from food wastage and maximize the profit, and ensure all products provided to customers are in good quality.

All in all, this thesis will focus on solving two problems; one is developing a technology solution which is able to provide four functions: 1) to trace and track the products from the suppliers to retailers. 2) to monitor and store important parameters during the processing and distribution of food products, such as temperature. 3) real time communication capability for prompt response. 4) capability of quantitative prediction of food safety. The other problem is how to manage the whole cold supply chain with the implementing of the technology system developed in this research. Optimization models will be developed to solve the second problem. In the models, the retailer is capable of managing their inventory system with actual shelf life of products; the price of products will be set based on real quality of products. With the implementation of the technology solution, a dynamic planning of the distribution for this cold supply chain is achievable. These two solutions will minimize the cost for the cold chain and ensure the food safety for customers.

CHAPTER 4. SYSTEM INTEGRATION (TECHNICAL SOLUTION)

4.1. Technical solution

In this chapter, we will discuss the hardware and software of the technical solution.

Figure 4.1 shows the schematic of a simple cold chain for meat products. There are stationary link points, such as distribution center, as well as the flow of food products indicated by arrow signs in the cold chain. At all the link points of the cold chain, monitoring of food products is relatively straightforward. Sampling can be performed and data can be stored locally. Necessary actions could also be taken immediately if environment parameters are out of control or food quality problems are directly detected. Moreover, the link points can easily be connected by the network to pass the historical information to their subsequent stages, so that the tracking of product flow can be partially achieved. Nevertheless, the physical product flow is realized by transportation, and the complete visibility of the cold chain cannot be achieved unless foods can be effectively monitored during transportation.

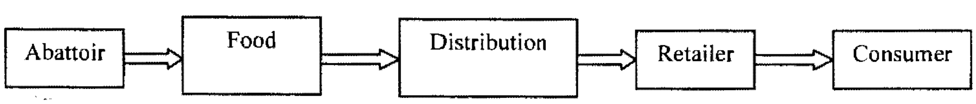

Figure 4.1. Schematic of a simple cold chain for meat products

For tracking and monitoring in transportation, the information that needs to be collected includes product identifications, location, and environmental parameters. Accordingly, barcode or RFID, GPS, and sensor technologies should be applied. One approach is to store and process the collected information locally. However, it requires the installation of sophisticated computing devices on carrier vehicles. More importantly, this approach isolates transportation from the rest of the cold chain, and evaluation of food health status may not be feasible if the historical data on the food items are required. To overcome the limitations, another approach is to establish a remote control center for data storage and processing for the entire cold chain and allow the information exchange between the carriers and the center. Figures 4.2 and 4.3 show the diagrams of both methods.

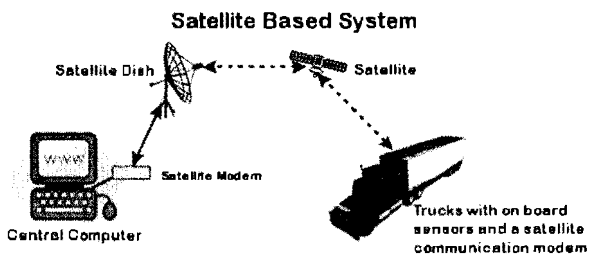

Figure 4.2. Wireless communication methods with satellite based system

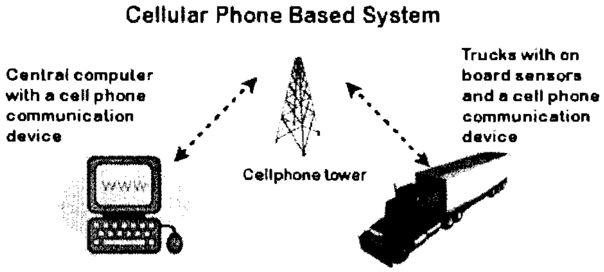

Figure 4.3. Wireless communication methods with cellular phone based system

For real-time information exchange between the mobile carriers and a remote control center, two communication methods are available for selection. One uses commercial cellular network, which is suitable for ground transportation in regional cold chains. The other uses Low Earth Orbiting (LEO) satellite network, which can be used for national or global cold chains. Compared with the satellite based method, the advantages of the cellular network based method are the relatively lower cost of equipment and deployment, and higher data transfer rate compared, while the downside is the poorer coverage compared with satellite based system.

4.1.1. Technical solutions

We developed several different tracking systems at the beginning after we did research on current situations of applications of GPRS/CDMA, shown in Figures 4.4, 4.5, and 4.6.

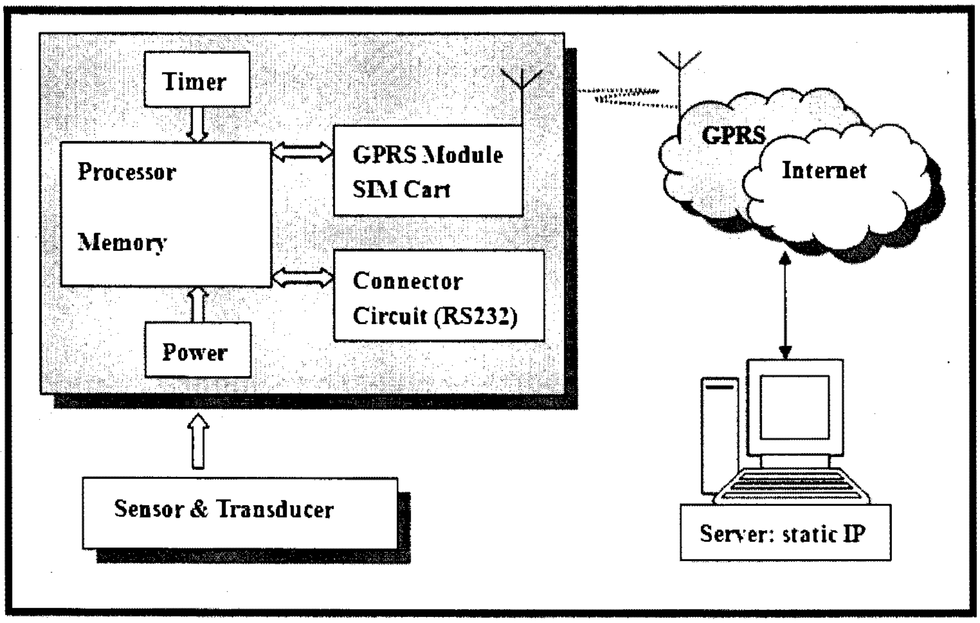

Figure 4.4. Technical solution (I)

From solution (I), in Figure 4.4, we can design a data terminal system which consists of single chip microcontroller, power, timer, GPRS Module, SIM card, and expanded circuit (RS232). The processor communicates with sensor circuit through RS232. GPRS module embedded with TCP/IP protocol will make communication between GPRS network and the processor.

GPRS allows data transmission speeds to over 100Kbps, that it is packet based, and that it supports the world's leading Internet communications protocols, Internet Protocol (IP) and X.25. Packet provides a seamless and immediate connection from a mobile PC to the Internet or corporate intranet allowing all existing Internet applications to operate smoothly without even needing to dial into an Internet service provider. With Packet data, users will only pay for the amount of data they actually communicate, and not the idle time.

IP support is becoming increasingly important as companies are now looking to the Internet as a way for their remote workers to access corporate intranets. X.25 defines a set of communications protocols that prior to the Internet constituted the basis of the world's largest packet data networks. We can think of cellular networks with GPRS service as wireless extension of the internet and existing X.25 networks.

Server with static IP address will receive data collected by single chip microcontroller. The key part in software development is how to send data from GPRS module to server through cellular network.

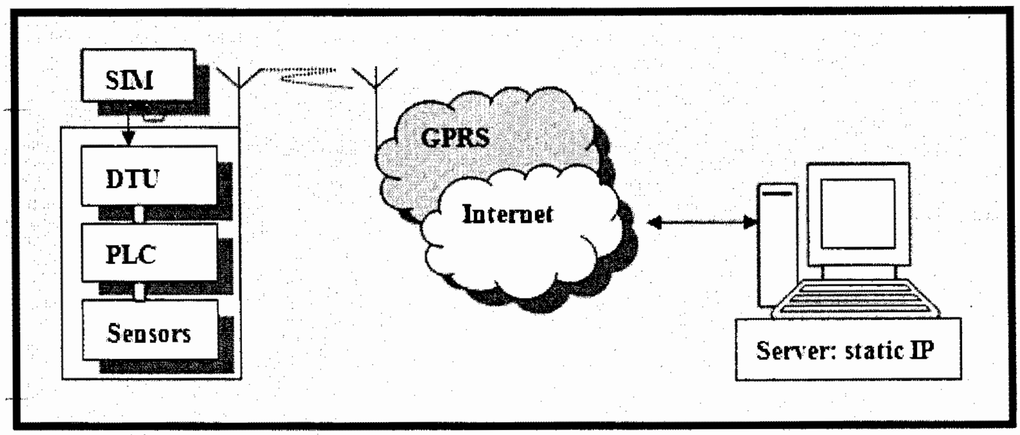

Figure 4.5. Technical solution (II)

From solution (II), in Figure 4.5, we select Data Terminal Unit (DTU) as data collection terminal. DTU is a product combined GPRS module and micro controller together, embedded with TCP/IP protocol. Customers can use DTU to connect with cellular network under the help of functions developed by vendors. DTU supports RS232/422/485 communication, but if the sensors circuit doesn't match the serial port on DTU, Programming Logic Control (PLC) will be used in this system as the interface between DTU and sensors. The server part has same structure as the solution (I).

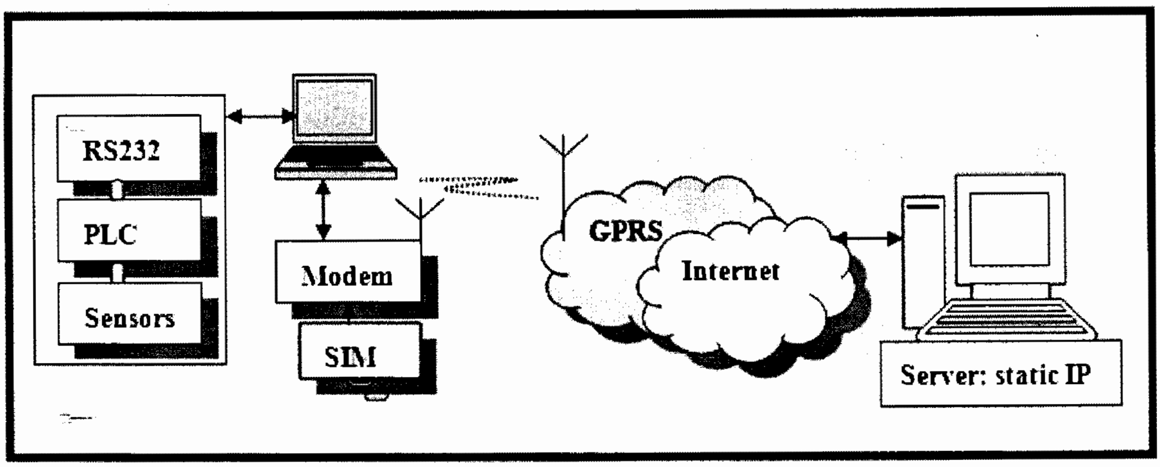

Figure 4.6. Technical solution (III)

From solution III, in Figure 4.6, we use personal computer or industrial PC as data terminal collecting data from sensors and communicating with GPRS modem.

In a typical application, a WSN is scattered in a region, and the information regarding the region is collected through its sensor nodes. In this research, we will use WSN as the sensor equipment in our system which makes our system different from above three existing solutions. People can put sensor notes at anywhere inside the container without considering the length of physical wires. Environmental data collected by sensors will be sent to data terminal through wireless network. During the transportation, we use Bluetooth as the communication method between data terminal and GPS. Bluetooth wireless technology is a short range communications system intended to replace the cables connecting portable and/or fixed electronic devices. The key features of Bluetooth wireless technology are robustness, low power, and low cost.

4.1.2. Software environment

Although many different programming languages are available for developers, C++, VB, C, we select JAVA as our software developing tools. Java offers a number of benefits to developers. Java is simple: Java was designed to be easy to use and is therefore easy to write, compile, debug, and learn than other programming languages. For example, Java uses automatic memory allocation and garbage collection, and by contrast, C++ requires the programmer to allocate memory and to collect garbage. Java is object-oriented: Java is object-oriented because programming in Java is centered on creating objects, manipulating objects, and making objects work together, which allows us to create modular programs and reusable code. The most important advantage of Java is platform-independent, can be easily migrated from one platform to another. For our system, this advantage is more significant; the program developed by Java can work on industrial PC, laptop and business PC with Windows or Linux system.

4.2. System description

4.2.1. Hardware structure

Based on the aforementioned concept, the food safety monitoring system can be designed based on the schematic shown in Figure 4.7.

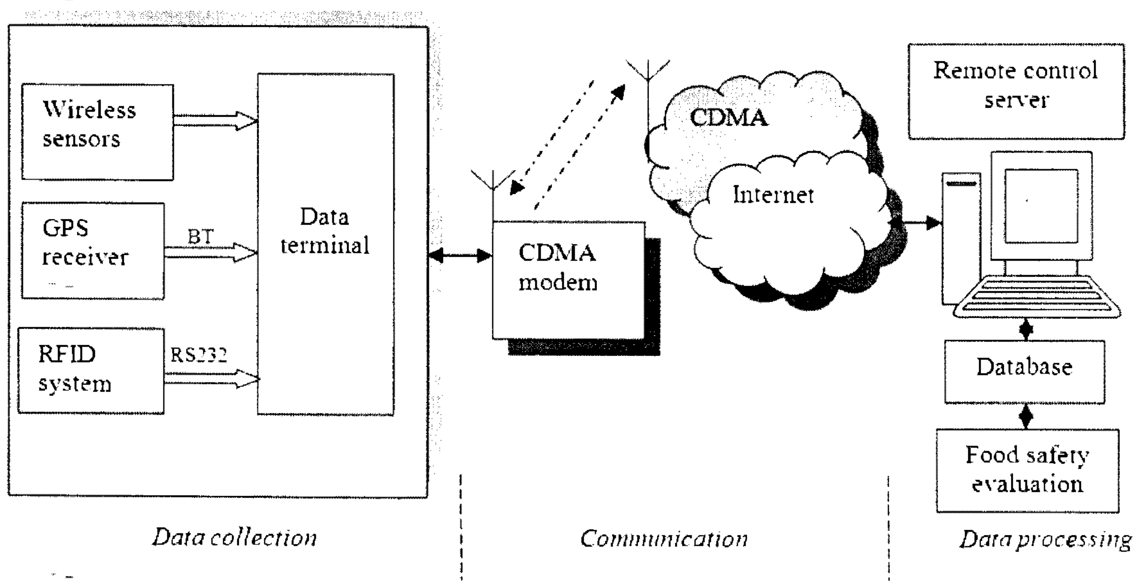

Figure 4.7. Schematic of the proposed system

It can be seen that the system consists of modules for data collection, communication, and processing. The arrows in the figure indicate the information flow. It is desired that the information flow between modules be two-way because both data collection from truck and passing of decisions from the control center are indispensible. The data collection module collects ID information from tagged food items, environmental information from wireless sensor nodes, and location information from a GPS receiver. The communication module sends and receives information via a cellular modem and an existing cellular network infrastructure, and thus connects the data terminal and the control center. The data processing function resides in the control center which is connected to the Internet. The data stream sent by data terminal is sorted and inserted into the corresponding tables in the database, and then computations are performed to evaluate the food safety. Note that we only consider ground transportation in this study, and with minor adjustments the system can be used for sea transportation as well.

The location information of the truck container is accomplished with GPS technology. The communication specification of GPS receivers, defined by the National Marine Electronics Association (NMEA), consists of lines of data which include position, velocity, and time information. The GPS receiver can be interfaced with the data terminal (controller) through a serial port or Bluetooth protocols. To automatically identify each product that is moved into or unloaded from the truck container, we employ the inexpensive passive UHF RFID technology. The product IDs will not be read during transportation to increase system efficiency. Multiple antennas can be equipped on the gate of the truck, and the reader is connected with data terminal through RS232 or LAN. The ISO containers have a width of less than 2.5 meters. As a result, the short reading distance

(2-5 meters) of passive RFID tags is not a concern here in that the food items must be within the reading range of one of the antennas during loading and unloading through the gate. Meanwhile, during transportation environmental parameters are constantly collected by the wireless sensor nodes and sent to the data terminal. Each sensor node has the capability of "sense and send", and it also has a unique ID, which acts as the liaison to link with the product IDs during transportation. Depending on the number of sensor nodes and their reading ranges, the sensor nodes can be configured as a centralized network so that all the data are directly transmitted to the data terminal, or as a decentralized network so that the information can go through a route of multiple sensor nodes before it reaches the data terminal. Figure 4.8 (a) – (d), (a) wireless sensors, (b) GPS receiver, (c) passive RFID tag and reader, and (d) CDMA modem, shows the wireless sensor device, portable GPS receiver, passive RFID system, and CDMA modem used in our prototype system respectively.

