Extended Food Supply Chain Traceability with Multiple Automatic Identification and Data Collection Technologies

HU, Yong

A Thesis Submitted in Fulfillment
of the Requirements for the Degree of
Master of Philosophy
in
Systems Engineering and Engineering Management

The Chinese University of Hong Kong
October 2007

Abstract

Abstract of thesis entitled: Extended Food Supply Chain Traceability with Multiple Automatic Identification and Data Collection Technologies
Submitted by Hu Yong
for the degree of Master of Philosophy
at The Chinese University of Hong Kong in October 2007

We define a notion of the extended traceability for food supply chains as the integration of tracking and tracing and the monitoring capability. The motivation of the thesis arises from the need of establishing the extended traceability in food supply chains and the lack of matured technologies and implementation specifications. The objective of the thesis is to present the ways in which we establish the extended traceability in food supply chains with multiple automatic identification and data collection (AIDC) technologies. The AIDC technologies adopted in this thesis include passive RFID, active RFID, barcode, and sensor technologies. The three layers of application system developed are the tracking and tracing management module, the storage and transportation monitoring module and the sensor networks enabled assessment module, which gradually establish the extended traceability.

The tracking and tracing management module establishes tracking and tracing across food supply chains. This module enables interoperable and scalable access to food product information across the supply chain, and thus provides foundations for the upper layers. The storage and transportation monitoring module provides in situ environment monitoring by making use of the sensor integrated active RFID systems. This module detects abnormalities in surrounding environment as an indication to food safety and quality problems during storage and transportation. The sensor networks enabled assessment module provides more comprehensive monitoring capability across the phases in food supply chains by using the sensor networks integrated active RFID systems.

In the thesis, the overall system architecture of the whole application system and the software and hardware issues in each layer of the application modules are discussed. In order to give a detailed explanation of how the extended traceability is established, a chicken supply chain is taken as an example.

Keywords: Extended Visibility; Automatic Identification and Data Collection Technology; RFID; Barcode; Sensor; Food Supply Chain.

摘要

我們將食品供應鏈上的追踪與溯源以及監控能力統稱爲擴展的可追溯性。本論文的動機來自于在食品供應鏈上建立擴展的可追溯性的迫切需求，以及相關所需技術和實施規範的不成熟。本論文的目標是演示我們如何運用多種自動識別與數據采集技術來在食品供應鏈上建立擴展的可追溯性。我們所采用的自動識別與數據采集技術包括：無源射頻識別、有源射頻識別、條形碼和傳感器技術。我們開發了三層應用系統，分別是：追踪與溯源管理模塊、儲存與運輸監控模塊和傳感器網絡測評模塊。這三層應用系統逐步實現了擴展的可追溯性。

追踪與溯源管理模塊在整個食品供應鏈上建立了追踪與溯源。這個模塊在供應鏈上實現了可互操作的和可擴展的食品產品信息訪問，爲更高層的應用系統提供了基礎。儲存與運輸監控模塊通過運用整合了傳感器的有源無綫射頻識別系統提供了現場環境監控能力，從而檢測出在儲存與運輸過程中食品環境的异常情況，作爲食品安全與質量問題的一個指示。傳感器網絡測評模塊通過在食品供應鏈的各個環節部署整合了傳感器網絡的有源無綫射頻識別系統，提供了更全面的環境測評功能。

在本論文中，我們會討論整個應用系統的系統架構，以及各層應用的軟件和硬件技術要點。爲了詳細解釋如何建立擴展的可追溯性，我們舉了一個鷄肉供應鏈的例子做了具體的介紹。

關鍵詞: 擴展的可追溯性； 自動識別與數據采集技術；無綫射頻識別；條形碼；傳感器； 食品供應鏈。

Acknowledgements

It is a pleasure to thank the many people who made this thesis possible.

Firstly, I would like to thank my supervisor, Professor Houmin Yan, who has a great desire and enthusiasm to use the cutting edge automatic identification and data collection technologies to change the world's supply chain management, and thus the daily life of every people. He not only guided me to complete this thesis, but also taught me how to explore and research, which will benefit me in my whole life.

Then, I would also like to thank the whole CUHK team working together. The team is an excellent synergy of three departments towards the same goal. Being with the teammates makes my past years in Hong Kong joyful. Among them are Professor Christopher Chuen Chi Yang, Professor Youhua Chen, Dr. Dorbin Ng, Dr. Yingjie Li, Di Yang, Leo Chong, and Ying Ma from the Systems Engineering and Engineering Management department; Professor Keli Wu, Dr. Hongyang Wang, Hongyang Li, and Dacheng Wei from the Electronic Engineering department; and Andy Mak from the Information Engineering department.

Lastly, but most importantly, I would like to thank my parents. They bore me, raised me, and loved me. To them I dedicate this thesis.

Thesis/Assessment Committee

Professor Chen Youhua (Chair)
Professor Yan Houmin (Thesis Supervisor)
Professor Yang Chuen-chi (Committee Member)
Professor Benjamin Yen (External Examiner)

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Chapter 1. Introduction

1.1. Background and Motivation

Owing to the advance in economy globalization and logistics development, nowadays we not only consume local food products but also have an unprecedented access to food produced from all over the world: people in the East Asia enjoy fresh catches from Australia and people in the North America taste newly picked lichees from China. However, this global food supply chain also posts an exceptional challenge to supply chain traceability.

The supply chain traceability has two aspects: tracking and tracing. The tracking provides the ability to follow the path of a product and the tracing provides the ability to identify the origin of a product. The perishable nature of food products requires the monitoring of environment and food products themselves. Therefore, we define a notion of the extended traceability for food supply chains as the integration of tracking and tracing and the monitoring capability.

The recent advance in the automatic identification and data collection (AIDC) technologies makes it possible for the implementation of the extended traceability for a food supply chain. The AIDC technologies provide methods of identifying objects, collecting data, and sending the data directly into computer systems without human involvement. Examples of those technologies are barcode, passive RFID, active RFID, and sensor technologies. However, the AIDC technologies and system architectures for establishing the extended traceability are far away from maturity yet.

Besides, there are particular difficulties in applying the AIDC technologies to the establishment of the extended traceability in food supply chains rather than the ones for common products. For example, the raw materials of food supply chains may be living animals or plants, it is more difficult to identify them than other well-packaged items; the heavy water content of some food may lower the detection rate of passive RFID tags; the perishable nature of food products makes the monitoring of environment and food products themselves quite necessary etc. There have been pilot projects around the world for establishing the extended traceability in food supply chains. However, there are widely recognized best practice and implementation specifications for such projects.

In a word, the motivation of this thesis arises from the need of establishing the extended traceability in food supply chains and the lack of maturity in related technologies and implementation specifications.

1.2. Objectives of the Thesis

A monitoring capability is integrated into the original supply chain traceability definition to form our scope of the extended traceability. The monitoring capability has two aspects: data capturing and information sharing. Data capturing means the capturing of environment data or food product sensory data. Examples of environment data are temperature and humidity. Examples of food product sensory data are toxin residues and color. Information sharing means the captured monitoring data is shared among all parties in the supply chain.

We carry out a lot of requirement escalation work with food supply chain practitioners. Based on the business requirements and researches on related technologies, the objective of the thesis is to present the ways in which we establish the extended traceability in food supply chains with multiple automatic identification and data collection technologies. The AIDC technologies adopted include passive RFID, active RFID, barcode, and sensors.

In order to achieve the extended traceability, a step-by-step approach is used. We develop three layers of application modules that gradually establish the extended traceability, as shown in the following figure. As a result, the research tends to fulfill three levels of objectives:

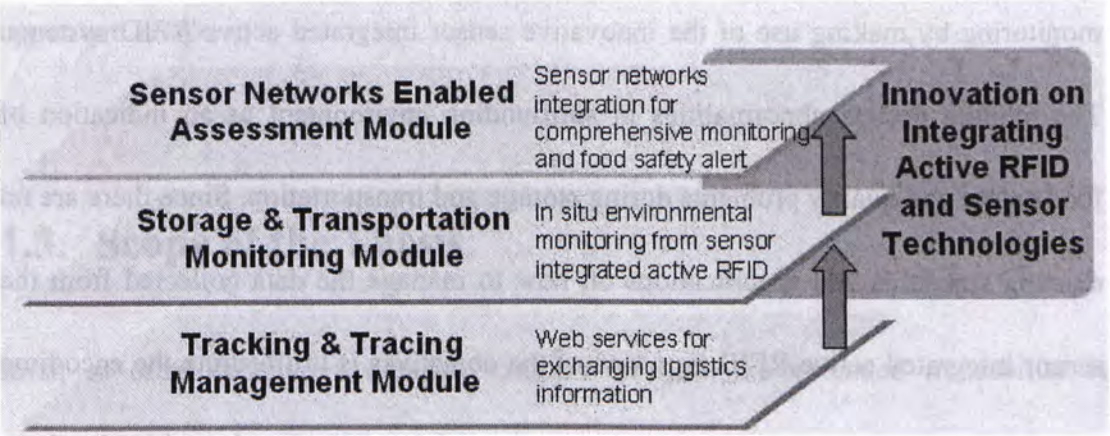


Figure 1.1. Module layers

The tracking and tracing management module establishes tracking and tracing across food supply chains. The module enables interoperable and scalable access to food product information across the whole supply chain. Although the application in this module is not new, it provides additional necessary foundations for the upper layers of new applications. So, there are still three research objectives in this module, which are as follows: 1) to create a methodology which establishes a nested visibility with appropriate nested AIDC technologies and thus is conducive to item level visibility of the food products, which is meaningful since so far there are no guidelines for achieving the nested visibility; 2) to illustrate how to integrate heterogeneous data collected from multiple AIDC technologies into an EPCIS, which is not specified in the current EPCIS specifications; 3) to come up with a suitable anti-counterfeit solution enabled by the AIDC technologies, which is urgent since counterfeiting in food supply chains of developing countries like China is a serious problem.

The storage and transportation monitoring module provides in situ environment monitoring by making use of the innovative sensor integrated active RFID systems. The module detects abnormalities in surrounding environment as an indication of food safety and quality problems during storage and transportation. Since there are no existing standards and specifications on how to manage the data collected from the sensor integrated active RFID tags, one of the objectives is to illustrate the encoding, filtering, compression, capturing, and accessing of the data. Another objective is to establish a responsive warning mechanism to support the analysis of food safety and quality during storage and transportation, which is enabled by the sensor integrated active RFID technology.

The sensor networks enabled assessment module provides more comprehensive monitoring capability across the phases in food supply chains by using sensor networks integrated active RFID systems. Since there are no existing standards and specifications to refer to, one of the objectives is to develop application program interfaces for the RFID middleware and the application software to support the use of sensor networks. Also, to achieve thorough and transparent monitoring to the supply chain activities by means of an active warning mechanism is another objective.

A key technology innovation in the thesis is the integration of sensors and active RFID tags, which is used in the upper two levels of application modules. Sensor integrated active RFID tags are able to send the sensory information collected by the sensors to active RFID readers. To develop this technology is the joint objective of the upper two levels.

1.3. Scope of the Thesis

First, in order to give a detailed example of how the extended traceability is established, a sample chicken supply chain is discussed on, because food supply chains may differ greatly from each other owing to the variety of product characteristics and supply chain processes. The scope and processes of the sample supply chain are clearly defined.