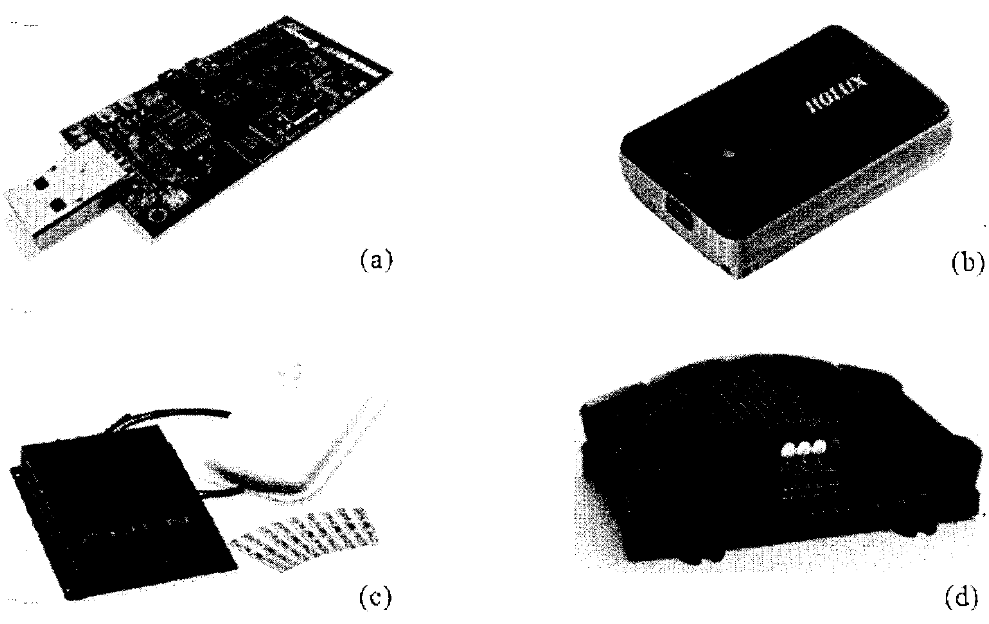

Figure 4.8. Devices used in the integrated system

4.2.2. Software environment setup

There are two main programs developed for data collection and transmission, one is used on data terminal, for data collection, communication with RFID, GPS, CDMA modem and WSN; the other is installed at data server in office as a platform of data received from trucks. In this section, 6 different functions will be discussed, Java setup, SQL database setup, RFID programming, GPS data collection, Socket connection and WSN communication.

We select JAVA as programming language considering that Java is secure, robust, object-oriented, simple and distributed. The next step is selecting a Java Integrated Development Environment (IDE). Eclipse is a multi-language software development environment comprising an IDE and a plug-in system to extend it originally created by IBM in November 2001. We selected Eclipse as Java programming environment although Jbuilder and Jcreator are much easier to be operated. Eclipse 3.1 is the first release with built-in support for Java Development Kit (JDK). JDK consists of the Application Programming Interface (API) classes, a Java compiler, and the Java Virtual Machine interpreter, used to compile Java applications and applets. We download JDK 1.5 from SUN webpage for WINDOWS XP system.

In our system, we picked the Alien RFID reader (ALR-9780) as our product tracking tools. Alien provides a development kit for customers, called "AlienRFID.jar". To use the Alien RFID library from within Java applications and Java applets, the "AlienRFID.jar" file must be added to the Classpath of the project of our system. The Alien reader can be operated either via serial communications or over the network. In our system, we connect the reader to the serial port of computer, using serial communication to control Reader.

First, we install some serial communications classes (the javax.comm package) inside our JDK.

Since in our system, location data need to be split from GPS receiver as record of location tracking information. The problem is how to get data by Java program from GPS receiver via Bluetooth which establishes connection from GPS Receiver and computer. We developed a very easy way to get data from GPS receiver via Bluetooth, receiving data by javax.comm package. To use this package, we need to download the file javacomm20-win32.zip, available on Sun Microsystems Inc. website, which includes three files, win32com.dll, comm.jar, javax.comm.properties.

4.3. Data management

With respect to data management, the system needs a central database to store all the information from different parties. It is anticipated that the database will experience an information explosion in food safety records for large-scale cold chains. This cannot be overlooked if the system is adopted at enterprise level. Microsoft SQL Server 2005 is used to manage the database. The basic configuration and the generation of core tables are introduced as follows. Each truck is equipped with an active RFID tag, and we use R_0 to represent its unique ID information. Each container is equipped with an active RFID tag and a GPS receiver, whose information is represented by R_1 and *LL* respectively. Inside the container, the space is evenly divided into *M* sub-spaces, and one multi-function sensor node, whose ID is represented by *SR*, is installed to monitor each sub-space. Each box of food product is identified by a UHF passive RFID tag with R_2 representing its unique ID.

Before loading operation, both R_0 and R_1 are read by an active RFID reader on the ground, and a table, $\mathbf{T_0}$, with tuples (R_0, R_1, *time*) is populated. Data table $\mathbf{T_1}$ is established to describe the relationship between the container and M sensor nodes. If the sensor nodes are fixed in the container, $\mathbf{T_1}$ will contain tuples (R_1, SR_1, SR_2, .., SR_M). If the sensor nodes are removable, then $\mathbf{T_1}$ will be a table of tuples (R_1, SR_1, SR_2, .., SR_M, *time*).

During the loading operation, product boxes with passive RFID tags are scanned. If the size of product boxes is uniform, the number of boxes, N, to fill a sub-space in the container can be easily calculated. In this case, the assignment of product IDs to sensor nodes is conducted as follows. The first sub-space is filled by the first N boxes, and accordingly the last sub-space is filled by the last N boxes. A table, $\mathbf{T_2}$, can be populated with tuples, ($R_{2,1}$, .., $R_{2,n}$, SR_1, *time*), …, ($R_{2,mxn+1}$, …, $R_{2,(m+1)n}$, SR_m, *time*). If the size of the product is not uniform, the assignment requires manual input effort. The sub-space is then filled one by one in an ascending order. If the current sub-space is filled, the operator is informed so that all the product tags, which have passed through the loading gate after the previous sub-space is filled, will be assigned to the current corresponding SR node. During transportation, the product tags are not read, while the sensor nodes and the GPS receiver collect data and pass them to the data controller. Therefore, data table $\mathbf{T_3}$ can be populated with tuples (SR_1, *temperature*, *humidity*, …, LL, *time*), …, (SR_m, *temperature*, *humidity*, …, LL, *time*). This helps reduce the burden of the data collection and transmission during transportation. The historical environmental data of individual products can be retrieved by querying tables $\mathbf{T_2}$ and $\mathbf{T_3}$.

4.4. Software introduction

4.4.1. Software structure

For the application on data terminal (client computer) side, the software code, developed in Java language, performs the functions of tag reading, data collection, and communication. Based on TCP/IP protocol, the program establishes the socket connection between the client and server – once the server computer is in *ON* status, the data terminal starts to send the data stream and continues the process at a certain time interval.

Figure 4.9 shows the flow chart of the operations defined by the code. It can be seen that, during transportation, the code starts with searching the wireless sensor nodes and GPS connection. Then it uses the CDMA modem to connect the data terminal with the CDMA network provided that data service has been subscribed from the cellular service provider. For any of these connections, a warning process will be initiated if the failure exceeds five times, and the operator or driver will look into the problem upon receiving the warning message. The data stream received from the sensor nodes and the GPS receiver need to be split and re-arranged into a pre-defined sequence before it is sent. The socket connection subprogram will establish a client request and send those data to the server center based on the time interval defined by customer.

On the side of the control center, the software code performs the following operations as shown in Figure 4.10. First of all, the program establishes a connection between Java and SQL Server 2005 with the help of Java Database Connectivity (JDBC) API of SUN Company, and makes connection between TCP/IP to JDBC in order to write data to SQL Server database. Then, the socket connection is established to accept the data stream from remote client via CDMA network, and the data are saved in different tables.

The center server also performs the computation to evaluate the food safety level for individual food items. This process starts with the update of the history of critical environmental parameters such as temperature for each item, which is accomplished by the automatic query of database.

Depending on the types of bacteria target, different predictive microbiology models can be adopted, and the bacterial load in foods is calculated and compared with the threshold value. A warning signal will be issued and sequential actions will be triggered if the value is exceeded.

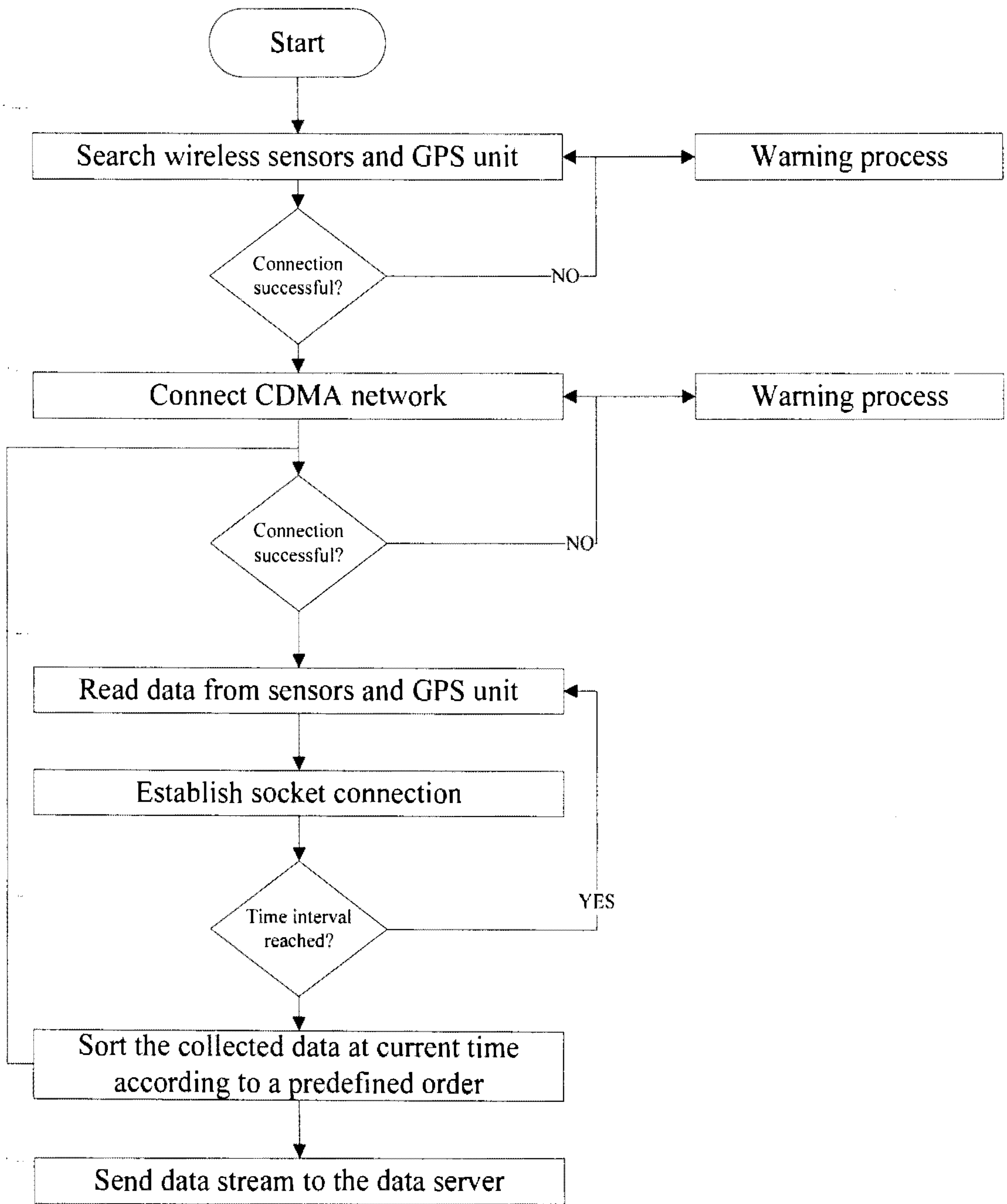

Figure 4.9. Flow chart for data collection during transportation

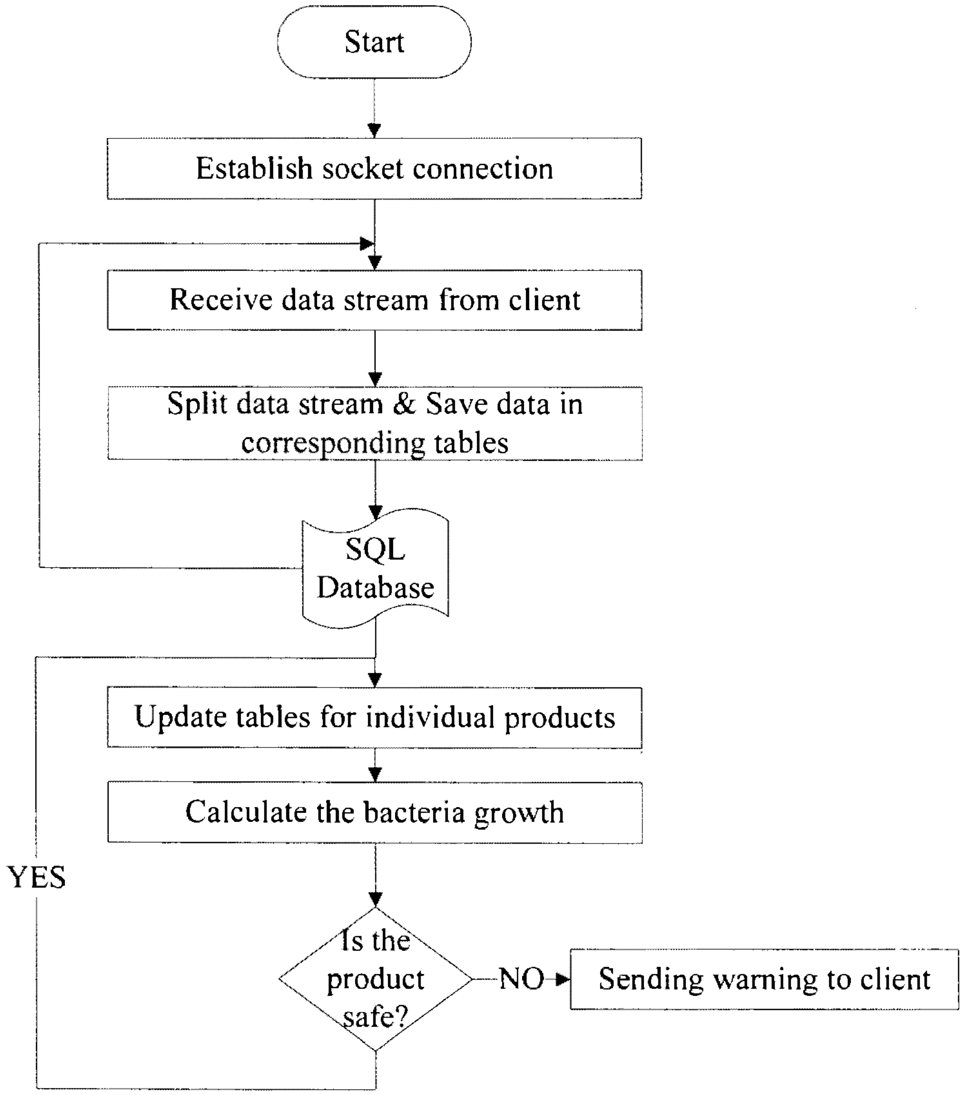

Figure 4.10. Flow chart for data processing

4.5. Experiment results of the tracking system

4.5.1. Experiment conduction

Considering the actual experiment is difficult to implement without sufficient funding, we used a refrigerator in our lab to simulate a container. A PC was used as the data terminal connected with GPS by Bluetooth, and another laptop was used as the center server. They were connected for data exchange with the service from a CDMA cellular service provider. Five empty boxes were attached with passive UHF RFID tags, and they were moved into the test environment through a gate with two RFID antennas. Two WSN motes are placed in refrigerator, as shown in Figure 4.11 (1 is data server; 2 is refrigerator simulated as container; 3 is two sensor motes, communicating with station mote; 4 is PC as data terminal (Client part); 5 is Bluetooth adaptor, connecting with GPS; 6 is GPS with Bluetooth function; 7 is Alien Reader; 8 is Alien Antenna; 9 is Alien Tags; 10 is station mote, communicating with other remote motes; 11 is CDMA modem).

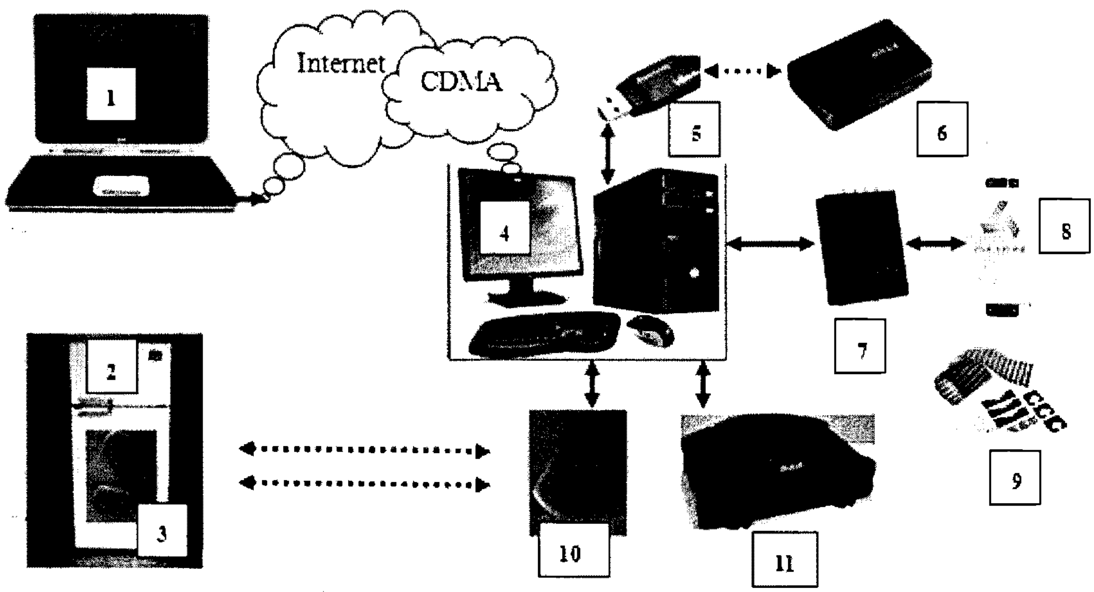

Figure 4.11. Hardware connection of the tracking system in experiment

If we relocate the server and client program on above hardware, we need to adjust the Java codes in order to ensure that programs work well on different machines.

4.5.1.1. Server operations

At data server part, before we running the server program, make sure we have created a database name as NDSU, and the user name is "sa" with the password "123456".

At first, we should accept tag id from the clients, the program name is "TagAccept.java", which will create a table named as the current time with format "MMddyyyyHHmm" and save all tag number into that table in SQL database automatically. If the program is on 'running' status, the client part could send tag id.

4.5.1.2. Client operations

At client part, first, open GPS and plug the Bluetooth in USB port, make connection by BlueSoleil software. After we double click the icon, there is a sphere in the center as the base station, which could inquire any equipment with Bluetooth around it. We just use the GPS, right click on the icon of GPS, and select "connection" option.

4.5.2. Experiment results

During this process, the tag IDs were collected by the passive RFID reader and sent to the data server through the network. Also, the relationship between each wireless sensor node and its corresponding food products was generated, and the data entries were stored in the table in SQL Server 2005 as shown in Figure 4.12.

Table - dbo.tag092320071436 | Table - dbo.tag092420071209 | Summary

TIME	Products	MoteId
09-23-2007:14:36	A5A5 8005 5629 4072	A5A5 8005 5629 4211
09-23-2007:14:36	A5A5 8005 5629 4070	A5A5 8005 5629 4211
09-23-2007:14:36	A5A5 8005 5629 4079	A5A5 8005 5629 4212
09-23-2007:14:36	A5A5 8005 5629 4211	A5A5 8005 5629 4212
09-23-2007:14:36	A5A5 8005 5629 4362	A5A5 8005 5629 4212
NULL	NULL	NULL

Figure 4.12. Table storing product IDs and sensor IDs

Temperature data were collected to simulate two scenarios with one being that the environmental temperature is constantly under control and the other being that it is slightly off the target value. Figure 4.13 shows a data table storing the temperature history of the beef products for the latter scenario. Note that the monitoring of other environment parameters is also possible with the wireless sensor devices used in the prototype system because they have multiple sensor modules on board. Figure 4.14 plots the temperature histories collected for both scenarios for a duration of 20 hours.

Table - dbo.A5A5800556294070 | Table - dbo.tag092320071436 | Table - dbo.tag092420071209 | Summary

TIME	MoteId	Temperature		Light	GPSLocation	
09-23-2007:16:51	A5A5 8005 5629 4211	28.228125	...	32.8622909330...	4654.0733,09647.8649	...
09-23-2007:16:55	A5A5 8005 5629 4211	28.25625	...	33.1717649647...	4654.0733,09647.8649	...
09-23-2007:16:59	A5A5 8005 5629 4211	28.25625	...	33.1717649647...	4654.0733,09647.8649	...
09-23-2007:17:03	A5A5 8005 5629 4211	28.25625	...	33.1717649647...	4654.0733,09647.8649	...
09-23-2007:17:07	A5A5 8005 5629 4211	28.25625	...	33.1717649647...	4654.0733,09647.8649	...
09-24-2007:12:12	A5A5 8005 5629 4212	28.715625	...	38.2265074823...	4654.0733,09647.8649	...
09-24-2007:12:17	A5A5 8005 5629 4212	28.70625	...	38.1233494718...	4654.0733,09647.8649	...
09-24-2007:12:22	A5A5 8005 5629 4212	28.70625	...	38.1233494718...	4654.0733,09647.8649	...
09-24-2007:12:27	A5A5 8005 5629 4212	28.70625	...	38.1233494718...	4654.0733,09647.8649	...
NULL	NULL	NULL		NULL	NULL	

Figure 4.13. Table collected by sensors and GPS device

4.5.3. Determining food safety

Monitoring environmental parameters alone can give good indications on the quality control of food items during transportation. For instance, usually target temperatures and process control limits are set for food products, and a temperature abuse beyond the control limits will clearly indicate the process variability and the deterioration of food quality. Besides the direct quality control, we can take a further step to quantitatively determine the level of food safety. As mentioned previously, predictive microbiology models can be used to predict the microbial growth in foods based on the collected data, such as temperature and light intensity. It is recognized that the microbial growth may be the combined result of several environmental parameters such as humidity, temperature, pH value, and lighting exposure. However, temperature appears to be the most critical parameter for many occasions, and a number of predictive models have been developed to establish the relative risk of temperature abuse in foods in terms of bacterial populations.

For illustration purpose, we applied the model [39] developed for beef products to calculate the bacteria number in the experimental beef items according to the temperature histories shown in Figure 4.14. Specifically, the model was developed for predicting the growth of Escherichia coli O157:H7 in hamburger meat based on environmental temperature history.

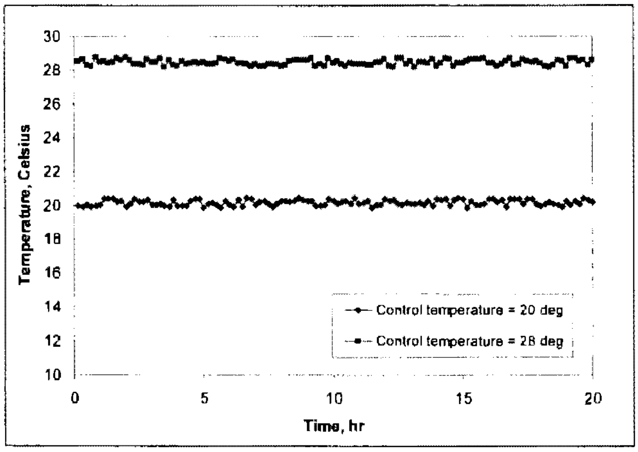

Figure 4.14. Two temperature histories for two simulated scenarios

The construction of the model is shown as follows,

$$L(t) = A + C\exp(-\exp(-B(t-M))) \tag{4-1}$$

where *L(t)* is the common log of the expected number of organisms at time *t*, *A* is the asymptotic minimum value for $t = -\infty$, *C* is the asymptotic difference between times $t = -\infty$ and $t = \infty$, B is a constant, and *M* is the time for which the relative growth rate, $dL(t)/dt$, is maximal. It is assumed that the maximum population density, *A*+*C*, is a constant quantity, and $A = \log_{10}(N_{0)})$, which is common logarithm of the initial number of organisms (*t=0*). The following equations are used to solve for the other parameters, namely, *B*, *C*, and *M*, in equation (4-1).

$$l = M - \frac{1}{B} + \frac{\log_{10}(N_0) - A}{C \cdot B / e} = M - \frac{1}{B} = \exp(c + d\ln(T)) \tag{4-2}$$

$$g = \log_{10}(2)e/(B \cdot C) = \exp(a + b\ln(\ln(T))) \tag{4-3}$$

$$A + C = e + fT \tag{4-4}$$

where g is the generation time, l is the lag time, and the estimated parameter constants for beef are a = 7.03, b = -6.31, c = 9.98, d = -2.69, e =10.08 and f=-0.014.

Based on this model, we calculated the population of E. coli O157:H7 for the two simulated scenarios in Figure 4.15.

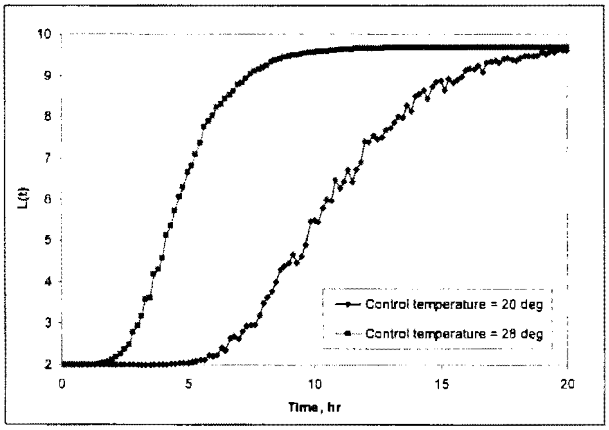

Figure 4.15. Estimated bacterial loads for two simulated scenarios

In our calculation, we assumed that the initial number of organisms (N_0) at $t = 0$ is 100/kg, and thus $A = 2$. We hereby use $L(t)$ to display the number of organisms results at time t, and the results are presented in Figure 4.15. It can be seen that the numbers of E. coli O157:H7 increase from 100 to 4.1 and 4.7 billion for the foods after 20-hour exposure to the environmental temperatures of 20 °C and 28 °C respectively.

On the other hand, the curves show different growth patterns at the two temperatures. At 20 °C, the growth starts after 1 hour exposure and reaches a saturated level after 10 hours. At 28 °C, the start of growth is delayed for more than 4 hours, and saturation is reached at the end of 20 hours.

As such, the increase of environmental temperature by 8 °C significantly accelerates the growth of E. coli O157:H7 in the beef products. Note that this model is only capable of predicting the growth of organisms under isothermal condition in which the temperature is nearly constant with regard to the evolution of time.

For an arbitrary temperature history, which is the case for many environments with intermittent temperature abuses, this model needs to be modified to handle such variations and the algorithm proposed by Zwietering seems to be a good option [40]. In addition, if necessary the calculated bacteria load can be easily inserted into the data table of a product, as shown in Figure 4.16.

Table - dbo.P...A5800556294070 Summary

TIME	Product	Temperature	Light	GPSLocation	Organisms
09-23-2007:16:51	A5A5 8005 5629 4070	28.228125	32.86229	4654.0733,09647.8649	0.100000000
09-23-2007:16:55	A5A5 8005 5629 4070	28.25625	33.171764	4654.0733,09647.8649	0.100000002
09-23-2007:16:59	A5A5 8005 5629 4070	28.25625	33.171764	4654.0733,09647.8649	0.100000012
09-23-2007:17:03	A5A5 8005 5629 4070	28.25625	33.171764	4654.0733,09647.8649	0.100000049
09-23-2007:17:07	A5A5 8005 5629 4070	28.25625	33.171764	4654.0733,09647.8649	0.100000186
09-24-2007:12:12	A5A5 8005 5629 4070	28.715625	38.226507	4654.0733,09647.8649	0.100001257
09-24-2007:12:17	A5A5 8005 5629 4070	28.70625	38.123349	4654.0733,09647.8649	0.100003829
09-24-2007:12:22	A5A5 8005 5629 4070	28.70625	38.123349	4654.0733,09647.8649	0.100010805
09-24-2007:12:27	A5A5 8005 5629 4070	28.70625	38.123349	4654.0733,09647.8649	0.100028081
NULL	NULL	NULL	NULL	NULL	NULL

Figure 4.16. Query results of a specific food item

There is no exact infective dose, regarding the density of E. coli O157:H7, for human beings right now, but retrospective analyses of foods associated with outbreaks of Enterohemorrhagic E. coli infection revealed that the infections dose is very low. For instance, between 0.3 to 15 colony-forming units (CFU) of E. coli O157:H7 per gram was enumerated in lots of frozen ground beef patties associated with a 1993 multistate outbreak in the western United States [41].

It is generally accepted by researchers that the dose may be similar to that of Shigella spp., as few as 10 organisms per gram [42]. If this criterion is applied to our case, the ground beef should be discarded after 4.6 hours at 28 °C, because the number of E. coli O157:H7 is more than 10 per gram under the assumption of an initial number of 100 per kilogram. Besides E. coli O157:H7, other bacteria that could be transmitted by food and cause human disease include Aeromonas hydrophila Yersinia enterocolitica, Listeria monocytogenes, and Vibrio parahaemolyticus [43].

Some food-borne pathogenic bacteria can multiply at temperatures as low as 3.3 °C [44]. All these indicate the importance of temperature control and monitoring for food products in cold chain, in particular, during transportation, in which effective real-time monitoring of environmental parameters is generally lacking, let alone the quantitative evaluation of food safety and the decision making for prompt response.

CHAPTER 5. SUPPLY CHAIN MODELING

5.1. Main function

To fully take advantage of the new tracking system developed for real world applications, a decision making model will be developed to utilize the information provided from the tracking system, such as the real-time temperature inside the container, as shown in Figure 5.1.

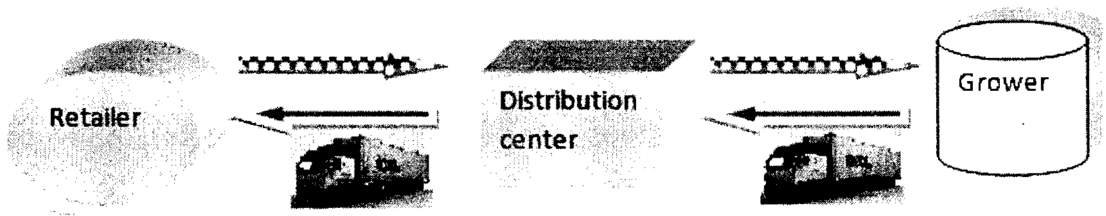

Figure 5.1. The cold supply chain network

In literature review part, we cited the references about the optimization models related to the cold supply chain. In this research, we developed a model to optimize the distribution network, setting different prices in retailers, planning distributions dynamically, managing inventory at retailers based on the real quality situation of foods. In the simple cold supply chain adopted in this research, we integrate three partners, retailers, distribution center and growers which should belong to one company.

Objective: to maximize the profit of the perishable food supply chain

Decision variables: the number of the product which will be delivered to retailers X; the number of the product which will be provided from suppliers Y.

Main Function:

$$\text{Profit} = \text{Revenue} - \text{TotalCost} \tag{5-1}$$

In this supply chain network, Figure 5.2, company could have multiple retailers and suppliers, but to make question simplified, there is only one distribution center for the whole supply chain. In future research, we could consider more complicated scenario, such as a supply chain with multiple retailers, suppliers and distribution centers.

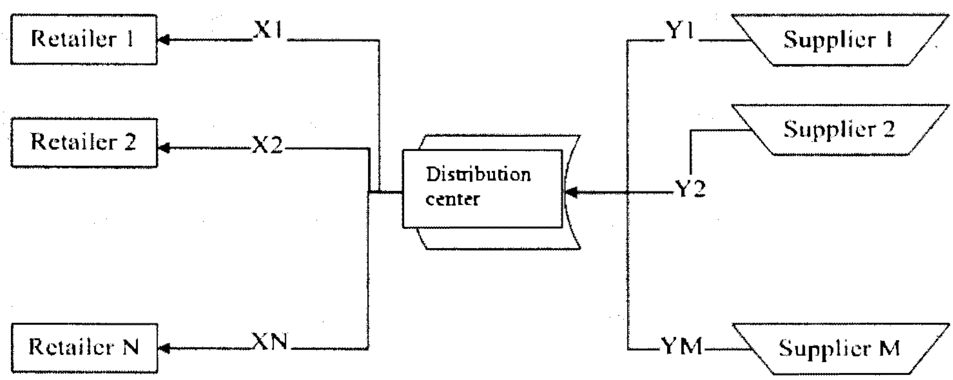

Figure 5.2. The cold supply chain with multiple retailers, suppliers, one distribution center

Before we discuss the details of the model, there are a lot of assumptions set to establish the environment of the model:

(1) The product demand (D) at retailer i is deterministic with price (P), and we will use the familiar downward sloping demand curve, with a regular demand function with demand rate

$$R(P_i) = k_i P_i^{-\alpha_i} \tag{5-2}$$

where α (>1) is the demand elasticity. The quantity of demand will rise due to a decrease in price. The demand rate $R(P_i)$ is the quantity of demand at retailer i per hour with price P_i [45].

(2) Price will be decided from the quality status of the products

$$P(t) = f(Q(t)) \tag{5-3}$$

(3) Quality value will be the function of temperature history

$$Q = f(T, t) \tag{5-4}$$

(4) Let t = 0 when the products are shipped from the supplier, and the ordering decisions are made at the beginning in a fixed order cycle considering the demand is deterministic.

(5) The perishability of food products depends on a lot of factors, such as temperature, humidity, and PH value. Researchers believe temperature is the main factor to determine the growth of organisms. Gompertz function is a widely used model to predict food microbiology, shown in Table 2.3, in which logarithm of relative population size will change with the constant temperature. In our research, since temperatures are continuously collected from containers during transportation, it is entirely possible that temperatures are changed at a certain point. However, even though we can access all temperature history at any time to calculate the real shelf life, currently there are no models to predict food microbiology with several temperature shifts. So we assume the preservation time t_i^p could be figured out with temperature history

$$t_i^p = f(T, t) \tag{5-5}$$

(6) Due to the perishable feature of the product, the amount of food carried by the vehicle decreases, as spoilage increases. In a certain situation, if the retailer does not receive the ordered food within the scheduled time point, the penalty cost will be applied to the model. In this study, a priori strategy will be applied, that is extra food, added to prevent delivery failure before departure of the vehicle from the

supplier, can be assessed and analyzed by the food spoilage rate, passage of time and temperature, during the delivery process [46].