Second, the overall system architecture of the whole application system is discussed in the thesis, because the three layers of application modules are built on the same architectural foundation. Besides, the system architecture, the implementation of software, and the selection and deployment of hardware for each layer of the application modules are explored, while the implementation of hardware is not covered in this thesis.

1.4. Structure of the Thesis

This thesis consists of seven chapters. The first chapter is an introduction to the study, presenting the background, objectives and scope of the thesis. Chapter 2 covers the review of related technology development. The third chapter presents the overall system architecture and scope for the whole application system. The following three chapters elaborate on the three application modules, which are tracking and tracing management module, storage and transportation monitoring module and sensor networks enabled assessment module. In Chapter 7, the conclusion of this thesis is made.

Chapter 2. Review of Related Technologies

This chapter gives a review of the related technologies, which are relevant to the building of the application system. Section 2.1 gives definitions to tracking and tracing, which is what the first module is trying to establish. Section 2.2 gives a review of the current development of the related AIDC technologies, which are used in the application system. Section 2.3 reviews the standards and specifications of the EPCglobal, because our application system is based on these standards but makes certain necessary extensions. Section 2.4 reviews current RFID applications in food supply chain management, which helps to explain the motivation and advantages of our proposed approach. Section 2.5 reviews the current anti-counterfeit technologies and solutions, which helps to explain why we have to come up with our anti-counterfeit mechanism in section 4.5. Section 2.6 reviews the current popular data compression algorithms, which helps to explain why we need to develop our new algorithm in section 5.2. Section 2.7 reviews the shelf life prediction models, which we use in the upper two modules.

2.1. Scope and Requirements of the Supply Chain Traceability

Many organizations have given definitions to the supply chain traceability. This section reviews the original definition of the supply chain traceability, which does not include the monitoring capability as an aspect.

ISO 8402:1994 [1] defines the supply chain traceability as: "traceability is the ability to trace the history, application or location of an entity by means of recorded information." The European Parliament and the Council [2] gives specific regulations for the food supply chain traceability: "the traceability of food, feed, food-producing animals, and any other substance intended to be, or expected to be, incorporated into a food or feed shall be established at all stages of production, processing and distribution. As a result, food and feed business operators shall be able to identify any person from whom they have been supplied with a food, a feed, a food-producing animal, or any substance intended to be, or expected to be, incorporated into a food or feed. Meanwhile, food and feed business operators shall have in place systems and procedures to identify the other businesses to which their products have been supplied. This information shall be made available to the competent authorities on demand."

According to the GS1 [3], there are two aspects of the food supply chain traceability, which are an internal traceability and an external (or chain) traceability. The internal traceability is the traceability within a company. The external traceability is the traceability between companies and countries.

According to the traceability standard issued by the GS1 [3], a traceable item is defined to be a physical object where there is possibly a need to retrieve information about its history, application, or location. A traceable item is a trade item crossing the Point of Sale (POS), such as a book; a batch/lot of trade items, such as a carton, or a box; a logistics unit, such as a pallet or a container; a shipment containing one or more logistics unit, such as a vessel.

The internal traceability takes place when a traceability partner receives traceable items that are subjected to internal processes as inputs and before the traceable items are outputted, where a traceability partner is defined to be a supply chain party in cooperation to establish traceability. A traceability partner may serve as a traceable item source or traceable item recipient. The following figure is an illustration of the internal traceability, which is cited from [3].

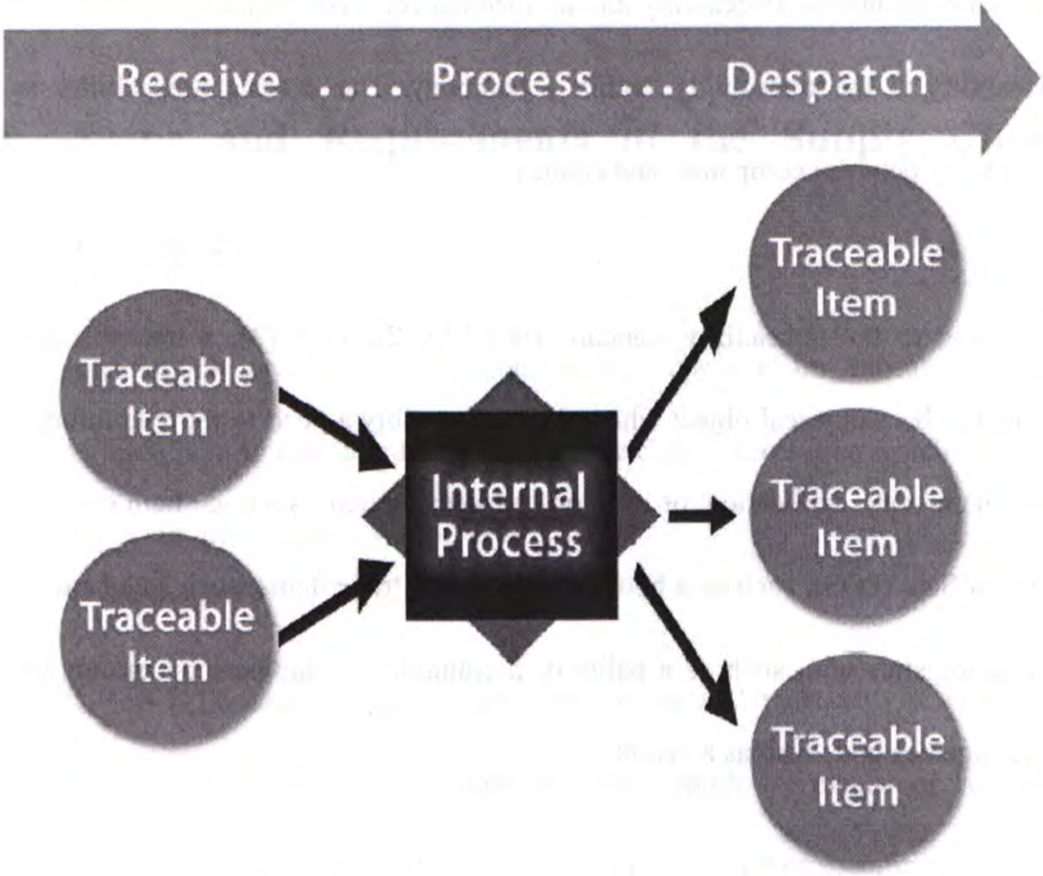


Figure 2.1. Illustration of the internal traceability

As shown in the above figure, an internal process is one or more sub-processes performed by the same traceability partner, or without a significant involvement of other traceability partners. An internal process consists of one or more of the four basic types of sub-processes: movement, transformation, storage, and destruction. Every traceability partner has a responsibility to maintain the links of data between input traceable items and output traceable items. If a transformation sub-process takes place, the data links between the original items and the outcome items must be maintained. If a movement sub-process takes place, the data links between the original and final location after movement must be maintained.

On the other hand, the external traceability takes place when a traceable item is physically handed over from one traceable partner to another. The following figure is an illustration of the external traceability, which is cited from [3].

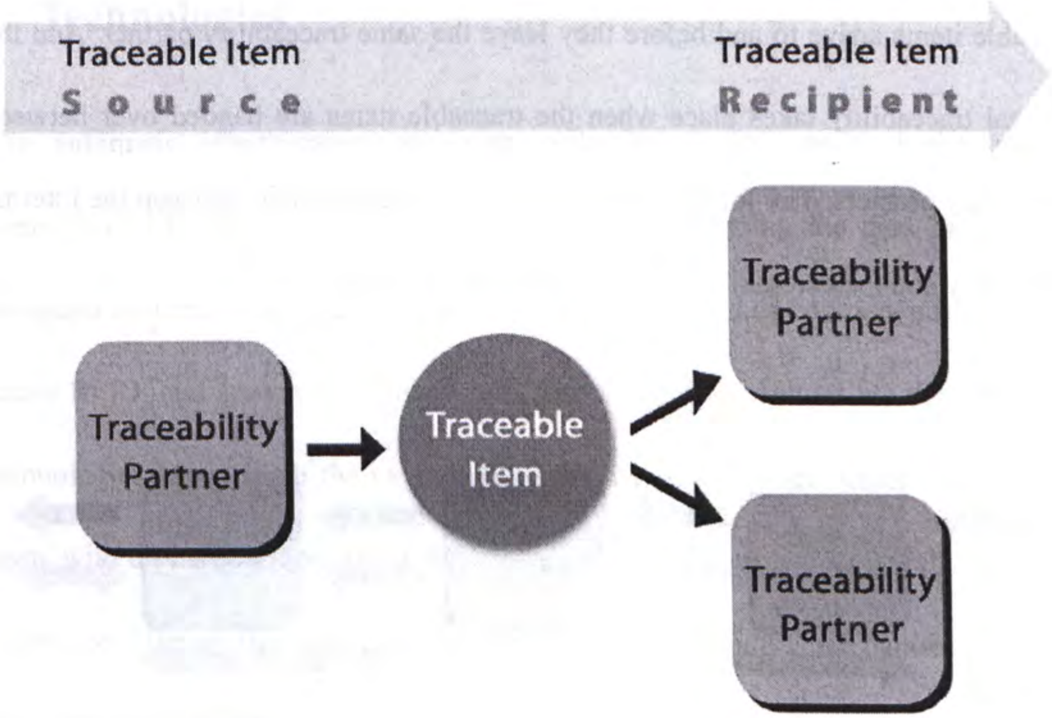


Figure 2.2. Illustration of the external traceability

As shown in the above figure, each traceability partner is able to trace back to the direct source and to identify the direct recipient of the traceable item. By using a "one step up, one step down" strategy, we are able to identify the origin point and the final destination of the traceable item. All traceable items must carry identification and be labeled, marked or tagged at the origin point (or at their creation). The identification carrier must remain on the traceable item or attached to it until the traceable item is consumed or destroyed. The identification carrier may use the AIDC technologies, i.e., passive RFID, active RFID, and barcode etc.

In order to achieve the traceability across the supply chain, both the internal and the external traceability must be established. The internal traceability takes place after the traceable items arrive to and before they leave the same traceability partner. And the external traceability takes place when the traceable items are handed over between traceability partners. The following figure shows the relationship between the internal traceability and the external traceability, which is cited from [3].