(7) The remaining preservation time of product k, such as milk or banana, at retailer i is equal to the subtraction of the total preservation and current time,

$$d_{ik} = t_i^p - t \tag{5-6}$$

(8) The model consists of three parts, multiple retailers, one distribution center and multiple suppliers, and there is only one kind of product in the supply chain.

(9) We assume that all the products will not be thrown away or lost during transport and processing, all products will be shipped to DC or retailers,

$$\sum_{i=1}^{N} X_i = \sum_{j=1}^{M} Y_j \tag{5-7}$$

(10) T_i^{cycle} the cycle length. Its start point is from the time point when the new products are shipped out from the suppliers, we neglect the ordering processing time at each retailer, so we set the time point when retailers re-order the products as the start point of one cycle.

(11) I_i^S : safety stock level. Retailers need to manage two things about inventory: not running out, and not having too much. This safety stock level will help retailers to identify the time when they need to order products.

The regular equation to calculate safety stock level is:

$$I_i^S = Z \times \sqrt{L_A \times D_{SD}{}^2 + D_A{}^2 \times L_{SD}{}^2} \tag{5-8}$$

Where Z value can be checked from the statistical z-table based on the percentage of service level at retailers; L_A is the average lead time; D_{SD} is the standard deviation of the demand; D_A is the average demand; L_{SD} is the standard deviation of the lead time. One way to find average demand and lead time is to look at historical records [49].

5.2. The function of revenue of the supply chain

In this part, we will discuss the function of revenue in different scenarios.

$$R = \sum_{i=1}^{N} P_i(t)\widetilde{V}_i \tag{5-9}$$

$P_i(t)$: the price of the product at retailer i, and the price is changing with the time, once the retailers receive the product, the price of the product will decrease with the time due to the deterioration. To simplify the equation and consider the real application, we will use another way to estimate the price for the retailers, discrete price. And the relevant revenue equations will be developed later.

Figure 5.3 shows that the quality tracking system and the two different prices will be applied based on quality value. We assume the preservation time t_i^p could be figured out based on the temperature history during the transport, t_i^n is the time when the retailers receive the product, which depends on the transportation time, including from suppliers to DC, and from DC to retailers, and processing time in the distribution center.

Basically, we can estimate the time point t_i^n if the distance is known and processing time in DC is fixed (processing time depends on the order lot sizing). When the quality of products drops to point $Q(t_i^c)$, the products will be sold in a discounted value, P_i^c, and when the time reaches the total preservation time, the products will be discarded.

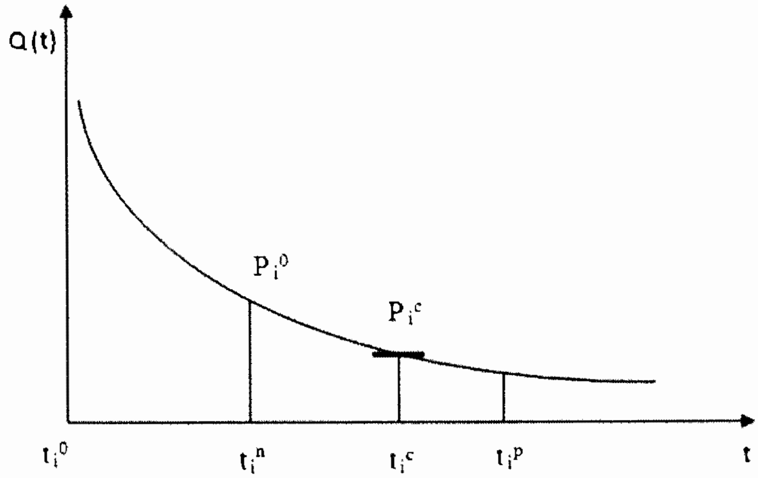

Figure 5.3. The relationship between quality value and price

For each retailer, we have

$$P_i(t) = \begin{cases} = P_i^0 & Q_i(t_i^n) \geq Q_i(t) > Q_i(t_i^c) \\ = P_i^c & Q_i(t_i^c) \geq Q_i(t) > Q_i(t_i^p) \\ = 0 & t \geq t_i^p \end{cases} \tag{5-10}$$

$\widetilde{V}_i$: the estimated sales of retailer i.

$$\widetilde{V}_i = \min\{D_i, \widetilde{A}_i\} \tag{5-11}$$

Where D_i is the estimated demand in retailer i, and we will use the regular demand function. Because we have two levels of price based on the quality of the product, the total demand will be the sum of the demands with different prices.

$$D_{i,} = D_i^0(P_i^0) + D_i^c(P_i^c) \tag{5-12}$$

The estimated available products at retailer i, $\widetilde{A}_i$ can be estimated:

$$\widetilde{A}_i = X_i + \varepsilon_i \tag{5-13}$$

X_i is the estimated quantity of the products received by retailer i, ε_i is the inventory quantity of the products at retailer i at time t_0, when products are shipped from suppliers.

To calculate the revenue, we need to figure out how many products will be sold in regular price, and how many products will be sold at discounted prices. In this problem, we assume that the on-hand inventory level is I_i^0 at $t = 0$, which is also the re-order point in inventory system.

At time t_i^n, the order products will be received at the retailers, the inventory will be filled up. The inventory will decrease with the inventory function

$$I(t) = f[R(P), t] \tag{5-14}$$

So there will be three different scenarios for the inventory situation when the new products reach to the retailer: (1) no inventory at t_i^n (2) shortages occurs before t_i^n (3) remain products at time point t_i^n from previous order which are still available for customers.

Before to discuss those three scenarios in detail, there are some assumptions used in the model:

1) The inventory system involves only one kind of product.
2) Replenishments are instantaneous with a known, constant lead time.
3) No backorder allowed.
4) Shortages are allowed.
5) FIFO (issuing the oldest items first) applied for issuing policies.
6) The retailers and distribution centers will belong to one company.
7) The price at each retailer can be adjusted based on the quality of products.

5.2.1. The Revenue in scenario (A)

In this scenario, the inventory will run out of products at t_i^l and the new products will be received by retailer at the same time.

Ultimately, the inventory reaches the re-order point I_i^S at $t = t_i^e$. (t_i^e is the end time of one order cycle). As the prescribed, we divide the price into two levels, one is regular, and the other is discounted price based on the quality value. There may be three different cases for the time start point: Case I: $t_i^0 = t_{i\_cycle\_N-1}^c$ ($t_{i\_cycle\_N-1}^c$ is the time point in previous order cycle after that all products will be on sale), Case II: $t_i^0 < t_{i\_cycle\_N-1}^c$, Case III: $t_i^0 > t_{i\_cycle\_N-1}^c$.

For the inventory function, the demand rate is known, and we have two different prices, so we can get the function of inventory system:

$$I_i(t) = \begin{cases} f(P_i^0) & t_0 \le t < t_i^c \\ f(P_i^c) & t_i^c \le t < t_i^p \end{cases} \quad (5\text{-}15)$$

1) Case I:

In this case, the cutting time point in previous cycle is equal to the start point of this cycle, $t_i^0 = t_{i\_cycle\_N-1}^c$, which means all products will be sold on a discounted price between time interval (t_i^0, t_i^n), as shown in Figure 5.4.

(a) We suppose there are no products from previous cycle reaching the total preservation time before they are sold out, $t_i^n \le t_{i\_cycle\_N-1}^p$. We assume the demand rate is dependent on the selling price, so the demand at retailer i is:

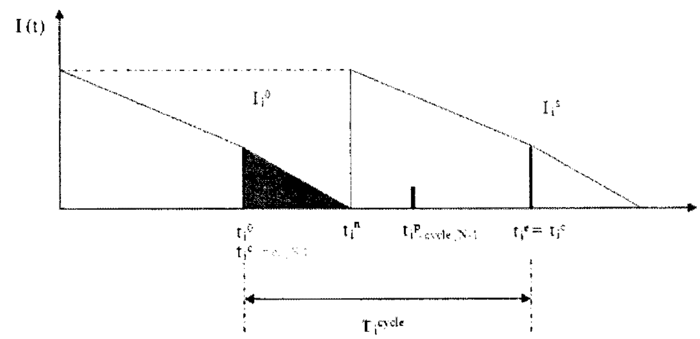

Figure 5.4. One order cycle of inventory situation in retailer under scenario (A), Case I (a)

$$D_i^0 = \int_{t_i^n}^{t_i^e} R_i^0(P_i^0)dt$$
$$D_i^c = \int_{0}^{t_i^n} R_i^c(P_i^c)dt \qquad (5\text{-}16)$$

the revenue will be:

$$R = \sum_{i=1}^{N} P_i^0 \widetilde{V}_i^0 + \sum_{i=1}^{N} P_i^c \widetilde{V}_i^c \qquad (5\text{-}17)$$

(b) There is another situation if we make a different assumption about the remaining preservation time $t_{i\_cycle\_N-1}^{p}$, shown in Figure 5.5.

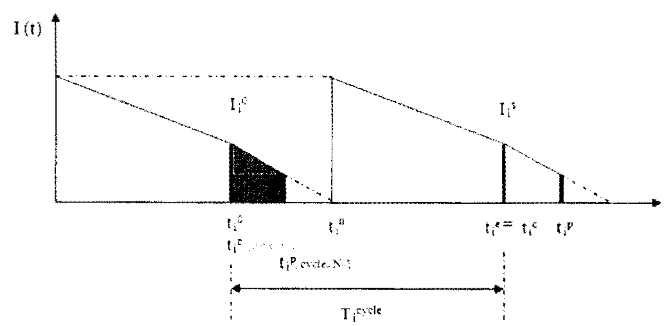

Figure 5.5. One order cycle of inventory situation in retailer under scenario (A), Case I (b)

Before the arrival of the new products, the products in previous order reach the total preservation time, so retailers will have to dispose those products although there is no product provided for customers before the time point t_i^n.

2) Case II:

In this case, $t_i^0 < t_{i\_cycle\_N-1}^c$, Figure 5.6 displays the inventory system in Case II.

(a) We suppose there are no products from previous cycle reaching the total preservation time before they are sold out, $t_i^n \le t_{i\_cycle\_N-1}^P$.

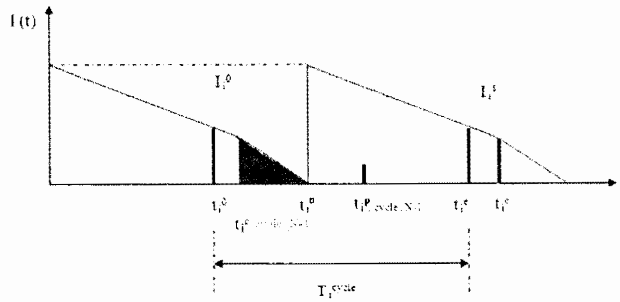

Figure 5.6. One order cycle of inventory situation in retailer under scenario (A), Case II (a)

Demand at retailer i is:

$$
\begin{aligned}
D_i^0 &= \int_0^{t_{i\_cycle\_N-1}^c} R_i^0(P_i^0)dt + \int_{t_i}^{t_i^c} R_i^0(P_i^0)dt \\
D_i^c &= \int_{t_{i\_cycle\_N-1}^c}^{t_i^n} R_i^c(P_i^c)dt
\end{aligned}
\qquad (5\text{-}18)
$$

The revenue will be the same equation as (5-17).

(b) Similarly, in Figure 5.7, we make different assumption about the remaining preservation time of products from previous order $t_{i\_cycle\_N-1}^P$.

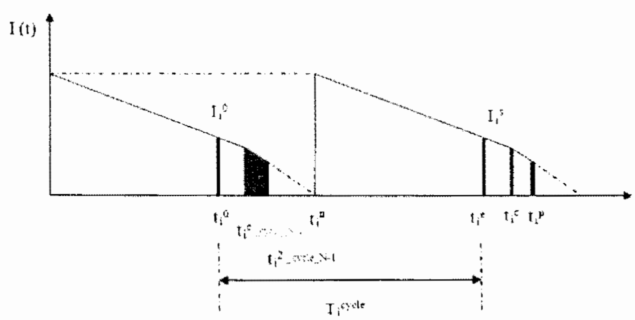

Figure 5.7. One order cycle of inventory situation in retailer under scenario (A), Case II (b)

(c) There is another special situation under this case, in Figure 5.8, $t^{c}_{i\_cycle\_N-1} \geq t^{n}_{i}$. Under this condition, retailers do not need to put any products in discounted price.

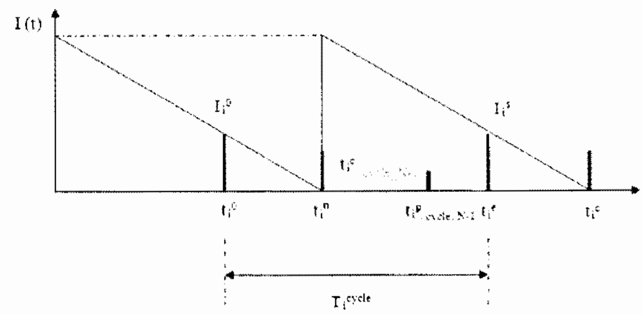

Figure 5.8. One order cycle of inventory situation in retailer under scenario (A), Case II (c)

3) Case III:

In this case, $t^{0}_{i} > t^{c}_{i\_cycle\_N-1}$.

a) We suppose that there are no products from previous cycle reaching the total preservation time before they are sold out, in Figure 5.9, $t^{n}_{i} \leq t^{p}_{i\_cycle\_N-1}$.

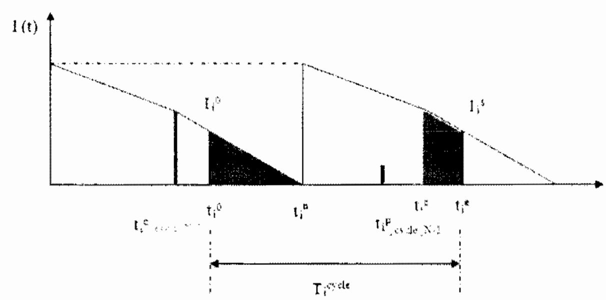

Figure 5.9. One order cycle of inventory situation in retailer under scenario (A), Case III (a)

Demand at retailer i is:

$$D_i^c = \int_0^{t_i^n} R_i^c(P_i^c)dt + \int_{t_i^c}^{t_i^e} R_i^c(P_i^c)dt$$
$$D_i^0 = \int_{t_i^n}^{t_i^c} R_i^0(P_i^0)dt \qquad (5\text{-}19)$$

(b) There is another situation if we make different assumption about the remaining preservation time $t^{p}_{i\_cycle\_N-1}$, in Figure 5.10.

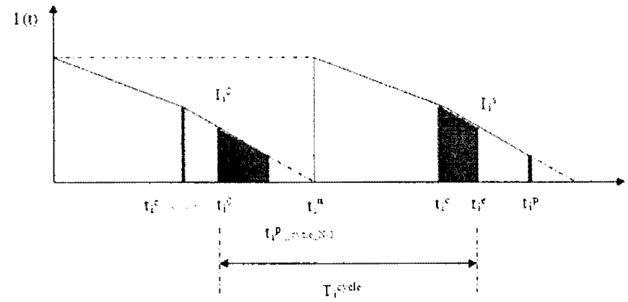

Figure 5.10. One order cycle of inventory situation under scenario (A), Case III (b)

5.2.2. The revenue in scenario (B)

In this scenario, the products run out of stock before the arrival of new products. Also, the assumption is that no back order is allowed. Recall in scenario (A), we made the following assumptions: all the products time in inventory will be within the total preservation time, no products will be disposed before the end of one cycle, and all products will be sold out just before the arrival of the new products. This is the ideal situation. However, actually the inventory before the new products coming is entirely possible empty due to the deterioration. So the assumption in scenario (B) is the remaining preservation time of product in inventory reach zero before the new products coming.

Similarly, there might be three different cases in scenario (B): Case I: $t^{0}_{i}= t^{c}_{i\_cycle\_N-1}$ ($t^{c}_{i\_cycle\_N-1}$ is the time point in previous order cycle after that all products will be on sale), Case II: $t^{0}_{i}< t^{c}_{i\_cycle\_N-1}$, Case III: $t^{0}_{i}> t^{c}_{i\_cycle\_N-1}$.

1) Case I:

The graphical representation of the inventory system in Case I in scenario (B) is depicted in figures below. In Case (I), $t^{0}_{i} = t^{c}_{i\_cycle\_N-1}$.

a) We suppose the shortage is due to the high demand rate in Case I, and we suppose there are no products from previous cycle reaching the total preservation time before they are sold out, shown in Figure 5.11, $t_i^n \le t_{i\_cycle\_N-1}^p$.

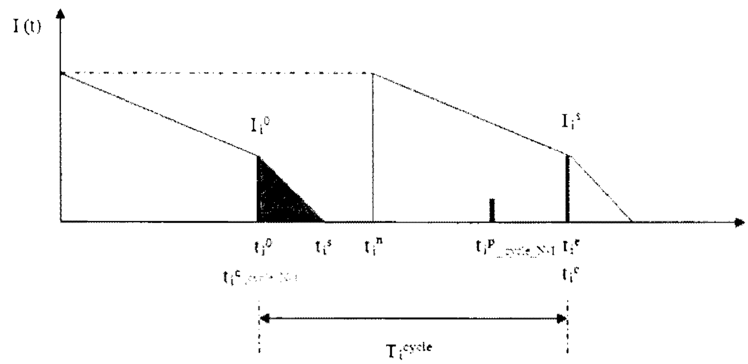

Figure 5.11. One order cycle of inventory situation in retailer under scenario (B), Case I (a)

b) There is another situation if we make a different assumption about the remaining preservation time $t_{i\_cycle\_N-1}^p$, shown in Figure 5.12.

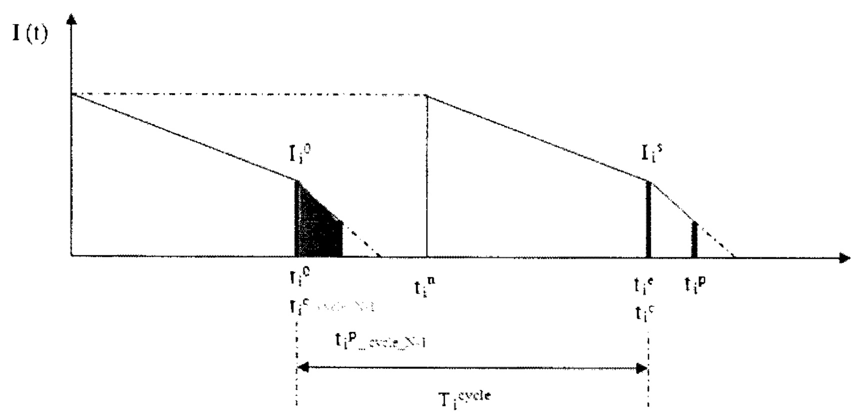

Figure 5.12. One order cycle of inventory situation in retailer under scenario (B), Case I (b)

2) Case II:

In Case II, $t_i^0 < t_{i\_cycle\_N-1}^c$, we also have three different situations.

a) We suppose the shortage is due to the high demand rate in Case II, in Figure 5.13, and we suppose there are no products from previous cycle reaching the total preservation time before they are sold out, $t_i^n \le t_{i\_cycle\_N-1}^p$.

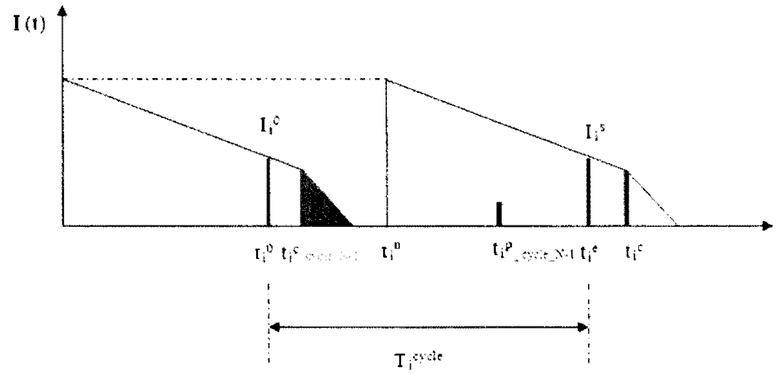

Figure 5.13. One order cycle of inventory situation in retailer under scenario (B), Case II (a)

b) In another situation under Case II, we suppose the products left from previous order cycle reach the end of total preservation time $t_{i\_cycle\_N-1}^p$ with the high demand rate before t_i^n, as illustrated in Figure 5.14.

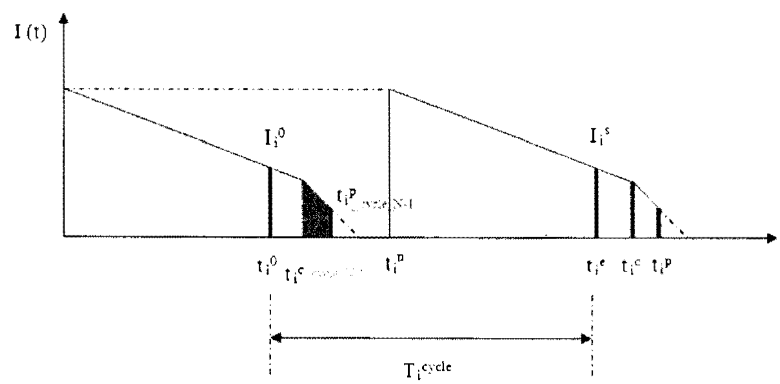

Figure 5.14. One order cycle of inventory situation in retailer under scenario (B), Case II (b)

c) There is one more special situation under Case II, $t^{c}_{i\_cycle\_N-1} \geq t^{n}_{i}$ and the quality of product in inventory can not reach to the discounted situation even after the products run out of stock due to high demand rate, shown in Figure 5.15.

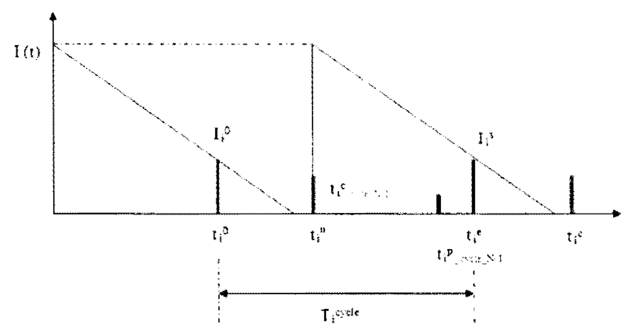

Figure 5.15. One order cycle of inventory situation in retailer under scenario (B), Case II (c)

3) Case III:

In Case III, $t^{0}_{i} > t^{c}_{i\_cycle\_N-1}$, we also have two different situations.

a) We suppose there are no products from previous cycle reaching the total preservation time before they are sold out, $t^{n}_{i} \leq t^{p}_{i\_cycle\_N-1}$, shown in Figure 5.16.

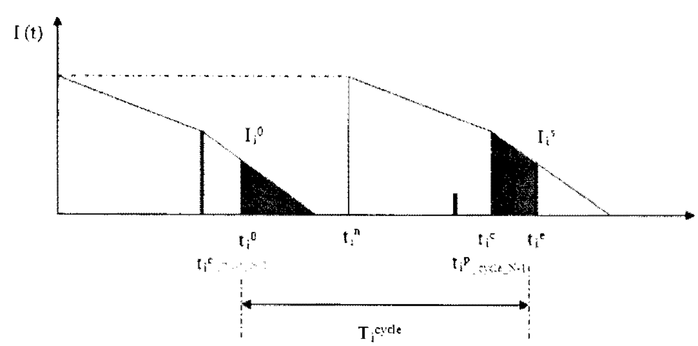

Figure 5.16. One order cycle of inventory situation in retailer under scenario (B) Case III (a)

b) Similarly, we make different assumption about the remaining preservation time of products from previous order $t^{p}_{i\_cycle\_N-1}$, as illustrated in Figure 5.17.

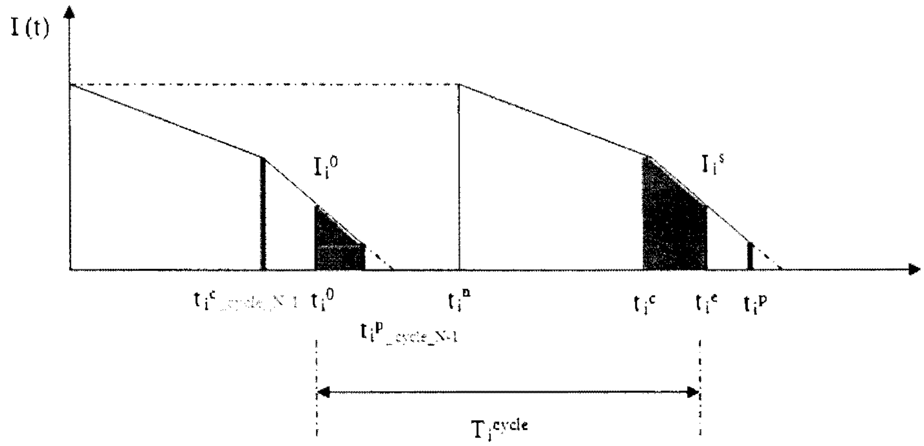

Figure 5.17. One order cycle of inventory situation under scenario (B) Case III (b)

5.2.3. The revenue in scenario (C)

In this scenario, there are still some products available when the new products arrive at the retailers. Recall that we assume that the temperature during the transportation and processing is constant, so basically we could predict the life time of the product in stock. For fixed life inventory problems, issuing the oldest items first (FIFO) is always the optimal way [47].

Similarly, there might be three different cases in scenario (2): Case I: $t^{0}_{i} = t^{c}_{i\_cycle\_N-1}$ ($t^{c}_{i\_cycle\_N-1}$ is the time point in previous order cycle after that all products will be on sale), Case II: $t^{0}_{i} < t^{c}_{i\_cycle\_N-1}$, Case III: $t^{0}_{i} > t^{c}_{i\_cycle\_N-1}$.

1) Case I:

In Case I, the cutting time point in previous cycle is equal to the start point of this cycle, in Figure 5.18, $t^{0}_{i} = t^{c}_{i\_cycle\_N-1}$, which means all products will be sold on a discounted price between the time interval (t^{0}_{i}, t^{n}_{i}).

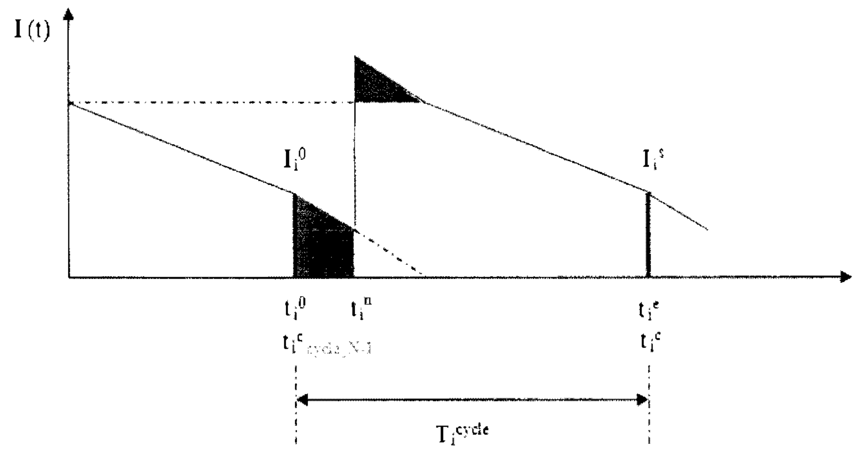

Figure 5.18. One order cycle of inventory situation under scenario (C) Case I

2) Case II:

In Case II, shown in Figure 5.19, $t_i^0 < t_{i\_cycle\_N-1}^c$, part of remaining products will be sold in a discounted price with FIFO issuing policy.

a) $t_{i\_cycle\_N-1}^c$ is in the time interval (t_i^0, t_i^n).

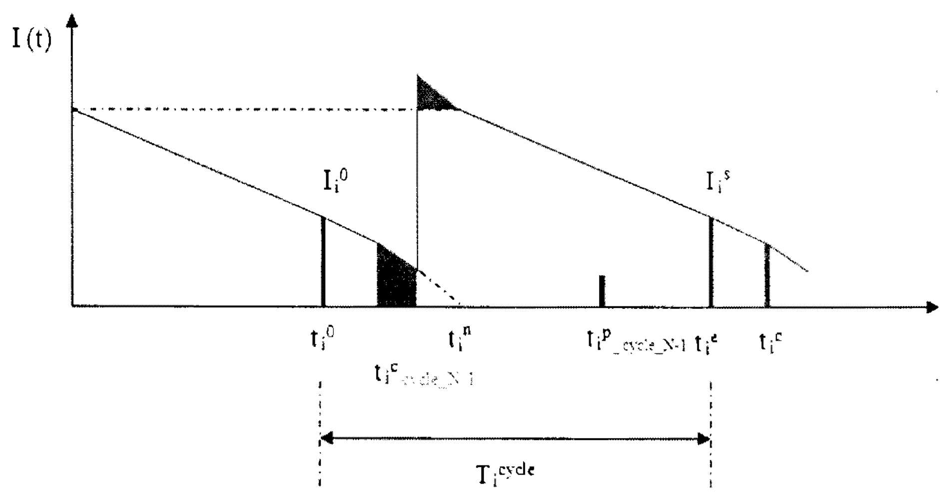

Figure 5.19. One order cycle of inventory situation under scenario (C) Case II (a)

b) In Case II, one more special case is that the quality of remaining products is still higher than the discounted quality after the replenishments, shown in Figure 5.20.

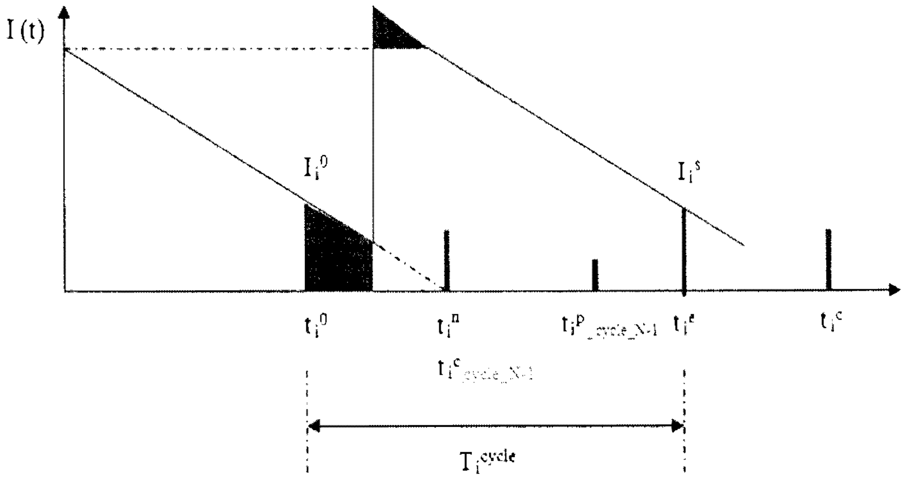

Figure 5.20. One order cycle of inventory situation under scenario (C) Case II (b)

c) If $t_{i\_cycle\_N-1}^c$ is equal to the time point when new products arrive, shown in Figure 5.21, then those remaining products will be sold at a discounted price.

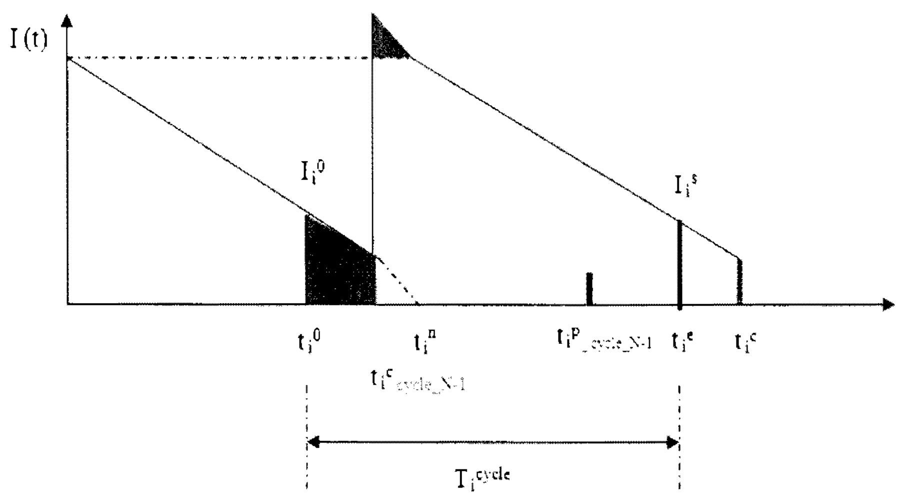

Figure 5.21. One order cycle of inventory situation under scenario (C) Case II (c)

d) If $t_{i\_cycle\_N-1}^c$ is greater than the time point when new products arrive, shown in Figure 5.22, then those remaining products will be divided into two parts, one with the regular price, the other with a discounted price.

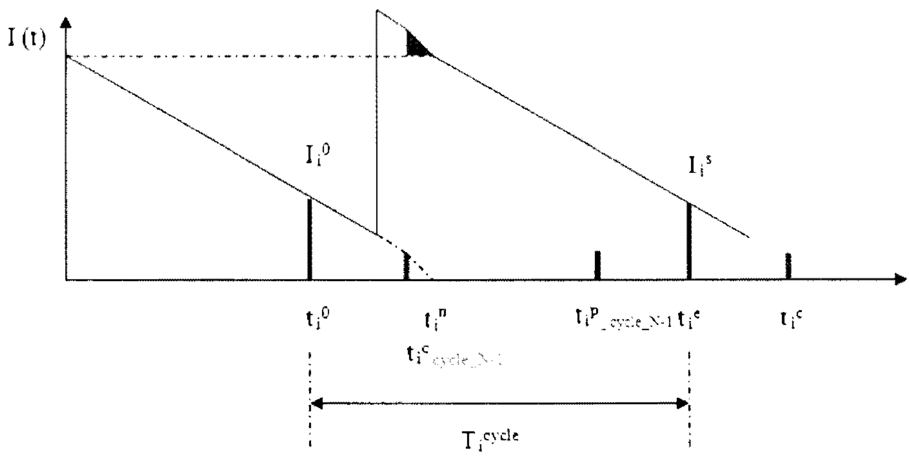

Figure 5.22. One order cycle of inventory situation under scenario (C) Case II (d)

3) Case III:

In Case III, $t_i^0 > t_{i\_cycle\_N-1}^c$, shown in Figure 5.23, the remaining products will be sold at a discounted price with FIFO issuing policy.