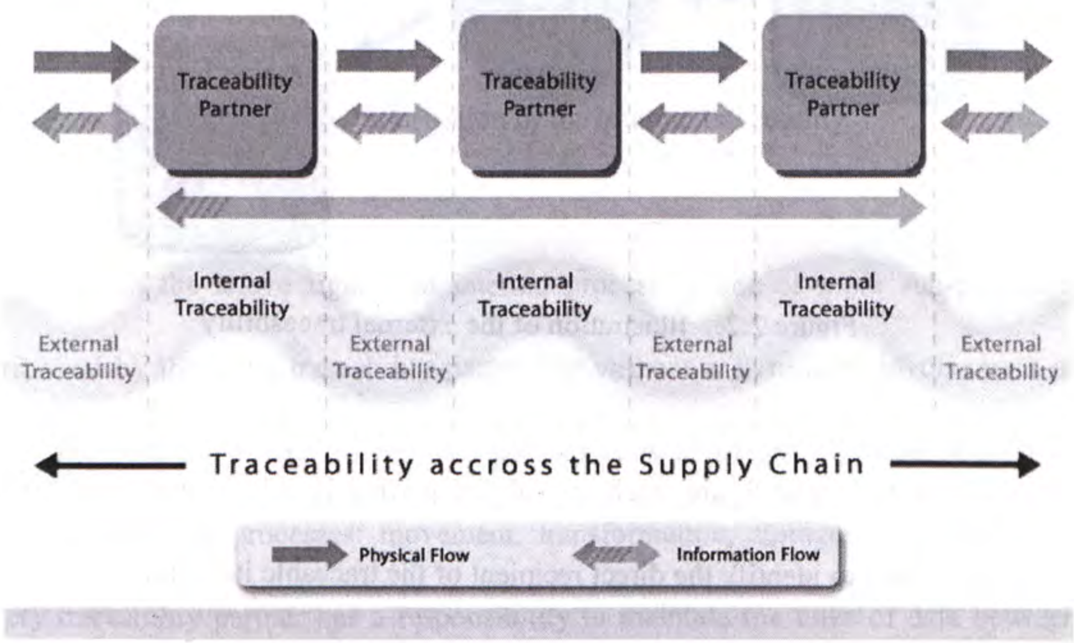


Figure 2.3. Relationship between the internal traceability and the external traceability

As shown in the above figure, the internal traceability within the same traceability partner and the external traceability between traceability partners constitute a linked traceability across the supply chain.

2.2. Automatic Identification and Data Collection Technologies

The automatic identification and data collection (AIDC) technologies provide methods of identifying objects, collecting data, and sending the data directly into computer systems without human involvement, which include barcode, passive RFID, active RFID, and sensor technologies etc. The AIDC technologies are the foundation technologies to establish the extended traceability in the supply chain. This section starts with an introduction of the AIDC technologies. Then two topics are discussed, which are different frequencies of RFID systems, and encoding mechanisms for RFID tags and barcode labels.

2.2.1. Introduction to the AIDC Technologies

2.2.1.1. The Barcode

The barcode technology is a matured technology. A printed barcode label is able to be attached to traceable items. A barcode scanner is able to read a barcode label at a short distance and transmit the digits on the label to a computer as an input terminal like a keyboard. There are two types of barcode scanners: wired scanners and wireless scanners. A wired scanner often uses USB cable for the data transmission. A wireless scanner is usually a PDA system running mobile operating systems such as Windows Mobile 2003. There are typically two ways for a wireless scanner to transmit the data. One way is transmitting by Wi-Fi networks. The other way is that the wireless scanner caches the data, and transmits the data to a computer when it is plugged into a data uploading dock. Supermarkets typically use wired scanners for regular operation. But in case of computer systems break down, supermarkets use wireless scanners to cache the data and upload the data after the supermarkets are shut down in the night. Besides, barcode symbols are text fonts for computer systems. In computer systems, writing barcode is like writing text with a specific barcode font. Thus, high level programming languages, such as Java and C++, are able to output barcode symbols by specifying the barcode fonts.

There exist a number of standards for barcode encoding, such as Codabar, DUN14, Pharmacode, PostBar, and Telepen etc. The most widely used standard is EAN-13. The EAN-13 barcode is used at retail point of sale. The following figure is an example of an EAN-13 barcode.

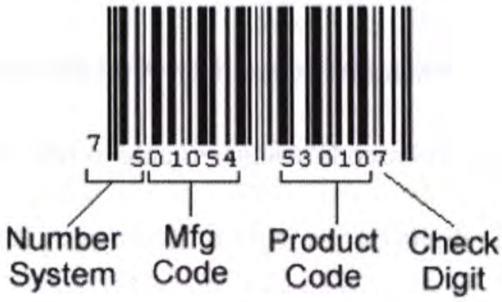


Figure 2.4. Example of an EAN-13 barcode

As shown in the above figure, the first two digits represent the number system. The following five digits represent the manufacturer code. The next five digits are the product code. And the last digit is the check digit.

The EAN-128 barcode is another barcode encoding that records more information on a label than the EAN-13 barcode. The GS1 has published EAN-128 implementation guidelines for achieving traceability of several kinds of food products, including banana, beef, fish, fresh produce, and wine. The following figure is example of an EAN-128 barcode applied to a piece of beef at the slaughterhouse, which is cited from [5].

(01)98712345670019(3102)003725(251)NL21243857

Figure 2.5. An example of an EAN-128 barcode on beef products at slaughterhouse

As shown in the above figure, the digits in the parentheses are called Application Identifiers (AI), which indicate the meanings of the following digits. For example, the AI(01) indicates that the following digits (98712345670019) is the Global Trade Item

Number (GTIN). The AI (3102) indicates the Net Weight of the product, in this example, 37.25 kilograms. The AI (251) indicates the Reference Number of the original animal, in this example NL21243857.

2.2.1.2. The Radio Frequency Identification (RFID)

The following figure shows the basic architecture of a typical RFID reader and tag system.

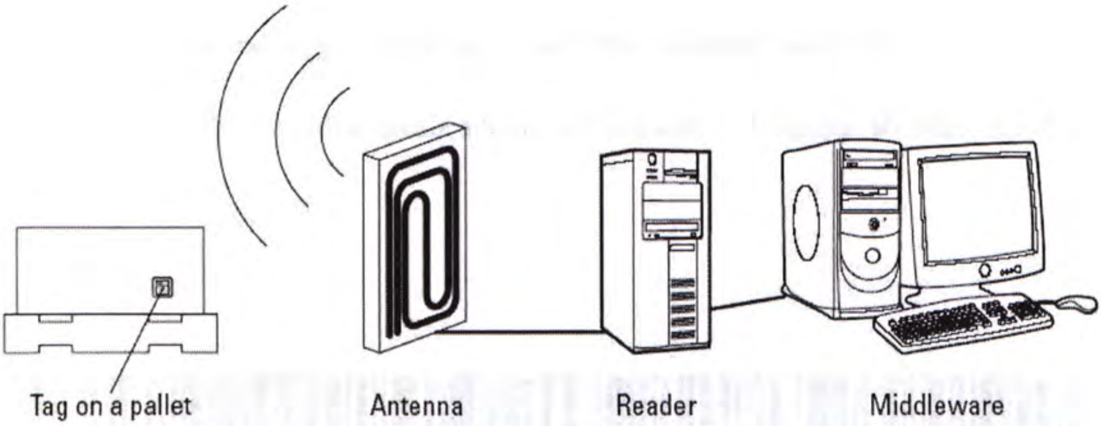


Figure 2.6. Illustrations of a typical RFID reader and tag system

As shown in the above figure, the RFID system consists of a RFID tag, a reader antenna, a RFID reader, and a middleware. The principle of passive RFID tag detections is as follows. When the passive RFID tag is in the magnetic field of the reader antenna, the tag receives the radio frequency signal from the antenna periodically. With the power of the signal received, the tag sends out the information stored on the chips. The principle of active RFID tag detections is as follows. The reader antenna sends out a wake-up signal to the active tags in the signal coverage range. The active tags that receive the signal send out the information on the chips with the power of the batteries on the tags. One major difference between passive and active tags is that passive tags do not have built-in power supplies, while active tags have. When the reader receives information from either kind of tags, it uploads the information to the RFID middleware for further processing.

Comparing with barcode labels, RFID tags generally have the following advantages: efficient and batch identification capability, quick and accurate data collection and transmission, high security against counterfeit, long distance and contactless reading mechanism, harsh environment tolerance, and flexible memory size.

The major disadvantage of the RFID versus the barcode is the cost. A wired barcode scanner costs around 1,500 Hong Kong Dollars (HKD), and a barcode label nearly adds no additional cost. On the contrast, a passive RFID tag costs around 2.5 HKD; a set of passive RFID reader and antennas costs around 5,000 HKD. The price of an active RFID tag in the market varies from 280 HKD to 720 HKD based on different capabilities. And an active RFID reader's price is at least 1200 HKD. Another disadvantage of the RFID is that people can not directly read the information stored on RFID tags by eyes, while people are able to directly read the digits printed on barcode labels, especially when the EAN-128 barcode uses Application Identifier to denote the meaning of each digit section, which makes the barcode information more readable. Besides, additional illustrative information is also able to be printed on the barcode labels, i.e., pictures.

Active RFID tags have some advantages versus passive RFID tags. Since the active RFID tags have independent power supply, their effective reading range is longer, and they are able to be integrated with sensors, such as temperature sensors. The active RFID tags using ultra high frequencies are able to be located to the accuracy of a matter of decimeters. The active RFID tags are often encapsulated into small boxes, and thus are more tolerant to harsh environment than passive RFID tags.

Passive RFID tags also have some advantages versus active RFID tags. Although the active RFID tags are reusable and the passive RFID tags are often not reusable, the cost for every use of active RFID tag is still much higher. Besides, the passive RFID tags are very thin in thickness. They are attachable to the surfaces of objects easily like a paster. But the active RFID tags can only be attached to large objects, such as boxes and pallets, because of the size of the active RFID tags.

2.2.1.3. The Sensors for Food

There are many types of sensors that are used during cultivation. Variabilities that have significant influences on cultivation phase are categorized into six groups: yield, field, soil, crop, anomalous factors and management. And there are some corresponding sensors for the six groups of variabilities.

The yield variability includes the history and the present yield distribution. The yield variability directly relates to the amount of food products that are delivered to customers. Thus by monitoring the yield variability, application software is able to make better demand fulfillment plan of food products. Yield sensing techniques for major crops are approaching maturity. For example, grain yields are measured using four types of yield sensors: impact or mass flow sensors, weight-based sensors, optical yield sensors, and gamma-ray sensors.

The field variability reflects the geographic factors of the cultivation field, including elevation, slope, aspect, terrace, and proximity to field boundary and streams, etc. The field variability information reflects the maximum yield of the field, and is able to be used in anti-counterfeiting, because it will be found if a farm delivers much more than maximum yields in a given geographic area. Commercial sensors receiving and processing GPS signals have become affordable for most farmers in developed countries. More detailed review of the GPS technology is in the following section.

The soil variability measures the soil fertility such as N, P, K, Ca, Mg, C, Fe, Mn, Zn, and Cu, soil fertility as provided by manure, soil physical properties-texture, density, mechanical strength, and moisture content etc. And the crop variability measures attributes of crops such as crop density, crop height, crop nutrient stress for N, P, K, Ca, Mg, C, Fe, Mn, Zn, and Cu, crop water stress, and crop biophysical properties etc. Information about the two types of variabilities is able to be used for cultivation intelligence and precision farming. And there are many types of related sensors developed for on-line measurement.

The variability in anomalous factors includes weed infestation, insect infestation, nematode infestation, disease infestation, wind damage and hay damage etc. The information is able to be used in not only carrying out corresponding actions for the abnormal cultivation situation, but also making decisions for the following-up supply chain phases. For example, when there is infestation situation in cultivation, the yield is typically reduced; once the sensors in the cultivation phase detect the possibility of the yield reduction, downstream supply chain partners are informed and start to plan replenishment from other sources. Sensors for some types of anomalous factors are available. For example, several weed sensors are commercially available, and an infrared plant-temperature transducer introduced by Michels etc. [19] is used to sense plant temperature changes caused by greenbug infestation, etc.