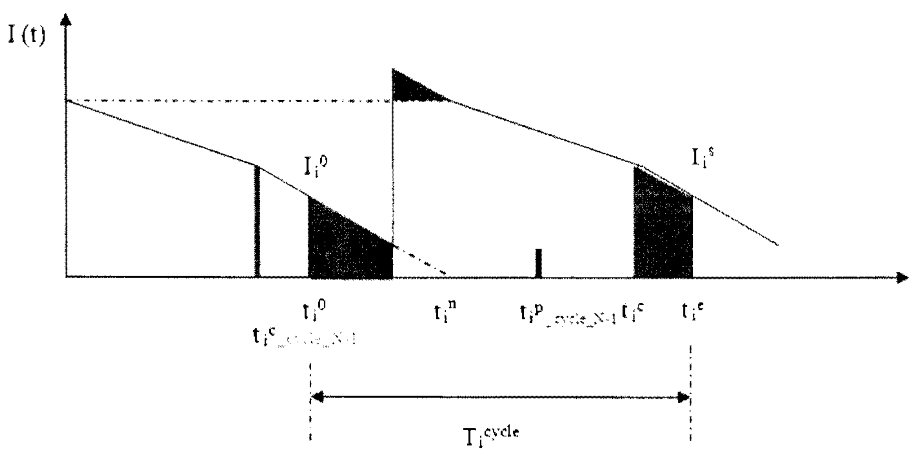

Figure 5.23. One order cycle of inventory situation under scenario (C) Case III

5.3. The function of total cost of the supply chain

The total cost of the supply chain will include ordering cost, shortage loss, disposal cost, holding cost, and transit cost [36].

$$M_{total} = M_o + M_s + M_w + M_h + M_t \qquad (5\text{-}20)$$

Where M_{total} is the total cost; M_o is total ordering cost; M_s is the total shortage loss; M_w is the total disposal cost; M_h is the total holding cost; M_t is the total transit cost.

(1) Total ordering cost

The ordering cost at retailers depends on the order size.

$$M_{total} = \sum_{i=1}^{N} c_i O_i^R \tag{5-21}$$

c_i : ordering cost for each unit at retailer i.

O_i^R :order quantity from retailer i, $O_i^R = D_i + e_i$, e_i is the amount of the extra products added for each order based on the priori strategy.

(2) Total shortage loss

In the scenario, the products received by retailer are less than the demand, in which case, there will be lost sales.

$$M_s = \sum_{i=1}^{N} s_i [D_i - \widetilde{A}_i]^+ \tag{5-22}$$

s_i : unit loss of shortage per product at retailer i.

$[D_i - \widetilde{A}_i]^+$: shortage of products of retailer i. if $D_i - \widetilde{A}_i \geq 0$, then $[D_i - \widetilde{A}_i]^+ = D_i - \widetilde{A}_i$, otherwise, $[D_i - \widetilde{A}_i]^+ = 0$.

(3) Total disposal cost

$$M_w = \sum_{i=1}^{N} w_i [\widetilde{A}_i - D_i]^+ \tag{5-23}$$

The total disposal cost consists two parts. One is that in the case that products received at retailer are greater than the demand due to the priori strategy applied, and there will be wastage of the product. The other part is spoilage disposal.

w_i : unit loss of wastage per product at retailer i.

$[\widetilde{A}_i - D_i]^+$: over supply of products of retailer i. if $\widetilde{A}_i - D_i \geq 0$, then

$[\widetilde{A}_i - D_i]^+ = \widetilde{A}_i - D_i$, otherwise, $[\widetilde{A}_i - D_i]^+ = 0$.

(4) Total holding cost

$$\mathrm{M}_h = \sum_{i=1}^{N} h_i \left(\sum_{k=1}^{[\widetilde{A}_i - \widetilde{V}_i]^+} (t_i^p - d_{ik}) \right) \tag{5-24}$$

h_i : unit holding cost per commodity per time unit of retailer i.

t_i^p : the length of preservation time for the perishable commodity

$[\widetilde{A}_i - \widetilde{V}_i]^+$: estimated unsold products at retailer i. if $[\widetilde{A}_i - \widetilde{V}_i] \geq 0$, then equal to $[\widetilde{A}_i - \widetilde{V}_i]$, otherwise, equal to zero.

d_{ik} : is the remaining preservation time of product *k* of retailer i.

(5) Transit cost

$$\mathrm{M}_t = \sum_{i=1}^{N} CS_i X_i + \sum_{j=1}^{M} CS_j Y_j \tag{5-25}$$

Transit cost between the partners, related with the lot sizing.

5.4. The function of total penalties of the supply chain

$$B_{total} = B_s + B_r \tag{5-26}$$

Where B_{total} is total penalties; B_s is total penalties incurred by suppliers; B_r is the total penalties incurred by retailers.

(1) Penalties incurred by retailers

$$B_r = \sum_{i=1}^{N} \Gamma_i^R \tag{5-27}$$

Γ_i^R : Penalty function for retailer i when products received do not match the contract amount.

$$\Gamma_i^R = \begin{cases} u_i^R(X_i - O_i^R) & (X_i - O_i^R) \ge 0 \\ v_i^R(X_i - O_i^R) & (X_i - O_i^R) < 0 \end{cases} \tag{5-28}$$

(2) Penalties incurred by suppliers

$$B_s = \sum_{j=1}^{M} \Gamma_j^S \tag{5-29}$$

Γ_j^S : Penalty function for supplier j when products shipped do not match the contract amount.

$$\Gamma_j^S = \begin{cases} u_j^S(Y_j - O_j^S) & (Y_j - O_j^S) \ge 0 \\ v_j^S(Y_j - O_j^S) & (Y_j - O_j^S) < 0 \end{cases} \tag{5-30}$$

5.5. The constraints of the model

Based on the discussion above, the objective function will be equation (5-31) and the rest equations are the constraints for this model; we suppose there is no inventory in distribution center, so the total products from suppliers will be equal to the output of DC. And any total coming products will be limited under the storage capacity.

$$\begin{aligned} \text{Max Profit} = & \sum_{i=1}^{N} P_i^0 \widetilde{V}_i^0 + \sum_{i=1}^{N} P_i^c \widetilde{V}_i^c - \sum_{i=1}^{N} c_i O_i^R - \sum_{i=1}^{N} s_i [D_i - \widetilde{A}_i]^+ - \sum_{i=1}^{N} w_i [\widetilde{A}_i - D_i]^+ \\ & - \sum_{i=1}^{N} h_i \Big(\sum_{k=1}^{[\widetilde{A}_i - \widetilde{V}_i]^+} (t_i^p - d_{ik}) \Big) - \sum_{i=1}^{N} CS_i X_i - \sum_{j=1}^{M} CS_j Y_j - \sum_{i=1}^{N} \Gamma_i^R - \sum_{j=1}^{M} \Gamma_j^S \end{aligned} \tag{5-31}$$

$$\sum_{i=1}^{N} X_i = \sum_{j=1}^{M} Y_j \tag{5-32}$$

$$0 \le X_i \le Q_i^R, i = 1,2,\dots,N \tag{5-33}$$

$$0 \le Y_i \le Q_j^S, j = 1,2,\dots,M \tag{5-34}$$

$$0 \le \sum_{i=1}^{N} X \le Q^{DC} \qquad (5\text{-}35)$$

$$0 \le \sum_{j=1}^{M} Y_j \le Q^{DC} \qquad (5\text{-}36)$$

$$X_i \ge 0, Y_j \ge 0 \qquad (5\text{-}37)$$

Where:

Q_i^R : Inventory capacity of the retailer i

Q_j^S : Production capacity of the supplier j

Q^{DC} : Distribution center capacity

As we discussed before, the objective function is to maximize the profit of the whole supply chain. The revenue includes the selling with the regular price and the discounted price. After subtracting total costs from revenue, including ordering cost, holding cost, shortage cost, and transit cost, the profit can be calculated. One of the constraints for this model is all products shipped from the suppliers will be delivered to the retailers, equation (5-32). In addition, there is a limitation of capacity of distribution center, equation (5-35) and (5-36). Similarly, products shipped from the suppliers cannot overpass the production capacity of the suppliers, equation (5-34); the retailers need to consider the capacity of the inventory, equation (5-33). All decision variables used in this model need to be positive.

CHAPTER 6. CASE STUDY AND DISCUSSION

6.1. The modified cold supply chain model

6.1.1. The modified linear programming model

Linear Programming (LP) is a tool that has saved many thousands or millions of dollars for most companies or businesses of even moderate size in the various industrialized countries of the world, which will be used to solve our model.

In previous chapter, we already established the objective function, equation (5-31), but we cannot solve this equation directly with the optimization software, because part of main equation is not in linear relationship. So we need to modify this objective function to a new one, shown in equation (6-1).

$$\begin{aligned} \text{Profit} = {} & M_i(\sum_{i=1}^{N} P_i^0 m_i^0 + \sum_{i=1}^{N} P_i^c m_i^c) - \sum_{i=1}^{N} c_i O_i^R - \sum_{i=1}^{N} s_i [D_i - \widetilde{A}_i]^+ \\ & - \sum_{i=1}^{N} w_i [\widetilde{A}_i - D_i]^+ - \sum_{i=1}^{N} h_i (\sum_{k=1}^{[\widetilde{A}_i - \widetilde{V}_i]^+} (t_i^p - d_{ik})) - \sum_{i=1}^{N} CS_i X_i - \sum_{j=1}^{M} CS_j Y_j \\ & - \sum_{i=1}^{N} (u_i^R Y_i^{t+} + v_i^R Y_i^{t-}) - \sum_{j=1}^{M} (u_j^S Z_j^{t+} + v_j^S Z_j^{t-}) \end{aligned} \tag{6-1}$$

The following sections discuss how we modified the equation to a linear one.

1) Revenue Function

As we discussed before, we have 20 different cases, $\widetilde{V}_i = \min\{D_i, \widetilde{A}_i\}$ is the general function of the sales, let $m_i = \min(D_i, \widetilde{A}_i)$, in LP, we need to ensure the minimal value between $(D_i, \widetilde{A}_i)$ will be picked in the model, so we add an very big value, big M, as the coefficient of m_i, since the model has a maximizing objective function, so once we add a very big coefficient to m_i, under the constrains, $m_i \le D_i$ and $m_i \le \widetilde{A}_i$,

$$R = M_i \sum_{i=1}^{N} P_i m_i = M_i (\sum_{i=1}^{N} P_i^0 m_i^0 + \sum_{i=1}^{N} P_i^c m_i^c) \quad (6\text{-}2)$$

Equation could be solved in linear programming method. When we try to find the solution under those 20 different cases, we need to add in the relevant data under regular price and discounted price respectively. The value of big M could be assigned based on the real data in cases study part, generally, 100 times larger than the biggest coefficient of the original objective function is big enough [48].

2) Cost Function

i) Total ordering cost

There is no need to change, basically, in equation (5-21), the total ordering cost will be a constant value in our model.

ii) Total shortage cost

If $D_i - \widetilde{A}_i > 0$, in equation (5-22), we will lost sale from the shortage, so based on the description before, we will only have this shortage cost in scenario (B), there is no shortage cost in scenario (A) and scenario (C).

iii) Total disposal cost

In another hand, if $D_i - \widetilde{A}_i < 0$, in equation (5-23), there will be two different situations, in situation one, we assume all the unsold products in the current cycle will be still qualified for the next cycle, in other words, by the end of the current cycle, the rest of products will be still in inventory for the next cycle, and also, there is no product left from previous cycle out of the limitation of the qualification defined in the previous model description section. So we do not need to consider the disposal cost in each cycle considering the assumption we made before, which is we suppose each cycle will be consistent with previous cycle, every retailer will be in the same scenario under same case for each cycle all the time. In the situation two, part of products will be disposed due to the limitation of preservation time. Under this situation, we need to figure out how many products left from pervious cycle will be disposed due to the limitation of the preservation time in the current cycle.

Generally, for the calculation of shortage or disposal cost, we will to formulate the cost base on 20 different cases under three different scenarios.

iv) Total holding cost

For the holding cost, in equation (5-24), it depends on the rest of preservation time, so we will get the holding cost easily from 20 different cases.

v) Total transit cost

In this model, in equation (5-25), transit cost function does not need to be modified.

3) Penalties Function

We will define two variables Y_i' and Z_j' to represent the difference between the number of contract and shipping quantity for retailers and suppliers.

Considering we are not sure Y_i' is positive or negative since X_i is the decision variable, we can replace Y_i' by two new nonnegative variables, $Y_i'^{+}$ and $Y_i'^{-}$.

$Y_i' = X_i - O_i^R = Y_i'^{+} - Y_i'^{-}$

$$Y_i'^{+} = (X_i - O_i^R)^{+} \qquad (6\text{-}3)$$

$$Y_i^{\prime -} = (X_i - O_i^R)^- \tag{6-4}$$

Where we interpret $Y_i^{\prime +}$ as representing the positive component of $Y_i^{\prime}$, and $Y_i^{\prime -}$ as its negative component, $Y_i^{\prime +} \geq 0$ and $Y_i^{\prime -} \geq 0$. In particular,

$$Y_i^{\prime +} = \begin{cases} +Y_i^{\prime}, & if\ Y_i^{\prime} \geq 0 \\ 0, & if\ Y_i^{\prime} \leq 0 \end{cases} \tag{6-5}$$

$$Y_i^{\prime -} = \begin{cases} 0, & if\ Y_i^{\prime} \geq 0 \\ -Y_i^{\prime}, & if\ Y_i^{\prime} \leq 0 \end{cases} \tag{6-6}$$

We define $Z_j^{\prime}$ represent the difference between the contract quantity and shipping quantity from supplier j.

$$Z_j^{\prime} = Y_j - O_j^S = Z_j^{\prime +} - Z_j^{\prime -}$$

$$Z_j^{\prime +} = (Y_j - O_j^S)^+ \tag{6-7}$$

$$Z_j^{\prime -} = (Y_j - O_j^S)^- \tag{6-8}$$

Where we interpreted $Z_j^{\prime +}$ as representing the positive component of $Z_j^{\prime}$, and $Z_j^{\prime -}$ as its negative component, $Z_j^{\prime +} \geq 0$ and $Z_j^{\prime -} \geq 0$. In particular,

$$Z_j^{\prime +} = \begin{cases} +Z_j^{\prime}, & if\ Z_j^{\prime} \geq 0 \\ 0, & if\ Z_j^{\prime} \leq 0 \end{cases} \tag{6-9}$$

$$Z_j^{\prime -} = \begin{cases} 0, & if\ Z_j^{\prime} \geq 0 \\ -Z_j^{\prime}, & if\ Z_j^{\prime} \leq 0 \end{cases} \tag{6-10}$$

Since we add new variables, there are two relevant constraints added into the model:

$$X_i - O_i^R = Y_i^{\prime +} - Y_i^{\prime -} \tag{6-11}$$

$$Y_j - O_j^S = Z_j^{t+} - Z_j^{t-} \tag{6-12}$$

We replace the new variables into penalty function, and then we will get the new penalties functions:

$$\mathrm{B}_r = \sum_{i=1}^{N} (u_i^R Y_i^{t+} + v_i^R Y_i^{t-}) \tag{6-13}$$

$$\mathrm{B}_s = \sum_{j=1}^{M} (u_j^S Z_j^{t+} + v_j^S Z_j^{t-}) \tag{6-14}$$

4) Constraints

New constrains will be added into this model, so the total constrains will be:

$$m_i \le D_i \qquad \forall i \tag{6-15}$$

$$m_i \le \widetilde{A}_i \qquad \forall i \tag{6-16}$$

$$X_i - O_i^R = Y_i^{t+} - Y_i^{t-} \qquad \forall i \tag{6-17}$$

$$Y_j - O_j^S = Z_j^{t+} - Z_j^{t-} \qquad \forall j \tag{6-18}$$

$$\sum_{i=1}^{N} X_i = \sum_{j=1}^{M} Y_j \tag{6-19}$$

$$0 \le X_i \le Q_i^R, i = 1,2,\ldots,N \qquad \forall i \tag{6-20}$$

$$0 \le Y_j \le Q_j^S \qquad \forall j \tag{6-21}$$

$$0 \le \sum_{i=1}^{N} X_i \le Q^{DC} \tag{6-22}$$

$$0 \le \sum_{j=1}^{M} Y_j \le Q^{DC} \tag{6-23}$$

$$m_i = \widetilde{V} \qquad \forall i \tag{6-24}$$

$$\widetilde{A}_i = X_i + \varepsilon_i^0 + \varepsilon_i^c \qquad \forall i \tag{6-25}$$

$$\widetilde{A}_i = \partial X_i \qquad 0 \le \partial \le 1 \qquad \forall i \tag{6-26}$$

$$m_i = m_i^0 + m_i^c \qquad \forall i \tag{6-27}$$

$$all\_Variables \ge 0 \tag{6-28}$$

6.1.2. Case study

In case study part, we will run three cases selected from three different scenarios and compare results. There are some assumptions under the case study.

(1) Each retailer will run in a certain case continuously.

(2) Each retailer in this cold supply chain will be in the same scenario under the same case environment.

(3) We do not consider the priori strategy in environmental setting.

(4) There are two retailers, two suppliers and one distribution center in a perishable food supply chain and those two retailers will be in a certain case under scenario A, B and C.

(5) Only one kind of product will be simulated in this model.

As shown in Figure 6.1, a company, ABC, has two retailers, two suppliers, and one distribution center. This company has a long term contract with supplier 1 and supplier 2 for product Z, 5000 pounds respectively.

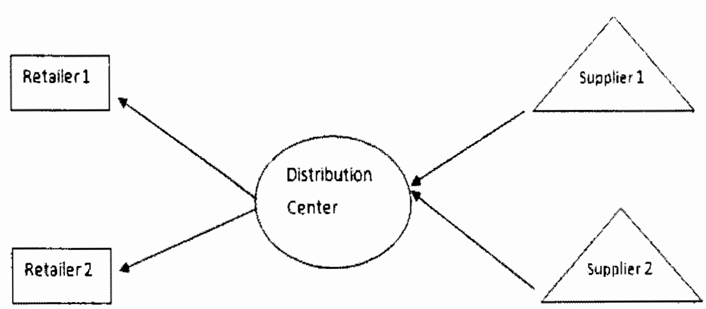

Figure 6.1. Supply chain network in case study

The model could be applied at any time during the transport. The price set at each retailer will be decided based on the data collected from container. As we discussed before, the demand will be calculated based on the price. Before we run the model, all parameters can be known based the data, and there will be three different results for decision variables, X and Y. Once the shipping quantity Y from the supplier is not equal the contract, 5000, the company need to do sensitivity analysis to decide if the truck need to go back to the supplier to return or add products since the change of transportation cost. Inventory situation is shown in Figure 6.2.

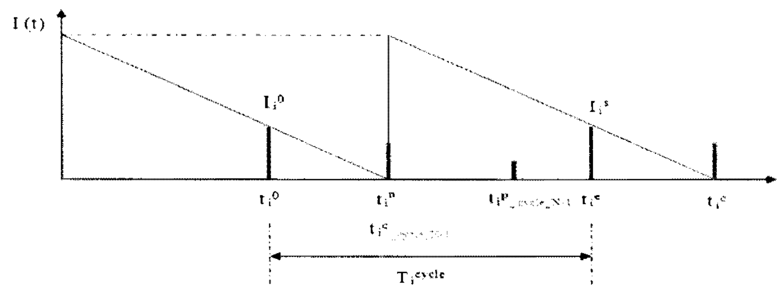

Figure 6.2. Inventory situation in scenario (A)

Scenario (A):

We run this model when products are shipped out from suppliers. In one cycle, from the start point, t_i^0, the remote control center will continuously receive products information from the containers. From GPS data which are sent from data terminal inside the container, we can estimate the time point t_i^n. From environmental data, temperature, we can predict the quality of products and preservation time t_i^p. From the quality of products, we can figure out the cutting time point t_i^c. Regular price and discounted price at each retailer are set from actual quality of products. Demand rate can be predicted with price. The safety stock level is known, and we made assumption about inventory function which will decrease by demand rate, so the end time of one ordering cycle t_i^e can be figured out. All coefficients of cost are estimated, shown in Table 6.1.

Table 6.1. Parameters used for retailers under scenario (A)

	Characteristics		Retailer 1	Retailer 2
1	Regular price at retailer i (unit: US$)	P_i^0	3	2.8
2	Discounted price at retailer i (unit: US$)	P_i^c	2	2
3	Demand rate	$R(P)$	200	180
4	Time point retailer receive the product (unit: hour)	t_i^n	10	13
5	Time point the products will be sold on sale (unit: hour)	t_i^c	10	13
6	The end time of one cycle (unit: hour)	t_i^e	25	27
7	The total preservation time (unit: hour)	t_i^p	40	45
8	Ordering cost for each unit at retailer i (unit: US$)	c_i	0.02	0.02
9	Unit loss of shortage per product at retailer i (unit: US$)	s_i	3	2.8
10	Unit loss of wastage per product at retailer i (unit: US$)	w_i	2	2
11	Unit holding cost per unit per time unit of retailer i (unit: US$)	h_i	0.2	0.2
12	Unit transit cost for retailer i (unit: US$)	CS_i^R	0.01	0.01
13	Unit penalty for retailer i when X_i greater than O_i^R (unit: US$)	u_i^R	0.3	0.4
14	Unit penalty for retailer i when X_i less than O_i^R (unit: US$)	v_i^R	0.4	0.3
15	Coefficient of m_i	M_i	500	500
16	Demand under regular price	D_i^0	5000	4860
17	Demand under discounted price	D_i^c	0	0
18	Order quantity from retailer i	O_i^R	5000	4860
19	Inventory capacity of the retailer i	Q_i^R	8000	8000

Table 6.2 shows parameters used for supplier1 and supplier 2. In Table 6.3, all costs and revenue are calculated with parameters listed in Tables 6.1 and 6.2.

Table 6.2. Parameters used for suppliers under scenario (A)

			Supplier 1	Supplier 2
1	Unit transit cost for supplier j (unit: US$)	CS_j^S	0.01	0.01
2	Unit penalty for supplier j when Y_j greater than O_j^S (unit: US$)	u_j^S	0.3	0.28
3	Unit penalty for supplier j when Y_j less than O_j^S (unit: US$)	v_j^S	0.28	0.3
4	Contract quantity of the supplier j	O_j^S	5000	5000
5	Production capacity of the supplier j	Q_j^S	8000	8000
6	Distribution center capacity	Q^{DC}	20000	

Table 6.3. Calculated results under scenario (A)

	scenario (A)		Retailer 1	Retailer 2
1	Revenue	$M_i(\sum_{i=1}^{N} P_i^0 m_i^0 + \sum_{i=1}^{N} P_i^c m_i^c)$	$3m_1^0$	$2.8m_2^0$
2	Total ordering cost	$\sum_{i=1}^{N} c_i O_i$	100	97.2
3	Total shortage cost	$\sum_{i=1}^{N} s_i[D_i - \widetilde{A}_i]^+$	0	0
4	Total disposal cost	$\sum_{i=1}^{N} w_i[\widetilde{A}_i - D_i]^+$	0	0
5	Total holding cost	$\sum_{i=1}^{N} h_i(\sum_{k=1}^{[A_i - \widetilde{V}_i]^+}(t_2 - d_{ik}))$	0	0
6	Transit cost	$\sum_{i=1}^{N} CS_i^R X_i$	$0.01X_1$	$0.01X_2$
7	Penalties incurred by retailers	$\sum_{i=1}^{N}(u_i^R Y_i^{t+} + v_i^R Y_i^{t-})$	$0.3Y_1^{t+} + 0.4Y_1^{t-}$	$0.4Y_2^{t+} + 0.3Y_2^{t-}$
			Supplier 1	Supplier 2
1	Penalties incurred by suppliers	$\sum_{j=1}^{M}(u_j^S Z_j^{t+} + v_j^S Z_j^{t-})$	$0.3Z_1^{t+} + 0.28Z_1^{t-}$	$0.28Z_2^{t+} + 0.3Z_2^{t-}$
2	Transit cost	$\sum_{j=1}^{M} CS_j^S Y_j$	$0.01Y_1$	$0.01Y_2$

Scenario (B):

In scenario B, shown in Figure 6.3, products at the retailers are sold out before the arrival of new products. Table 6.4 shows parts of parameters used for this case study. The rest of parameters used in the model have the same value as case study in scenario A. The calculation results of costs and penalties are shown in Table 6.5.

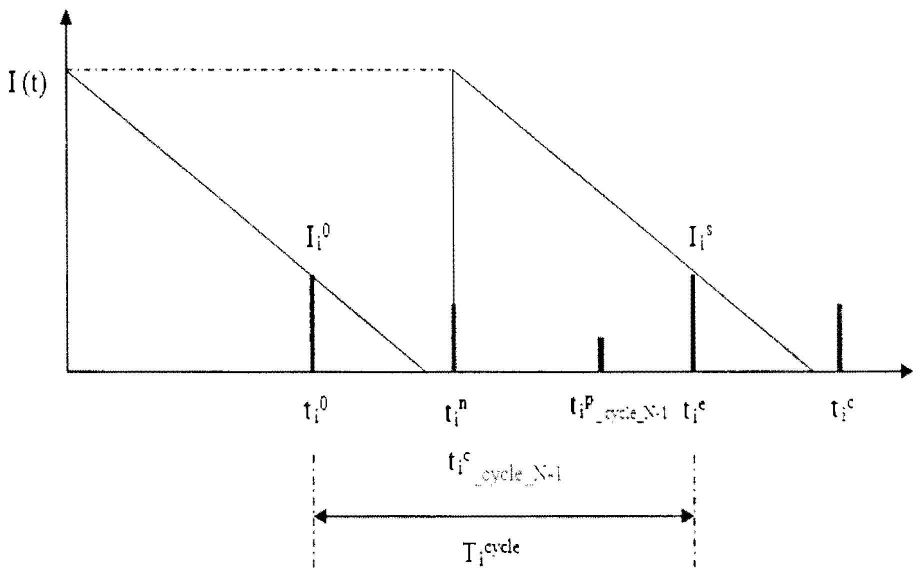

Figure 6.3. Inventory situation in scenario (B)

Table 6.4. Parameters used for retailers under scenario (B)

	Characteristics		Retailer 1	Retailer 2
1	Time point retailer sold out products (unit: hour)	t_i^s	8	10
2	The total preservation time (unit: hour)	t_i^p	30	30
3	Unit loss of shortage per product at retailer i (unit: US$)	s_i	3	2.8
4	Demand under regular price	D_i^0	4600	4320
5	Demand under discounted price	D_i^c	0	0
6	Order quantity from retailer i	O_i^R	4600	4320

Table 6.5. Calculated results under scenario (B)

	Scenario (B)		Retailer 1	Retailer 2
1	Revenue	$M_i(\sum_{i=1}^{N} P_i^0 m_i^0 + \sum_{i=1}^{N} P_i^c m_i^c)$	$3m_1^0$	$2.8m_2^0$
2	Total ordering cost	$\sum_{i=1}^{N} c_i O_i$	92	90
3	Total shortage cost	$\sum_{i=1}^{N} s_i [D_i - \widetilde{A}_i]^+$	3*2*200	2.8*3*180
4	Total disposal cost	$\sum_{i=1}^{N} w_i [\widetilde{A}_i - D_i]^+$	0	0
5	Total holding cost	$\sum_{i=1}^{N} h_i (\sum_{k=1}^{[\widetilde{A}_i - \widetilde{V}_i]^+} (t_2 - d_{ik}))$	0	0
6	Transit cost	$\sum_{i=1}^{N} CS_i^R X_i$	$0.01X_1$	$0.01X_2$
7	Penalties incurred by retailers	$\sum_{i=1}^{N} (u_i^R Y_i^{t+} + v_i^R Y_i^{t-})$	$0.3Y_1^{t+} + 0.4Y_1^{t-}$	$0.4Y_2^{t+} + 0.3Y_2^{t-}$
			Supplier 1	Supplier 2
1	Penalties incurred by suppliers	$\sum_{j=1}^{M} (u_j^S Z_j^{t+} + v_j^S Z_j^{t-})$	$0.3Z_1^{t+} + 0.28Z_1^{t-}$	$0.28Z_2^{t+} + 0.3Z_2^{t-}$
2	Transit cost	$\sum_{j=1}^{M} CS_j^S Y_j$	$0.01Y_1$	$0.01Y_2$

Scenario (C):

Figure 6.4 shows the inventory situation of scenario C. Parameters and calculation results are listed in Tables 6.6 and 6.7.

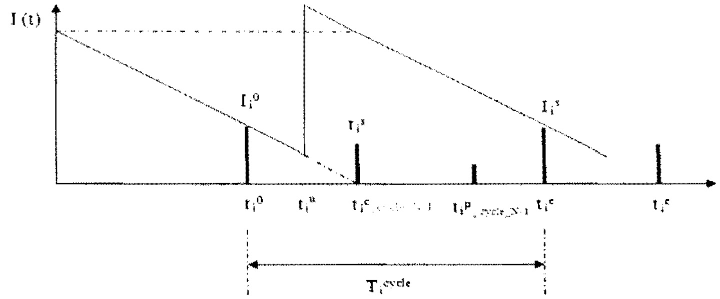

Figure 6.4. Inventory situation in scenario (C)

Table 6.6. Parameters used for retailers under scenario (C)

	Characteristics		Retailer 1	Retailer 2
1	Time point retailer receive the product (unit: hour)	t_i^n	6	7
2	Time point products would be sold out if no new products coming (unit: hour)	t_i^s	10	13
3	The total preservation time (unit: hour)	t_i^p	30	30
4	Demand under regular price	D_i^0	5000	4860
5	Demand under discounted price	D_i^c	0	0
6	Order quantity from retailer i	O_i^R	5000	4860
7	Inventory capacity of the retailer i	Q_i^R	8000	8000

Table 6.7. Calculated results under scenario (C)

			Retailer 1	Retailer 2
1	Revenue	$M_i(\sum_{i=1}^{N} P_i^0 m_i^0 + \sum_{i=1}^{N} P_i^c m_i^c)$	$3m_1^0$	$2.8m_2^0$
2	Total ordering cost	$\sum_{i=1}^{N} c_i O_i$	100	97.2
3	Total shortage cost	$\sum_{i=1}^{N} s_i [D_i - \widetilde{A}_i]^+$	0	0
4	Total disposal cost	$\sum_{i=1}^{N} w_i [\widetilde{A}_i - D_i]^+$	0	0
5	Total holding cost	$\sum_{i=1}^{N} h_i (\sum_{k=1}^{[\widetilde{A}_i - \widetilde{V}_i]^+} (t_2 - d_{ik}))$	0.2*6*200	0.2*6*180
6	Transit cost	$\sum_{i=1}^{N} CS_i^R X_i$	$0.01X_1$	$0.01X_2$
7	Penalties incurred by retailers	$\sum_{i=1}^{N} (u_i^R Y_i^{t+} + v_i^R Y_i^{t-})$	$0.3Y_1^{t+} + 0.4Y_1^{t-}$	$0.4Y_2^{t+} + 0.3Y_2^{t-}$
			Supplier 1	Supplier 2
1	Penalties incurred by suppliers	$\sum_{j=1}^{M} (u_j^S Z_j^{t+} + v_j^S Z_j^{t-})$	$0.3Z_1^{t+} + 0.28Z_1^{t-}$	$0.28Z_2^{t+} + 0.3Z_2^{t-}$
2	Transit cost	$\sum_{j=1}^{M} CS_j^S Y_j$	$0.01Y_1$	$0.01Y_2$

6.1.3. Results from Lindo

Since the whole model has been converted into a linear model, and we have assigned the values for the model parameters for three different cases, the table 6.8 shows the results from the optimization software, Lindo. Lindo is a PC-based tool for solving linear programming problems. It is a command oriented program.

Table 6.8. Decision variables results in different scenarios

	Scenario A	Scenario B	Scenario C
m10	5000	4600	5000
m20	4860	4320	4860
x1	5000	4600	5000
x2	4860	4320	4860
y1	4860	3920	4860
y2	5000	5000	5000
z1_t+	0	0	0
z1_t-	140	1080	140
z2_t+	0	0	0
z2_t-	0	0	0
y1_t+	0	0	0
y1_t-	0	0	0
y2_t+	0	0	0
y2_t-	0	0	0

We use Lindo to assist with solving of LP problems in the case study. Table 6.9 shows the calculation results in three different scenarios. Costs and revenue for each retailer in scenarios A, B, and C are calculated based on the results from Lindo. The profit for each retailer in different scenarios is calculated based on the main function.

Table 6.9. Profit results in different scenarios

		Scenario A		Scenario B		Scenario C	
		R1	R2	R1	R2	R1	R2
1	Revenue	15000	13608	13800	12096	15000	13608
2	Total ordering cost	100	97.2	92	90	100	97.2
3	Total shortage cost	0	0	1200	1512	0	0
4	Total disposal cost	0	0	0	0	0	0
5	Total holding cost	0	0	0	0	240	216
6	Transit cost	50	48.6	46	43.2	50	48.6
7	Penalties incurred by retailers	0	0	0	0	0	0
	Total cost	433.6		3374.8		791	
1	Penalties incurred by suppliers	39.2	0	302.4	0	39.2	0
2	Transit cost	48.6	50	39.2	50		
	Profit	28174.4		22521.2		27817	

6.2. Results discussion

From above results, the number of quantity of products, X, shipped from distribution center is just equal to the demand at retailers in three different scenarios. The reason why we get these results is there is no big difference between the values we gave to two different retailers, including price of products, transit cost, penalties cost and shortage cost, to maximize the whole supply chain profit, the model will assign the demand quantity of product to each retailer.

But we can see the result of shipping quantity, Y1, from Lindo is not equal to the contract for supplier 1, in this situation, the company needs to decide if the truck should go back to supplier 1 to return products. This decision is dependent on the change of transit cost to supplier 1. If the transit cost adds within a certain range, the truck needs to go back to supplier 1 to return part of products. We will discuss this in the sensitivity analysis of transit cost.