The management variability includes tillage practice, crop hybrid, crop seeding rate, crop rotation, fertilizer application, pesticide application, and irrigation pattern etc., which keeps record of cultivation activities. Setting up sensors keeps surveillance of the activities. For example, regulations prohibit the use of pesticides a certain period of time before consumption. The sensors set up in the field monitor the use of pesticide. Thus, the illegal use of pesticides is able to be reported to government bureaus.

In addition to the sensors used in cultivation phase, many other types of sensors are able to be deployed in the following up supply chain phases, including processing, storage, and transportation. Color and other aspects of the appearance are dominant in determining the first impression and influence the choice of food products by customers. Aroma, taste, and texture or mouthfeel influence the enjoyment of the food and determine whether the customer would come back to buy more of the product. The following table summaries the most significant food properties measurements that are related to food safety and quality in processing, storage, and transportation.

	Food safety			Food quality					Compliance	
	Microbial aspects	Chemical aspects	Physical aspects	Nutritional aspects	Appearance	Texture	Aroma	Taste	Regulations	Customer acceptance
Color					×					×
Temperature	×	×	×							
Time-emperature Series	×	×	×	×	×	×	×	×	×	×
Pressure	×	×	×							
Particle size			×		×	×				×
Water Content				×	×	×		×	×	×
Fat, protein, etc.				×	×	×		×	×	×
pH	×	×							×	×
Alcohols				×			×		×	×
Flavorings				×	×		×			×
Toxin residues		×							×	×
Microbial	×	×			×		×	×	×	×

contamination										

×: direct linkage

Table 2.1. Summary of food property measurements

Although human beings are able to assess all these food properties, sensors provide automatic data collection capability and more frequency process control. Sensors for the measurement of color attributes, variables related to chemical composition, and those related to physical structure of the food are available for some desired specification. Electronic noses and tongues have been developed in recent years to mimic the human sense of smell and taste for specific applications. For those food property measurements that do not have available sensors for on-line measurement, off-line measurement such as laboratory testing is used. Data get from the on-line measurement is typically used for on-site decision making, while data get from the off-line measurement is typically used for long term calibration of decisions.

2.2.1.4. The Global Positioning System (GPS)

The full name for the GPS is Global Positioning System, which is originally designed as a worldwide radio-navigation system formed from a constellation of 24 satellites and their ground stations. The GPS uses man-made satellites as reference points to calculate positions to the accuracy of a matter of meters. With the most advanced forms of the GPS, we are able to make accuracy to better than a centimeter.

The principle of how the GPS works for the precise positioning is the triangulation from the satellites. For example, suppose we measure our distance from a satellite and find it to be 11,000 miles. Then, we measure our distance to a second satellite and find out that it's 12,000 miles away. If we then make a measurement from a third satellite and find that we're 13,000 miles from that one, we narrow our position to just two points in space. But usually one of the two points is a ridiculous answer (either too far from Earth or moving at an impossible velocity) and is rejected. A GPS receiver measures the distance using the travel time of the radio signals by a very accurate timing technology. Along with the distances, we need to know exactly where the satellites are in space and we must correct for any delays the signal experiences as it travels through the atmosphere.

The GPS has been a matured technology and has gone far beyond its original design goal of navigation. Scientists, sportsmen, farmers, soldiers, pilots, surveyors, hikers, delivery drivers, sailors, dispatchers, lumberjacks, fire-fighters, and people from many other jobs are using the GPS in ways that make their work more productive, safer, and sometimes even easier.

There are already innovations about integrating the GPS and the RFID technologies. For example, Fujitsu Software Technologies developed a device that integrates an active RFID tag and a GPS receiver. The GPS receiver first detects its location with the accuracy of 3-5m. Then the active RFID tag sends out the location data along with its unique ID to an RFID reader. As a result, the precise position of the tagged item is received.

2.2.2. Frequencies of the RFID Systems

There are many different communication frequencies in use for RFID systems. As for the passive RFID systems, the most popular frequencies are Low Frequency (LF) in 125-134 kHz, High Frequency (HF) in 13.56 MHz, Ultra High Frequency (UHF) in 433 MHz and 860-930 MHz, and Microwave (MW) in 2.45 GHz and 5.8 GHz. As for the active RFID systems, the most popular frequencies are UHF in both 433 MHz and 860-930 MHz. Frequency selection is a crucial issue in implementation of RFID systems, which must not only adapt to the need of different application requirements, but also comply with the country's related regulation of radio frequency bandwidth usage and transmission power.

As for the passive RFID systems, generally speaking, the transmission power between the readers and tags in lower frequencies, i.e. LF and HF, is lower, so that the data transmission speed is slower and the radio frequency coverage range is smaller. Thus some tags need to use two antennas to achieve coverage of all directions. However, the directionalism of the antenna is not very strong, so that the signals have stronger ability to by pass obstacles. The signals in LF are able to penetrate any obstacles except metals without reducing effective reading range, and the signals in HF are able to penetrate obstacles except metals with reading range reduced. Besides, the costs for the RFID systems are lower. The reading ranges of the RFID systems are more easily defined.

On the contrary, the transmission power between the readers and tags in higher frequencies, i.e. UHF and WM, is higher, so that they are suitable for applications that need longer communication distances with faster speed and better data transmission quality. The tags are able to cover more directions. But the signals are more easily blocked, reflected or affected by obstacles, even such as human beings. The reading ranges of the systems are more difficult to define. Thus the deployment of the reader antennas needs to be adjusted to every specific application.

The following table summaries the passive RFID frequency bands and some of their characteristics.

Frequency Band	Common Frequency	Communication Range		Data Rate	Technology Maturity	Reader Cost
		Typical	Maximum			
LF	125-134kHz	20 cm	100 cm	Low	Very mature	Low
HF	13.56 MHz	10 cm	70 cm	Medium	Established	Medium
UHF	433MHz/860-930 MHz	3 m	10 m	High	New	Very high
MW	2.45 GHz	3 m	10 m	High	In development	Very high
	5.8 GHz	3 m	10 m	High	Future development	Very high

Table 2.2. Summary of the passive RFID bands and characteristics

The active RFID systems are not as widely deployed as the passive RFID systems. The active systems are more customer designed for specific applications. As a result, there are no existing standards for the active RFID systems. The most popular frequency band for active RFID is UHF, especially in the 433 MHz, 889 MHz, and 902 to 928 MHz bands.

The LF frequency is an open frequency in most of the countries, which means the use of the LF frequency does not involve any regulation and license application problems. As a result, the LF frequency is widely used around the world in short communication distance and low cost applications. The related standards for passive RFID communication include ISO 18047-2: RFID Device Conformance Test Methods, Parameters for Air Interface Communications below 135 kHz, ISO 18000-2: Information Technology AIDC Techniques-RFID for Item Management - Air Interface, Parameters for Air Interface Communications below 135 kHz, and ISO 11785: Radio frequency identification of animals -- Technical concept, etc.

Different countries have various regulations governing the HF frequency. So if one is developing an application that is deployed across borders, different frequencies may have to be used. For the passive RFID systems, the EPCglobal publishes 13.56 MHz ISM Band Class 1 Radio Frequency (RF) Identification Tag Interface Specification that defines communications interface and protocol, RF, and tag requirements. The ISO also publishes standards for the HF frequency, such as ISO 15693: Identification cards -- Contactless integrated circuit(s) cards -- Vicinity cards (has been now included into 18000-3: Parameters for Air Interface Communications at 13.56 MHz), and ISO 14443: Identification cards -- Contactless integrated circuit(s) cards -- Proximity cards etc.

Both the ISO and the EPCglobal publish standards for UHF passive RFID systems, such as ISO 18000-6: Parameters for Air Interface Communications at 860 to 960 MHz, and EPCglobal Class 1 Generation 2 UHF Air Interface Protocol Standard etc.

The standardizations in the MW frequency are still in development. Also, since active RFID systems are not as widely deployed as passive RFID systems, no much standardization work has been carried out.

In China, the resources of radio frequencies belong to the country, which is regulated by law. The country is responsible for the centralized planning, development, and management of radio frequencies by a pay-for-use principle. The frequency used in the RFID systems must be approved from the country's wireless administrative institute. Currently in China, there are HF, UHF, MW (2.45 GHz) frequencies in use for the RFID systems. But the UHF frequency is already occupied by several other wireless communication applications, such as GSM and CDMA. At the time being, testing work of the UHF frequency has been carrying out by China. A scheme to allocate the UHF frequency spectrum in China is under development.

The most widely adopted standards for farm animal tracing and tracking is ISO 15693 in the HF frequency. The second is ISO 11785 in the LF frequency. ISO 15693 tags are small for short range systems and have controllability of the detection ranges. ISO 11785 tags are tolerant to a considerable amount of obstructions, including metal. But these tags have limitations in the restricted detection ranges and relative lack of multi-tag simultaneous reading capability.

As for the passive RFID tags to track and trace food products, different frequencies have been adopted. We have done a research of frequencies adopted for establishing traceability on food supply chains (Appendix 1 shows the list of case studies). The distribution of frequencies is in the following figure.

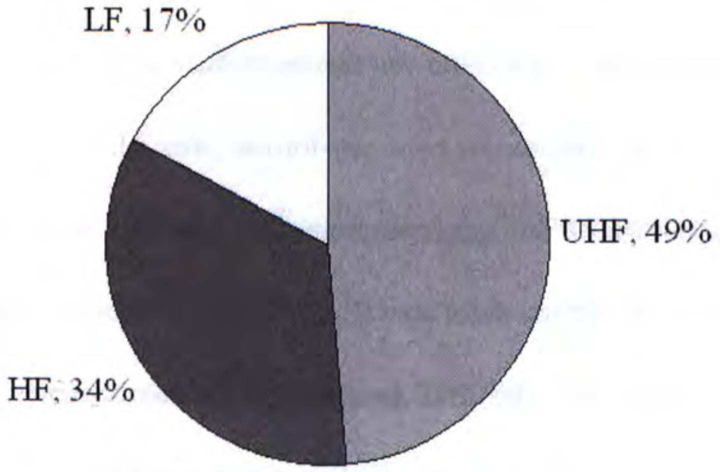


Figure 2.7. Distribution of frequency used to track and trace food products

As shown in the above figure, the most widely adopted frequency is the UHF frequency. The UHF tags have significantly longer effective detection ranges than the HF and LF tags. However, prices of the UHF readers are higher than the HF and LF readers, and the HF tags have a strong ability to penetrate water contents of food items.

2.2.3. Encoding Mechanisms for the RFID Tags and Barcode Labels

ISO 11784[6] defines the code structure for the RFID systems of animal tracking and tracing. The following table shows the code structure suggested by ISO 11784.

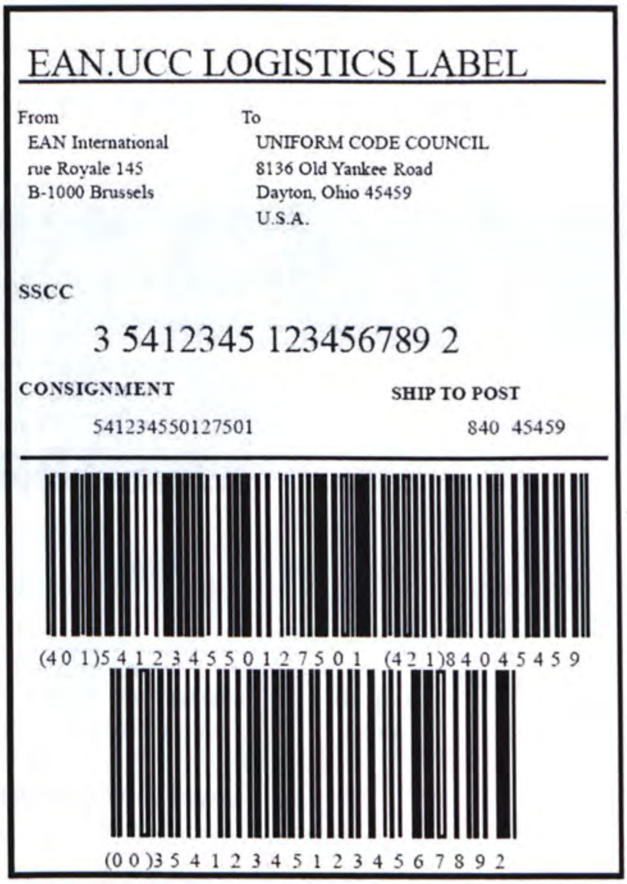
Digit number	Encoding	Remark
1	Animal application 1/ Non-animal application 0	Are the readers and tags used for animal identifications
2-15	Reserved	For future application
16	Have following data 1/ Do not have following data 0	Check digit to identify whether there are following data
17-26	Country code	Country code, 999 means testing readers
27-64	Defined by each country	Defined the encoding in each country

Table 2.3. ISO 11784 encoding mechanism

The most impacting RFID tag data encoding specification is the Tag Data Standards from the EPCglobal [7], which defines the encoding of Electronic Product Code (EPC). The EPC is a family of coding schemes that is designed to meet various industries, while guaranteeing uniqueness for all EPC-compliant tags. The EPC accommodates existing coding schemes, such as the widely applied EAN.UCC schemes, and defines new schemes where necessary. The EPC coding schemes family includes the Serialized Global Trade Item Number (SGTIN), the Serial Shipping Container Code (SSCC), the Serialized Global Location Number (SGLN), the Global Returnable Asset Identifier (GRAI), and the Global Individual Asset Identifier (GIAI). The Serialized Global Trade Item Number identifies a particular class of object, such as a particular kind of product or SKU. The Serial Shipping Container Code (SSCC) is intended for assignment to individual shipping containers. The Global Location Number (GLN) represents either a discrete, unique physical location such as a dock door or a warehouse slot, or an aggregate physical location such as an entire warehouse. In addition, the GLN represents a logical entity such as an "organization" that performs a business function such as placing an order. The serialized Global Location Number (SGLN) uniquely identifies each physical location.

The EAN-13 barcode identifies a class of objects like a specific kind of products. So, the EAN-13 is encoded by the Global Trade Item Number (GTIN). Since the GTIN has 14 digits, adding a '0' at the beginning of an EAN-13 code yields a GTIN code.

The EAN-128 barcode uses Application Identifiers (AI) to denote what kind of identifiers each code section belongs to on the same barcode label. The following figure is a sample of EAN-128 barcode for a logistics unit used for fresh produce, which is cited from [8].



EAN.UCC LOGISTICS LABEL

From
EAN International
rue Royale 145
B-1000 Brussels

To
UNIFORM CODE COUNCIL
8136 Old Yankee Road
Dayton, Ohio 45459
U.S.A.

SSCC

3 5412345 123456789 2

CONSIGNMENT
541234550127501

SHIP TO POST
840 45459

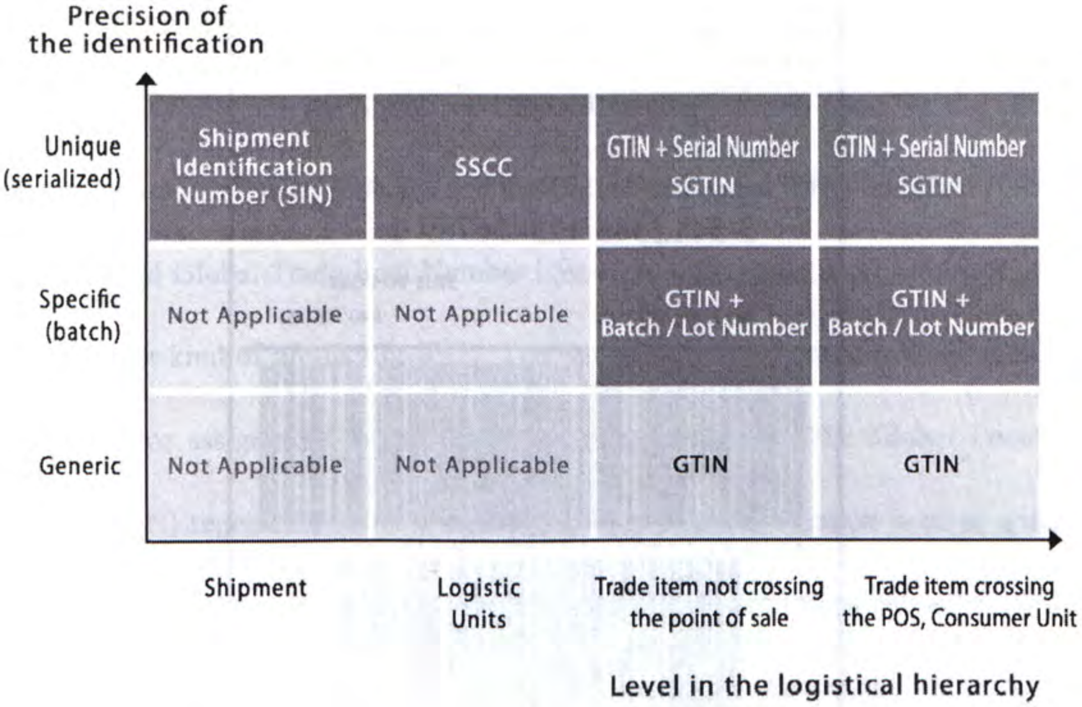
(401)541234550127501 (421)84045459

(00)354123451234567892

Figure 2.8. Sample of EAN-128 logistics label

As shown in the above figure, this EAN-128 barcode label contains a Serial Shipping Container Code (SSCC), a consignment code, and a ship to post code. The AI (401) denotes 541234550127501 is a consignment code, (421) denotes 84045459 is a ship to post code, and (00) denotes 354123451234567892 is a SSCC code. Text information is also printed on the label so that people can get abundant information by simply reading the label.

In the traceability standard of the GS1 [3], different identifiers are required for each level of traceable items. The following figure illustrates the identification requirements from the GS1, which is cited from [3].



	Shipment	Logistic Units	Trade item not crossing the point of sale	Trade item crossing the POS, Consumer Unit
Unique (serialized)	Shipment Identification Number (SIN)	SSCC	GTIN + Serial Number SGTIN	GTIN + Serial Number SGTIN
Specific (batch)	Not Applicable	Not Applicable	GTIN + Batch / Lot Number	GTIN + Batch / Lot Number
Generic	Not Applicable	Not Applicable	GTIN	GTIN

Figure 2.9. Identification requirement of the GS1

As shown in the above figure, shipment vehicles like trucks should be identified by the Shipment Identification Number (SIN). Logistics units like pallets and containers should be identified by the Serial Shipping Container Code (SSCC). Cartons and item level products should be identified by the Serialized Global Trade Item Number (SGTIN) to achieve unique level identification, or by the GTIN plus a batch/lot number to achieve batch level identification, or by the GTIN to achieve the identification of generic product type.

2.3. Standards and Specifications of the EPCglobal

To support the use of the passive RFID technology, the EPCglobal develops a series of industry standards and specifications. This section reviews some of these standards and specifications developed by the EPCglobal.

2.3.1. The EPCglobal Architecture Framework

The architecture framework for passive RFID systems developed by the EPCglobal [4] provides a standard architecture framework to exchange product information around the world. The framework is designed to implement on heterogeneous software and hardware platforms. The framework specifications are platform independent, which means that the structure and semantics of the data is in abstraction and specified separately from the concrete details of the data access services and bindings to particular interface protocols. When possible, interfaces between the architectural components are specified using platform and programming language neutral technology, i.e., Web Services Description Language (WSDL), which is a platform independent language describing web services. The framework is also designed to scale to meet the needs of different end-users, from a minimal pilot implementation conducted entirely within an enterprise's four walls, to a global implementation across entire supply chains. The following figure illustrates the interactions between the architectural components in the architecture framework, which is cited from [4].