During the actual application, if there are some accidents happen during the transportation causing bigger transit cost for one supplier, or the price of one kind of product has big difference between two retailers, or one retailer has big shortage cost, the above results will be changed totally, and the following sections will discuss the changing results from this model under different coefficient values.

6.2.1. Sensitivity analysis

(1) Changes in the transit cost

In some certain cases, if the transit costs suddenly are increased resulting from some unpredictable reasons, such as, the trucks need to be adjusted due to the changes of weather or the quality of products inside containers, or oil price and high way transit fee increase, or the trucks need to go back to the supplier to return or add products. Through our model, distribution center will reassign the number of products shipped from DC to retailers. The trucks might need to go back to the supplier.

Table 6.10 shows the different results from Lindo with different value of the transit cost of supplier 1, CS_1^S. In scenario (A), when the transit cost from supplier 1 to distribution center is increased to 0.57, through the model, we can see the model will decrease the number of products shipped from supplier 1 from 4860 to 1860 to maximize the profit. We continue to increase the transit cost to 3.4 per product, the model will stop shipping products from supplier 1. Since the production capacity from supplier 2 is 8000, the model will ship 8000 products from supplier 2 to meet the demand, and because the products selling price in retailer 1 is greater than in retailer 2, so the model will ship 5000 products to retailer 1 to meet the demand of retailer 1, and the rest of products at distribution center, 3000, will be shipped to retailer 2.

Table 6.10. Lindo results under different coefficient of Y1 in scenario (A)

	Transit cost of Supplier 1	Y1	Y2	X1	X2
1	$CS_1^S = CS_2^S = 0.01$	4860	5000	5000	4860
2	$3.4 > CS_1^S \geq 0.57$	1860	8000	5000	4860
3	$CS_1^S \geq 3.4$	0	8000	5000	3000

(2) Changes in the product price at retailers

The price of products at retailers depends on the quality of product, and in our tracking system, we can predict the quality of the shipping products. However, in some cases, the quality of products might be changed due to some accidents, and then the price of the products will be changed dramatically. In this section, we will change the price of products at retailer 1 in scenario (B). As we discussed before, in this scenario, two retailers in this supply chain are both in shortage situation due to the previous inventory is not enough with high demand for next cycle or the delay of transportation. At the same time, we will change the shortage cost of the retailers to analyze the difference of the results.

The table 6.11 shows the results under different price at retailers and different shortage cost incurred at retailers in scenario (B). We designed four different tests, test 1 (T1), test 2 (T2), test 3 (T3), and test 4 (T4).

When the shortage cost and products price are the same at retailers 1 and 2, in test 1, the model will ship products to retailers based on the contract order to minimize the shortage cost, so X1 is 4600, X2 is 4320. The penalties incurred from suppliers used the previous value in this case study, shortage penalties from supplier 2 is greater than supplier

1, that's why all products, in test 1 to 4, shipped from supplier 2 is equal to the contract value, 5000, and the rest demand shipped from supplier 1, 3920.

Table 6.11. Lindo results under price changes in scenario (B)

	T1	T2	T3	T4
Shortage cost R1, S_1	2	2	≥ 2.7	2.7
Shortage cost R2, S_2	2	2	2	2
Price R1, P_1^0	2.8	≥ 3.5	2.8	2.8
Price R2, P_2^0	2.8	2.8	2.8	≥ 4.2
X1	4600	5000	5000	4060
X2	4320	3920	3920	4860
Y1	3920	3920	3920	3920
Y2	5000	5000	5000	5000
S1	400	0	0	940
S2	540	940	940	0

In test 2, keeping the same value of shortage cost in retailers, and increasing the price at retailer 1, when the price is greater than 3.5, the products shipped from distribution center to retailer 1 is changed to 5000, equal to demand value, and at the same time, the products shipped to retailer 2 is changed to 3920 with the shortage value 940.

In test 3, keeping the same price value at retailers, increasing the shortage cost at retailer 1, when shortage cost at retailer 1 is greater than 2.7, model output the same results as test 2. In test 4, remaining the value of shortage cost at retailers, increasing the price value at retailer 2, when the price is greater than 4.2 per product, the model will increase the products shipped to retailer 2 with no shortage.

(3) Changes in holding cost at retailers

It is possible that there are extra products left at retailer even after new products coming, and as we discussed before, we issue products with FIFO, so retailers need to pay more on inventory holding cost. In this case, we will change the coefficient of holding cost to see the different output from the model, shown in Table 6.12.

Table 6.12. Lindo results under holding cost changes in scenario (C)

	Holding cost at retailer 1	X1	X2	Y1	Y2
T1	$h_1 = h_2 = 0.2$	5000	4860	4860	5000
T2	$h_2 = 0.2$, $h_1 \geq 3.5$	3800	4860	3660	5000
T3	$h_2 = 0.2$, $h_1 \geq 3.5$	3800	6060	4860	5000

We can see if retailer 1 needs to pay more than 3.5 per product, distribution center will decrease the number of products shipped to retailer 1. Since we suppose the products already shipped to distribution center from two suppliers in test 3, the Lindo will run under the constraints, $X_1 + X_2 = 9860$, the model will ship 3800 products to retailer 1 to meet the demand under shorter cycle time.

6.2.2. Conclusion

Based on the Lindo results, we can conclude that this model could maximize the profit of total supply chain. In different scenarios, through this model, we can make different decisions with different inputs. After suppliers receive the order from distribution center, the system will record the initial quality status of products from suppliers, and RFID tracking system will record the ID of every product. Supply chain management group could predict the quality status of products inside the containers and decide the price of product in retailers. During the transportation time, the model will provide the outputs for the whole supply chain based on the characteristics related with this cold supply chain, including the products shipped to retailers. From sensitivity analysis, we know when coefficients changed over some certain values; the model could give different results to optimize the results.

The above analysis only discussed the situation in which two retailers are both in same scenario, but in real life, there will be different combination situation happed in different retailers, so there are more work need to do in future research. This model is only for optimization part of the cold supply chain with certain demand, and there are lot of assumptions and limitations with this model. Apparently more strategies are needed to be designed to make supply chain more flexible to meet practical requirements.

CHAPTER 7. CONCLUSION AND FUTURE RESEARCH

7.1. Conclusion

Improper control of environmental parameters for food products in the cold supply chain leads to the growth of bacteria such as E. coli O157:H7. It in turn deteriorates food quality and causes food-borne diseases in humans. Monitoring the quality of food products during transportation is of great importance to ensure safe delivery at point of consumption. In this study, we propose to integrate a variety of technologies, including the inexpensive passive RFID technology, wireless sensor technology, GPS, and communication based on a cellular network, to effectively real-time monitor the environmental parameters of food items during transportation. By introducing a modular structure and a data management method, the real-time monitoring of food products at item/box level becomes feasible. Furthermore, a prototype system was built for continuously monitoring environmental temperature using specific preliminary tests to be performed on ground beef products. The temperature data together with GPS information were successfully collected from the wireless sensors and sent to the data server via the CDMA network. The safety of foods was then quantitatively evaluated by using a predictive model for the growth of E. coli O157:H7.

The proposed approach can be applied to manage food safety for numerous food products and a variety of bacteria in cold supply chain. Besides temperature, other on-board sensing modules on the sensor device can collect additional environmental information if needed. It not only enhances the safety of foods in cold supply chain and prevents the unsafe products from reaching consumers, but also helps companies to develop smart pricing strategies based on the estimated safety level, and provides an effective means for bio-terrorism threat prevention. With proper modification, the system can also be used for the distribution of other products such as pharmaceutical.

After we obtain all values, including products' identification, quantities of products loaded in trucks, and environmental values, such as temperatures inside of the containers, we can use the model to optimize the profit of the whole supply chain. From the previous chapter, we know there are some models which could predict the quality of products based on the environmental data and initial quality status, and based on these values, we can manage the whole cold supply chain dynamically. There are more than 20 different cases under three different scenarios, and the price of products could be set based on the quality of products which could be used to predict the demand. Through the case study, we know this model could optimize the profit of the whole supply chain via managing the quantities of products shipped to retailers from suppliers.

Our technology system could track and trace the products even during transit time, and based on our model, the supply chain distribution could be optimized. Lost or damaged goods could be minimized, and most importantly, food safety could be ensured.

7.2. Future research

A number of concerns have been raised with regards to the use of this new tracking system and evaluation model, such as security, stability. Some of these are general issues related to wireless sensor, RFID applications and cold supply chain models. Issues such as reliability and flexibility could be addressed in the future.

i) Reliability.

We use RFID as a tracking tool for products during the supply chain, but we will have to face the problems which exist when using this new technology. Examples include the reader cannot read the data inside of the tag due to the harsh environment, which will create an incorrect record of loading and unloading. Similarly, GPS sometimes cannot get signals from satellites when truck goes under high buildings.

ii) Flexibility.

One of the assumptions used in cold supply chain modeling is that the demand at retailer is deterministic with the price. However, in reality, stochastic demand is more acceptable by food companies, since the demand is uncertain in most cases. The extended model is needed to be developed in the future under stochastic demand.

Only one distribution center is used in our study, but there are usually several distribution centers in a cold supply chain in reality. So we need to extend the model to be more applicable and flexible.

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APPENDIX A. NOTATION

Table A. Notation used in supply chain model

		Characteristics
1	$R(P_i)$	Demand rate, $R(P_i)=k_i P_i^{-\alpha_i}$, P is the price, α (>1) is the demand elasticity, i is the retailer, from 1 to N
2	$P_i(t)=f(Q_i(t))$	Dynamic price of the products, decreasing with the quality
3	$Q=f(T,t)$	Quality value will be the function of temperature history, T is temperature during the process
4	$t_i^p=f(T,t)$	The total preservation time of the products based on the temperature history
5	I_i^s	Safety stock level at retailer i
6	$d_{ik}=t_i^p-t$	The rest preservation time of the product k at retailer i, k is different kind of products at retailers
7	T_i^{cycle}	The cycle length of retailer i
8	X_i	The products will be shipped from distribution center to retailer i, i is from 1 to N
9	Y_j	The products will be shipped from supplier j to distribution center, j is from 1 to M
10	I_i^0	Retailer i will reorder products from distribution center once the inventory reach to the level I_i^0
11	t_i^n	The time point new products coming to the retailer i, replenishments
12	t_i^c	The time point when the quality of products reach to the quality situation in which the products have to be sold in a discounted price
13	t_i^0	The start time point of one ordering cycle of the retailer i, $t_i^0=0$
14	D_i^0	The quantity of demand under the regular price at retailer i
15	D_i^c	The quantity of demand under the discounted price at retailer i
16	D_i	The total demand at retailer i in one ordering cycle, $D_i=D_i^0+D_i^c$
17	P_i^0	Regular price at retailer i
18	P_i^c	Discounted price at retailer i
19	t_i^e	End time of one order cycle of the retailer i

20	$\widetilde{V}_i^0$	The estimated sales with regular price of retailer i
21	$\widetilde{V}_i^c$	The estimated sales with discounted price of retailer i
22	ε_i^0	The inventory quantity of the products with the higher level quality in retailer i at time t_i^n
23	ε_i^c	The inventory quantity of the products with the higher level quality in retailer i at time t_i^c
24	$\widetilde{A}_i^0$	The available products with higher level quality at retailer i, will be sold in regular price at time t_i^n
25	$\widetilde{A}_i^c$	The available products with lower level quality at retailer i, will be sold in discounted price at time t_i^c
26	$\widetilde{A}_i$	The available products at retailer i in one ordering cycle
27	c_i	Ordering cost for each unit at retailer i
28	O_i^R	Order quantity from retailer i
29	e_i	The amount of the extra products added for each order based on the priori strategy
30	s_i	Unit loss of shortage per product at retailer i
31	$[D_i - \widetilde{A}_i]^+$	Shortage of products of retailer i. if $D_i - \widetilde{A}_i \geq 0$, then $[D_i - \widetilde{A}_i]^+ = D_i - \widetilde{A}_i$, otherwise, $[D_i - \widetilde{A}_i]^+ = 0$
32	w_i	Unit loss of wastage per product at retailer i
33	$[\widetilde{A}_i - D_i]^+$	Over supply of products of retailer i. if $\widetilde{A}_i - D_i \geq 0$, then $[\widetilde{A}_i - D_i]^+ = \widetilde{A}_i - D_i$, otherwise, $[\widetilde{A}_i - D_i]^+ = 0$
34	h_i	Unit holding cost per unit per time unit of retailer i
35	$[\widetilde{A}_i - \widetilde{V}_i]^+$	Estimated unsold products at retailer i. if $[\widetilde{A}_i - \widetilde{V}_i] \geq 0$ then equal to $[\widetilde{A}_i - \widetilde{V}_i]$, otherwise, equal to zero
36	CS_i^R	Transit cost per unit between the retailer i and distribution center, related with the lot sizing
37	CS_j^S	Transit cost per unit between the supplier j and distribution center, related with the lot sizing
38	Γ_i^R	Penalty function for retailer i when products received do not match the contract amount
39	u_i^R	The unit penalty for retailer i when $(X_i - O_i^R) \geq 0$
40	v_i^R	The unit penalty for retailer i when $(X_i - O_i^R) < 0$

41	O_j^S	Contract quantity of the supplier j
42	Γ_j^S	Penalty function for supplier j when products shipped do not match the contract amount
43	u_j^S	Unit penalty for supplier j when Y_j greater than O_j^S
44	v_j^S	Unit penalty for supplier j when Y_j less than O_j^S
45	Q_i^R	Inventory capacity of the retailer i
46	Q_j^S	Production capacity of the supplier j
47	M_i	Coefficient of m_i, need to be assigned a value which 100 times larger than the biggest coefficient of the original objective function
48	Q^{DC}	Distribution center capacity
49	$\widetilde{V}_i$	The estimated sales of retailer i
50	t_i^s	Time point retailer i sold out products
51	$m_i = m_i^0 + m_i^c = \widetilde{V}_i$	The estimated sales of retailer i, used in linear formulation; m_i^0 is the sales with the regular price; m_i^c is the sales with the discounted price
52	Y_i^t	The difference between the quantity of contract and the number of shipping for retailer i
53	Z_j^t	The difference between the quantity of contract and the number of shipping for supplier j
54	Y_i^{t+}	Representing the positive component of Y_i^t
55	Y_i^{t-}	Negative component of Y_i^t
56	Z_j^{t+}	Representing the positive component of Z_j^t
57	Z_j^{t-}	Negative component of Z_j^t
58	R	Total revenue of the whole chain
59	$_{cycle-N-1}$	This subscript represents the value in previous cycle, for example, $t_{i\_cycle\_N-1}^P$ is the preservation time in previous cycle.
60	$I(t) = f[R(P), t]$	Inventory function, decrease with demand rate
61	∂	The proportion of the products received by retailers
62	$_i$	This subscript represents the parameter is related to retailer i
63	$_j$	This subscript represents the parameter is related to retailer j
64	D_i^0	Demand under regular price

65	D_i^c	Demand under discounted price
66	M_{total}	Total cost
67	M_o	Total ordering cost
68	M_s	Total shortage cost
69	M_d	Total disposal cost
70	M_h	Total holding cost
71	M_t	Total transit cost
72	M_w	Total wastage cost
73	B_{total}	Total penalties
74	B_s	Total penalties occurred at suppliers
75	B_r	Total penalties occurred at retailers

APPENDIX B. LINDO CODES

scenario (A)

```
MAX 3m10+2.8m20-0.01x1-0.01x2-0.3y1tp-0.4y1tn-0.4y2tp-0.3y2tn-0.3z1tp-0.28z1tn-
0.28z2tp-0.3z2tn-0.01y1-0.01y2

subject to

m10-x1<=0
m20-x2<=0
m10<=5000
m20<=4860
x1+x2<=20000
y1+y2<=20000
x1-y1tp+y1tn=5000
x2-y2tp+y2tn=4860
y1-z1tp+z1tn=5000
y2-z2tp-z2tn=5000
x1+x2-y1-y2=0
x1<=8000
x2<=8000
y1<=8000
y2<=8000

end
```

Scenario (B)

```
MAX 2.8x1+4.2x2-0.01x1-0.01x2-0.3y1tp-0.4y1tn-0.3y2tp-0.4y2tn-0.3z1tp-0.28z1tn-
0.28z2tp-0.3z2tn-0.01y1-0.01y2-2.6s1-2s2

subject to

x1<=5000
x2<=4860
x1+x2<=20000
y1+y2<=20000
x1-y1tp+y1tn=4600
x2-y2tp+y2tn=4320
y1-z1tp+z1tn=5000
y2-z2tp-z2tn=5000
x1+x2-y1-y2=0
y1<=8000
y2<=8000
s1+x1=5000
```

s2+x2=4860
x1+x2<=8920

end

Scenario (C)

MAX 2.8x1+2.8x2-0.01x1-0.01x2-0.3y1tp-0.4y1tn-0.3y2tp-0.4y2tn-0.3z1tp-0.28z1tn-0.3z2tp-0.28z2tn-0.01y1-0.01y2-0.2h1-0.2h2

subject to

x1-h1<=3800
x2-h2<=3600
x1<=5000
x2<=4860
x1+x2<=20000
y1+y2<=20000
x1-y1tp+y1tn=5000
x2-y2tp+y2tn=4860
y1-z1tp+z1tn=5000
y2-z2tp-z2tn=5000
x1+x2-y1-y2=0
x1<=8000
x2<=8000
y1<=8000
y2<=8000

end