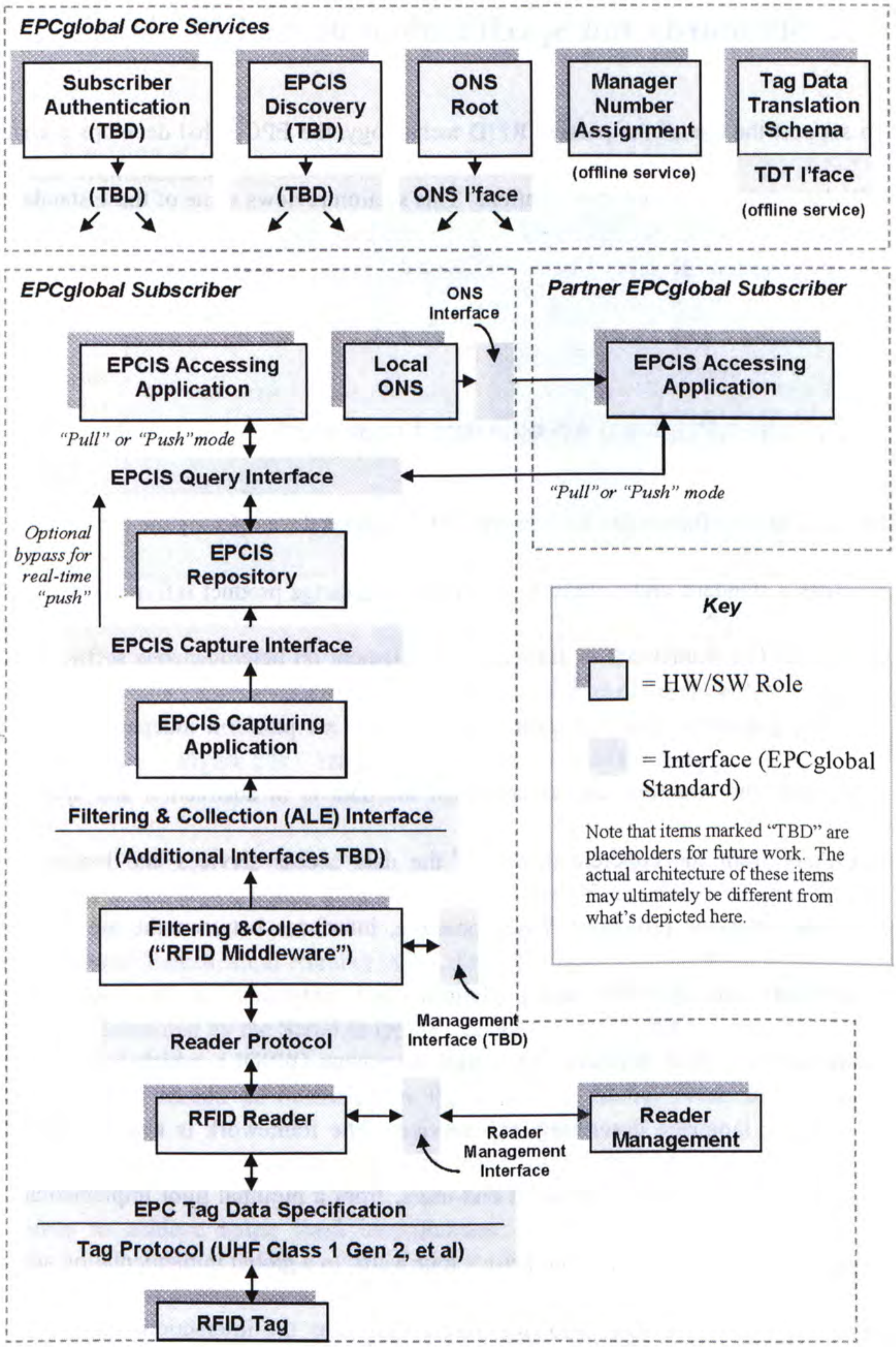


Figure 2.10. EPCglobal architecture framework

In the above figure, the plain green bars denote interfaces governed by EPCglobal standards, while the blue shadowed boxes denote hardware and software components. To illustrate how the data is shared between partners in the supply chain, the above figure shows one subscriber (labeled as "EPCglobal Subscriber") who observes a physical object having an identification (the identification is denoted as an EPC code) on an passive RFID tag, and shares the data about that observation with a second subscriber (labeled as "Partner EPCglobal Subscriber"). This interaction is shown as one way, for clarity. Also, the Partner EPCglobal Subscriber may be observing physical objects and sharing that data with the first EPCglobal Subscriber. In that case, the full picture will show a mirror-image set of roles, interfaces, and interactions. There are the following layers in the architecture framework.

1. RFID Tag and Reader

An observation of a physical object occurs when the physical object attached with an RFID tag that contains an EPC code passes through a RFID reader. The EPC Tag Data Specification of the EPCglobal [7] defines the format and meaning of the EPC code, which is a unique number issued by the EPC Manager Number Assignment service. A tag protocol of the EPCglobal [21] defines the communication between the RFID reader and the RFID tag.

2. RFID middleware and ALE Interface

The RFID middleware filters and collects raw tag reads, over time intervals delimited defined by the EPCIS Capturing Application (discussed below). The Application Level Events (ALE) Standard of the EPCglobal [12] defines that the role of the Application Level Events (ALE) interface is to provide independence between the RFID middleware and the application software that uses the data. The independence allows changes in one application software do not require changes in the other application software, which offers significant benefits to both the technology provider and the end-user.

3. EPC Information Services (EPCIS)

The primary vehicle for data exchange between the EPCglobal Subscribers in the EPCglobal architecture framework is the EPC Information Services (EPCIS). The EPCIS involves three architectural components, which are the EPCIS Capturing Application, the EPCIS Repository, and the EPCIS Accessing Application. The EPCIS Capturing Application captures raw data from the RFID middleware through the ALE interface, transforms the raw data to EPCIS data by adding business context to the raw data, and stores the EPCIS data to EPCIS Repository through the EPCIS Capture Interface. The EPCIS Repository keeps record of the EPCIS data generated by the EPCIS Capturing Application, and makes the EPCIS data available for later queries by the EPCIS Accessing Application. The EPCIS Accessing Application locates the EPCIS Repository and queries the EPCIS data that is related to the interested physical objects through the EPCIS Query Interface.

The EPCIS Specification of EPCglobal [17] defines the EPCIS data into two categories. The first is static data, which does not change over the life of a physical object; for examples, date of manufacture, lot number, expiration date, etc. The second is the transactional data, which does grow and change over the life of a physical object; for example, "the pallet with EPC XXX was shipped in fulfillment of ABC Company purchase order #123 at 12:23." In addition, [17] defines the EPCIS Capture Interface and the EPCIS Query Interface. [17] has superseded the previous development effort on Physical Markup Language (PML).

4. Object Name Services (ONS)

The Object Name Service (ONS) is a global lookup service. In the EPCglobal architecture framework, the ONS is architected as an application of the Internet Domain Name Service (DNS). When an EPCglobal Subscriber wishes to locate a service with related to an EPC code, the subscriber first consults the Root ONS service controlled by the EPCglobal. The Root ONS service identifies the local ONS service of the EPC Manager organization for the EPC code. The subscriber then completes the lookup by consulting the local ONS service, which provides the pointer to the service in question. There is a ratified standard for ONS from the EPCglobal

[22].

5. EPCIS Discovering Service

The EPCIS Discovery Service provides a means to locate all EPCIS services that may have information about a specific EPC code. Currently the EPCIS Discovering Service is not yet a defined part of the EPCglobal architecture framework, but rather a placeholder for functionality that is envisioned for the EPCglobal Network but not yet architected.

2.3.2. The EPCglobal EPCIS Specification

The EPCglobal EPCIS specification [17] defines five categories of data that should be stored in the EPCIS Repository. The five categories include: 1) Class-level static data; that is, the data which is the same for all objects of a given object class. For consumer products, for example, the "class" is the product type, or stock keeping unit (SKU), as opposed to distinct instances of a given product. 2) Instance-level static data, which may differ from one instance to the other within the same object class. Examples of the instance-level static data include the date of manufacture, the lot number, and the expiration date etc. 3) Instance observations, which record events that occur in the life of one or more specific EPCs. For example, the EPC X was shipped at 12:05pm, 15 April 2007 from Acme Distribution Center #2. 4) Quantity observations, which record events concerning the measurement of objects quantity within a particular object class. For example, there were 100 instances of object class C observed at 3:00am, 16 Jan 2007 in 7-11 Store #23. 5) Business transaction observations, which record an association between one or more EPCs and a business transaction. For example, the pallet with the EPC X was shipped in fulfillment of the Acme Corp purchase order #23 at 2:20pm.

The EPCIS Capture Interface is used to capture EPCIS data from the EPCIS Capturing Application to the EPCIS Repository for a permanent storage. The EPCIS Query Interface is used to access EPCIS data from the EPCIS Repository by the EPCIS Accessing Application.

There is only one mode in the EPCIS Capture Interface. Here is the most significant method signature of the EPCIS Capture Interface:

```
capture(event : List<EPCISDataEntry>) : void
```

The capture() method takes only one argument, which is a list of EPCIS data entries, and returns no results. The list of EPCIS data entries will be captured into the ECPIS Repository. The interface is exposed through Simple Object Access Protocol (SOAP), Hypertext Transfer Protocol (HTTP) or Java Message Service (JMS).

There are two modes in the query interface. One is the poll mode; the other is the subscription mode. The most significant method signature for the poll mode is:

poll(queryName : String, params : QueryParams) : QueryResults

The method requests for a synchronous query response. It invokes a previously defined query having the specified name "queryName". The "params" argument provides the values to be used for the parameters embedded in the query definition. The query result will be returned to the output value "QueryResults".

The most significant method signature of the subscription mode is:

subscribe(queryName : String, params : QueryParams, dest : URI, controls : SubscriptionControls, subscriptionID : String)

A subscription is a query for an asynchronous notification. The registered subscriber will get the subscribed EPCIS events when there is new information available. The "subscribe" method registers a new subscription with the name of the query "queryName", the parameters set for the subscription definition "params", the URI destination "dest" where the subscribed information will be delivered to, the controls "controls" of how the subscription is to be processed and the subscription id "subscripitionID".

2.3.3. The EPCglobal Tag Data Standards

In the EPCglobal Tag Data Standards [7], EPC tag encodings and corresponding Uniform Resource Identifier (URI) representations are defined. The EPC tag encodings are used in the RFID tags and readers, while the URI representations are used in the RFID middleware, the EPCIS, and the application software to manipulate the EPCs. In that way, the application logic of the RFID middleware, the EPCIS, and the application software is decoupled from the tag level representation in which a particular EPC is obtained from a tag. Here are the corresponding URI representations to these identifiers of the Serialized Global Trade Item Number (SGTIN), the Serial Shipping Container Code (SSCC), the Serialized Global Location Number (SGLN), the Global Reusable Asset Identifier (GRAI), and the Global Individual Asset Identifier (GIAI).

urn:epc:id:sgtin:CompanyPrefix.ItemReference.SerialNumber

urn:epc:id:sscc:CompanyPrefix.SerialReference

urn:epc:id:sgln:CompanyPrefix.LocationReference.ExtensionComponent

urn:epc:id:grai:CompanyPrefix.AssetType.SerialNumber

urn:epc:id:giai:CompanyPrefix.IndividualAssetReference

2.4. RFID Applications in Food Supply Chain Management

There are already many applications that the RFID technology is used for food product and livestock management. The involved countries include UK, Spain, Portugal, Sweden, Germany, Holland, USA, Argentina, Malaysia, Thailand, Japan, Singapore, Korea, and Australia. The domain of the applications includes animal/farming, security & safety, logistics, and retailing. The most common motivation of the applications is tracking and tracing the products. The following is security and quality control. The most widely adopted RFID frequency is the UHF. The following are the HF and the LF. However, most of the applications are in trial or pilot phase.

An example is the RFID application in Australian Sheep Industry. The initiative was taken by the Australian government. In the farms, every person needs to manage 10,000 sheep. Without RFID technology, only folks of sheep are able to be identified, and only two parameters are used to identify sheep, which are a sheep's age and body weight. However, nine parameters are needed to best manage them for achieving maximum revenue. After they attached passive RFID tags to sheep's ear, they are able to identify individual sheep instead of folks of sheep with the nine parameters. RFID technology enables automatic drafting (classification) and precise management of the sheep used for wool, meat, parasites, and reproduction, and thus maximizes the revenue.

There are also some RFID applications for food product and livestock management in China. For example, with the support of Shanghai government, Shanghai Agriculture Information Co. Ltd. develops a "livestock cultivation management system" that helps enterprises and the government control and inspect the livestock quality. In the farms that deployed the system, every livestock is tagged by an ear tag with a unique ID number. The feeders use handheld equipments to write the feeding, immunity, and quarantine information to the tags. The information is sent to the government bureau for inspection. And the receivers of the livestock also use handheld equipments to check the identifications, feeding history, and so on.

In current typical RFID applications for food product and livestock management, some information is inputted manually or offline when the products are leaving a certain supply chain partner. As a result, the inputted data are not reliable and real-time enough. Inputting counterfeit data is easy. In addition, the data is not complete enough. It is limited within one or two phases of the supply chain and without environment information, i.e. temperature and humidity. Consequentially, the support to enterprise level decisions is not strong enough.

2.5. Anti-counterfeit Technologies and Solutions

Some anti-counterfeit technologies focus on the label printing, i.e. anti-counterfeit label technology and anti-counterfeit ink technology. Examples of anti-counterfeit labels are holography labels, heat sensitive labels etc. Examples of anti-counterfeit inks are pressure sensitive ink, light sensitive ink etc. The labels can only be printed by particular suppliers with the label printing technologies. And the cost for printing such labels with these technologies is relatively higher than ordinary labels. So when we see such labels are attached to some products, we suppose the products are from the particular suppliers. However, as the technology develops, it becomes easier and easier to counterfeit such labels and the printing cost is becoming lower and lower.

An EPCglobal whitepaper [11] proposes an anti-counterfeit solution enabled by the RFID technology. When a product with a RFID tag arrives at the retailer, i.e. a supermarket, the retailer queries the EPCglobal ONS service to locate the address of the manufacturer's EPCIS. Then the retailer sends a request to the manufacturer's EPCIS. If the requestor is the customer that the pallet is intended for, and the specified location corresponds to a ship-to location recorded in the manufacturer's business system, the response indicates that the product is authenticated to come from the manufacturer and the product is shipped to the distribution center 1. Then the retailer sends a request to the distribution center 1 to authenticate the product is from distribution center 1 until an authenticated path is found from the manufacturer to the retailer, as shown in the following figure. Then it is trusted that the product is really from the manufacturer.

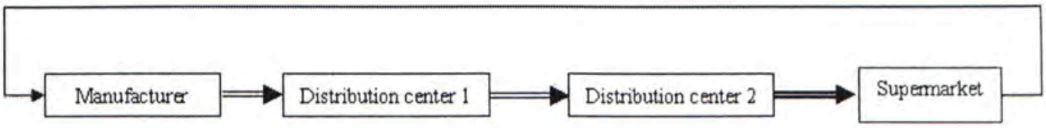


Figure 2.11. Finding an authenticated path

However, if the EPC number has not been properly recorded in the manufacturer's EPC repository, the response suggests that the pallet may be counterfeit or stolen. If the location specified in the query does not correspond to a product distribution area linked to the ship-to location in the manufacturer's business system, the responding system generates a "gray market" condition and takes the action defined by the business process. If the requestor is not the customer that the product is intended for, the query returns information suggesting the appropriate action – to return the product, for example.

This anti-counterfeit solution is effective and practical in some supply chains, such as pharmaceuticals supply chains in western developed countries. In such supply chains, if there are scandals about poor quality products, the business of the manufacturer will be seriously affected. So the manufacturer is attaching much importance to the credibility of the products.

2.6. Data Compression Algorithms

There are two categories of compression algorithms. One is the lossy compression algorithms. The other is the lossless compression algorithms. The lossy compression algorithms do not allow the exact original data to be reconstructed from the compressed data. As a result, they are used when it is not necessary to keep all data after reconstruction. Examples of the lossy compression algorithms are some audio, image, and video compression algorithms. Some data loss in the audios, images and videos does not affect people viewing and listening. On the contrast, the lossless compression algorithms allow the exact original data to be reconstructed from the compressed data. They are used when it is important that the original and the decompressed data be identical, or when no assumption can be made on whether certain deviation is uncritical. Examples are zip file format and gzip in the Unix.

The lossless compression algorithms are categorized according to the type of data they are designed to compress. The three main types of targets for the lossless compression algorithms are text, images, and sound. In principle, any general-purpose lossless compression algorithm (general-purpose means that they can handle all binary input) is able to be used on any type of data. However, many are unable to achieve significant compression on data that is not of the form for which they are designed to compress. The sound data, for instance, is not able to be compressed well with the text compression algorithms.

Most lossless compression uses two kinds of algorithms: one generates a statistical model for the input data, and the other maps the input data to bit strings using this model in such a way that the "probable" (e.g. frequently encountered) data will produce shorter output than "improbable" data.

Burrows-Wheeler transform (BWT) is a useful statistical modeling algorithm for text. When a character string is transformed by the BWT, none of its characters change value. The transformation permutes the order of the characters. If the original string had several substrings that occurred often, then the transformed string will have several places where a single character is repeated multiple times in a row. This is useful for compression, since it tends to be easy to compress a string that has runs of repeated characters by techniques such as move-to-front transform and run-length encoding.

Huffman coding is a famous lossless compression algorithm to produce bit sequences. Huffman coding uses a specific method for choosing the representation for each symbol, resulting in a prefix-free code that expresses the most common characters using shorter strings of bits than are used for less common source symbols. The prefix-free code is the bit string representing some particular symbol is never a prefix of the bit string representing any other symbol. The technique works by creating a binary tree of nodes. These can be stored in a regular array, the size of which depends on the number of symbols (N). A node can be either a leaf node or an internal node. Initially, all nodes are leaf nodes, which contain the symbol itself, the weight (frequency of appearance) of the symbol and optionally, a link to a parent node which makes it easy to read the code (in reverse) starting from a leaf node. Internal nodes contain symbol weight, links to two child nodes and the optional link to a parent node. As a common convention, bit '0' represents following the left child and bit '1' represents following the right child. A finished tree has N leaf nodes and N-1 internal nodes. A linear-time method to create such a tree is to use two queues, the first one containing the initial weights (along with pointers to the associated leaves), and combined weights (along with pointers to the trees) being put in the back of the second queue. This assures that the lowest weight is always kept at the front of one of the two queues.

2.7. Shelf Life Prediction Models

Food products begin to degrade once they are produced. This section introduces the popular mathematics models to predict the shelf life of the food products.

In general, the loss of the shelf life of the food products is evaluated by measuring a characteristic quality index, A. The change of index A with time dA/dt is usually represented by the following kinetic equation

$$-dA/dt = kA^n ,$$

where k is a rate constant depending on temperature, product, and packaging characteristics; n is a power factor that defines whether the rate of change is dependent on the amount of A. If the environment factors are held constant, then n determines the shape of deterioration curve.

The kinetic equation is also be written as

$$f(A) = kt ,$$

where f(A) is the quality function, while k and t are the same. The form of f(A) depends on the value of n. When n equals zero, it is called zero-order reaction kinetics, which implies the food quality loss rate is constant when the environment condition is constant. The quality function is written as

$$f(A) = A_o - A = k_z t .$$

When n equals one, it is called first-order reaction kinetics, which implies an exponential food quality decrease. The quality function is written as

$$f(A) = \ln A_o - \ln A = k_f t ,$$

where A_o is the initial quality value. If A_e is the quality value at the end of shelf life, the shelf life θ is formulated as

$$\theta = (A_o - A_e) / k_z$$

for the zero-order reaction kinetics, and

$$\theta = \ln(A_o / A_e) / k_f$$

for the first-order reaction kinetics.

The most important measurement affecting the food products quality that people most often concern is the temperature. The shelf life prediction models often use the historical temperature to do the prediction.

According to Zaritzky [15], the Arrhenius relationship is often used to describe the temperature dependence of the food quality deterioration rate for the either zero or first order:

$$k = k_o \exp(-E_a / RT),$$

where k_o is a pre-exponential factor, E_a is an activation energy in cal/mol, R is the gas constant in cal/mol K and equals to 1.986, and T is an absolute temperature in K.

Williams-Landel-Ferry model is another famous equation for the temperature dependence of food quality deterioration rate:

$$\log(k_T / k_g) = C_1(T - T_g^{'}) / [C_2 + (T - T_g^{'})],$$

where T_g is the glass transition temperature, $T_g^{'}$ is the T_g of a maximally freeze-concentrated system, C_1 and C_2 are constants.

As for the food that is exposed to a variable temperature environment, the quality function is written as

$$f(A) = \int k_{T(t)} dt.$$

If the temperature data is collected on discrete time points, the quality function is written as

$$f(A) = \sum k_{T(t)} \Delta t.$$

The end of shelf life is the time when the quality function equals $f(A_e)$.

Chapter 3. Architecture and Scope of the Application System

The first topic of the chapter is the architecture of the whole application system, which establishes the extended traceability. As food supply chains differ from each other greatly in product features and supply chain processes, in order to illustrate how we establish the extended traceability on food supply chains, we use a chicken supply chain as an example. The second topic is the scope definition of the application system, which includes a scope definition of the sample chicken supply chain and a business workflow overview of the application system.

3.1. Application System Architecture

The architecture of the application system refers to the architecture framework of the EPCglobal [4]. As reviewed in details in Chapter 2, the architecture framework is as follows: the RFID reader detects the tags within the range of its antennas and sends the raw detection data to the RFID middleware. The EPCIS Capturing Application transforms the data obtained by the middleware ALE interface to EPCIS events. The EPCIS events are sent to the EPCIS Repository for a long-term storage. And the EPCIS Accessing Application makes use of the EPCIS events by accessing them in the EPCIS Repository.

In our application system architecture, the internal traceability is established within each traceability partner. And the internal traceability data is managed and maintained in the EPCIS of each traceability partner. The process of internal traceability data exchange includes two steps: step one, the EPCIS Accessing Application of one traceability partner locates the address of the EPCIS of another traceability partner. There are two approaches to locate the EPCIS. The first approach is that the EPCIS Accessing Application locates the EPCIS through the EPCglobal Network by using the shared services of the EPCglobal, such as EPCIS Discovery Service etc. The second approach is that the traceability partners store the EPCIS addresses of their trusted traceability partners in advance. A search mechanism is implemented in the application system to search the EPCIS address that contains the data about the interested products. Step two, the EPCIS Accessing Application accesses the internal traceability data through the EPCIS Query Interface.

3.2. Application System Scope

As food supply chains differ from each other greatly in product features and supply chain processes, in order to illustrate how we establish the extended traceability on food supply chains, we use a chicken supply chain as an example. This section first defines the scope of the sample chicken supply chain, and then the business workflow of the application system enabled by the extended traceability is presented.

The chicken supply chain consists of four phases: cultivation, processing, storage and transportation, and retailing. The cultivation phase refers to the time period during which chickens are raised in farms. The cultivation phase ends once the grown-up chicken leaves the farm. The processing phase starts in slaughter houses or in processing factories. In this phase, the live poultry become packaged items ready for sale. When the packaged food items are delivered from the processing partners, the processing phase ends and the storage and transportation phase starts. When the packaged food items reach their final destination such as supermarkets for retailing, the storage and transportation phase ends and the retailing phase starts. When customers buy the packaged food items and the items leave the retailers' shop, the retailing phase ends.

Taking into consideration of the ISO traceability standard [1], the regulations of European Parliament and the Council [2], and the requirement escalation with food supply chain practitioners, the traceable items of the chicken supply chain are identified. In the cultivation phase, poultry of chickens, feeding stuff units, operators, and logistics units and vehicles for poultry are traceable items. In the processing phase, flavoring stuff units, operators, packaged food items, and cartons, logistics units and vehicles for the food items are traceable items. In the transportation and storage phase, operators, packaged food items, and cartons, logistics units and vehicles for the food items are traceable items. In the retailing phase, operators, packaged chicken food items, and cartons and logistics units for the food items are traceable items. The following table shows a summary of the traceable items in the four phases.

Cultivation Phase	Processing Phase	Transportation & Storage Phase	Retailing Phase
Poultry Feeding stuff Operators Logistics units Vehicles	Packaged food items Flavoring stuff Operators Cartons Logistics Units Vehicles	Packaged food items Operators Cartons Logistics Units Vehicles	Packaged food items Operators Cartons Logistics Units Vehicles

Table 3.1. Summary of traceable items in chicken supply chain

The application system consists of three application layers, which are the tracking and tracing management module, the storage and transportation monitoring module and the sensor networks enabled assessment module. The three layers of application system gradually establish the extended traceability.

As the name suggests, the tracking and tracing management module provides two key capabilities, which are the tracking and tracing capability. The tracking capability provides the ability to follow the path of a product. The path is from the farms in the cultivation phase to the supermarkets in the retailing phase, even when the poultry in the cultivation phase will become packaged food items in the retailing phase. For example, poultry batch No. 45 has been sent to processing factory No. 2, then sent to distribution center No. 4, and then sent to supermarket No. 3. The tracing capability provides the ability to identify the origin of a product. When we find a potentially contaminated food item, we use the tracing capability to find out the related farm and poultry batch number. Typically, we further use the tracking capability to find out the locations of the items related to that poultry batch and try to call them back.

The storage and transportation management module provides monitoring capability in the storage and transportation phases. Active RFID tags integrated with sensors are tagged to the storage units and transpiration units, i.e. cartons. The sensors monitor the storage and transportation environment, such as temperature and humidity, and the conditions of the food, such as color and smell. Check points are typically deployed in entrance and exit points of warehouses or distribution centers. Active RFID readers are installed in the check points to collect the data from the active RFID tags and sensors. The data is then analyzed by shelf life prediction models. When the data indicates potential food contamination problems, alerts are triggered through web services to corresponding operators.

The sensor networks enabled assessment module deploys sensor networks in different phases of the food supply chain to achieve a more compressive monitoring of supply chain activities. The upload of the data from the active RFID tags and sensor networks does not reply on fixed check point. Mobile active RFID readers integrated with GPRS communication modules are able to upload the data through GPRS networks in real time. In order to trigger more precise alerts, data mining is used to find out the patterns of sensor network data that may indicate potential food contamination problems.

Chapter 4. The Tracking and Tracing Management Module

4.1. Overview

As the name suggests, the tracking and tracing management module provides two key capabilities, which are the tracking and tracing capability. The tracking capability provides the ability to follow the path of a product. The path is from the farms in the cultivation phase to the supermarkets in the retailing phase, even when the poultry in the cultivation phase will become packaged food items in the retailing phase. The tracing capability provides the ability to identify the origin of a product. When we find a potentially contaminated food item, we use the tracing capability to find out the related farm and poultry batch number. Although there are already some RFID application for food and livestock tracking and tracing management, this module is unique in two aspects. One is that the scope of this module is on the whole supply chain, while most of the current applications are focusing on only one or two phases of the supply chains, such as only managing the sheep in the farms. The other is that the implementation in this module provides necessary foundations to build the upper two modules, which are the nested visibility and information integration of heterogeneous data in the EPCIS. Since the upper two modules are rare in the current market, the ideas of how to provide such foundations for them are also new.

The tracking and tracing management module provides tracking and tracing in food supply chains with the adoption of multiple automatic identification and data collection (AIDC) technologies. The adopted AIDC technologies include the barcode, passive RFID and active RFID technologies. In order to enhance the ability to monitor food products during business processes, the module keeps track of not only the traceable items like trade items, logistics units, and shipments, but also the entities that have direct contact with the food products during the business process. The module provides web-based information subscription service for organizations involved in the supply chain. The capability of tracking and tracing food products greatly improves the monitoring process for the food safety and quality throughout the life cycle of food products.

Since there are no fully-developed standards and specifications on selecting and deploying multiple AIDC technologies on food supply chains, it is necessary for us to presents our methodology regarding the sample chicken supply chain. Nested visibility provides item level visibility to food products, and provides very essential foundations to implement the upper two layers. Because it is not cost effective to deploy sensor integrated active RFID tags to every single item whose environment we want to monitor, so that we need to use the nested visibility to map the monitored environment data to the item level. But there are no guidelines to achieve it. Here our methodology to achieve the nested visibility is fully illustrated. As multiple AIDC technologies are adopted, it is necessary for us to explain how we integrate heterogeneous data into an EPCIS, which is not specified in the current EPCIS specifications and thus is regarded as an innovation. The integration of heterogeneous data into the EPCIS also provides essential foundations to build upper application modules. Considering that counterfeiting in food supply chains in developing countries such as China is serious, this chapter introduces our innovative anti-counterfeit solution enabled by the AIDC technologies to make sure the whole application system is effective.

In this chapter, the following aspects about how we establish the tracking and tracing in food supply chains are discussed: the AIDC technologies adopted for the traceable items in the module, the mechanism to achieve the nested visibility, the information integration in the EPCIS, and the anti-counterfeit mechanism in the module.

4.2. AIDC Technologies Adopted for the Traceable Items

The tracking and tracing management module adopts the barcode, passive RFID, and active RFID technologies to achieve the tracking and tracing in the food supply chain. These AIDC technologies all have their advantages and disadvantages. However, there are no fully-developed standards and specifications on selecting and deploying multiple AIDC technologies on food supply chains. So, it is necessary to present our methodology on such selection. Our selection depends on the tradeoff between the cost and traceability functionalities. Three parts are involved in the selection. The first part is to select appropriate AIDC technologies for the traceable items in the sample chicken supply chain. The second part is the frequency selection for the RFID tags. And the last part is the encoding mechanisms for the RFID tags and labels.

The selections for the AIDC technologies to each traceable item in the sample chicken supply chain and corresponding reasons are as follows. In the cultivation phase, the poultry are tagged with leg ring tags. The following figure is an example of a leg ring tag.

Figure 4.1. Example of a leg ring tag

A leg ring tag is able to be fastened around a leg of poultry, such as chickens or pigeons. Typically, the poultry tags are passive RFID tags because they need to be very small. Also, the farms are hardly able to afford the cost of active RFID tags, where usually great numbers of poultry are raised at one time.

As for the packaged chicken food items in the processing phase and the transportation and storage phase, the barcode is used because of the large quantity of food items and the cheaper value per use of barcode labels. As every package needs to be uniquely identified in the two phases for tracking and tracing purpose, the EAN-128 barcode instead of the EAN-13 barcode is used to provide more tracking and tracing information.

As for the packaged chicken food items in the retailing phase, the EAN-13 barcode are used to minimize the impact to retailing systems. However, if the retailer hopes to allow the customers to uniquely identify the product items and trace their origins, the EAN-128 barcode should be adopted.

The cartons in the last three phases are tagged with the passive RFID tags. One reason is for cost saving consideration, because the cartons are still in relative large quantity. Another reason is that the cartons are able to be piled up tightly together with thin passive RFID tags that are easily attached to them. However, in situations that the detection rate of the passive RFID tags is greatly affected because of the heavy water content of the chicken products, the active RFID tags should be adopted.

The logistics units in cultivation phase are often cages while the logistics units in the last three phases are often pallets. They are big in size and reusable. And the market value of all the items in the logistics units is much higher than that of an active RFID tag. The active RFID tags are able to provide longer effective detection ranges and larger tag memories. Also considering the size, value and reusability of the logistics units, the active RFID tags are chosen. The vehicles used in all phases also choose the active RFID tags due to the same reason.

The operators in all phases are identified by personal cards like octopus cards, which are passive RFID tags. If we want to reduce the impact on existing business systems, the manual recording is adopted. The bottom line is that the person who is responsible for each operation is kept record of.

The feeding stuff in the cultivation phase and the flavoring stuff in the processing phase are identified by the existing barcode that is printed on them. The existing barcode is typically in the EAN-13 format. If the EAN-128 format barcode with serial number is be adopted, the scope of the tracking and tracing further reaches to the suppliers of the feeding stuff and flavoring stuff, which exceeds the scope of the tracking and tracing that we are aiming to establish.

The following table summaries the AIDC technologies adopted for each traceable item.

Cultivation Phase		Processing Phase	
Poultry	Passive RFID	Packaged food items	EAN-128 barcode
Feeding stuff	EAN-13 barcode	Flavoring stuff	EAN-13 barcode
Operators	Passive RFID/ Manual	Operators	Passive RFID/ Manual
Logistics units	Active RFID	Cartons	Passive/Active RFID
Vehicles	Active RFID	Logistics Units	Active RFID
		Vehicles	Active RFID
Transportation & Storage Phase		**Retailing Phase**	
Packaged food items	EAN-128 barcode	Packaged food items	EAN-128/EAN-13 barcode
Operators	Passive RFID/ Manual	Operators	Passive RFID/ Manual
Cartons	Passive/Active RFID	Cartons	Passive/Active RFID
Logistics Units	Active RFID	Logistics Units	Active RFID
Vehicles	Active RFID	Vehicles	Active RFID

Table 4.1. Summary of the AIDC technologies recommended in chicken supply chain

Here we list the different RFID frequencies adopted in different situations. As the most popular RFID standards adopted for farm animals tracing and tracking are the ISO 15693 (HF) and ISO 11785 (LF), we adopt the ISO 15693 and ISO 11785 for poultry leg ring tags. The final selection depends on testing result of each specific farm environment.

As for the RFID tag cards used to identify operators, the most widely used RFID standard is the ISO 14443 and the following is the ISO 15693. Both of them are using the HF frequency. So we choose the HF frequency with either the ISO 14443 or ISO 15693 standard.

As for the passive RFID tags used to track and trace food products, different frequencies are adopted around the world. According to our study, the most common frequency is the UHF, followed by the HF and LF. The UHF tags have significantly longer effective detection ranges than the HF and LF tags. However, the prices of the UHF readers are higher than those of the HF and LF readers. One advantage of the HF tags is they do better in penetrating water contents of the food products, compared with the other two. We make the final decision based on the specific working environment and cost consideration.

As the most commonly used active RFID frequency is UHF, we apply the UHF frequency to the active RFID reader and tag systems in the module.

The following table summaries the different RFID frequencies adopted for each traceable item.

Phase	Traceable item	AIDC adopted	Frequency
Cultivation phase	Poultry	Passive RFID	HF/LF
	Operators	Passive RFID/ Manual	HF
	Logistics units	Active RFID	UHF
	Vehicles	Active RFID	UHF
Processing phase	Operators	Passive RFID/ Manual	HF
	Cartons	Passive/Active RFID	UHF/HF/LF
	Logistics Units	Active RFID	UHF
	Vehicles	Active RFID	UHF
Storage & transportation phase	Operators	Passive RFID/ Manual	HF
	Cartons	Passive/Active RFID	UHF/HF/LF
	Logistics Units	Active RFID	UHF
	Vehicles	Active RFID	UHF
Retailing phase	Operators	Passive RFID/ Manual	HF
	Cartons	Passive/Active RFID	UHF/HF/LF
	Logistics Units	Active RFID	UHF

	Vehicles	Active RFID	UHF

Table 4.2. Summary of RFID frequencies in chicken supply chain

Here is a detailed illustration of the encoding mechanisms adopted for RFID tags and barcode labels. As for the leg ring tags used to identify poultry, the ISO 11784 standard [6] is adopted. The ISO 11784 is an international standard specifically for defining RFID code structure for animals. In the ISO 11784 code structure, there is a section that is left to be defined by each country. Since there aren't any existing regulations for the poultry tags in China, we use the Global Trade Item Number (GTIN) together with a batch number. In the sample supply chain, the poultry only need to be identified on batch level. Typically, the poultry are raised in cages. Those in the same cage are fed with the same feeding stuff. If some of the poultry are found to be ill, others in the same cage are also considered to be contaminated. So, we define the same batch of poultry as the poultry raised in the same cage and use the GTIN plus a batch number to identify the poultry batches.

As for the passive RFID tags used to identify operators, the Serialized Global Trade Item Number (SGTIN) is used, since we need to uniquely identify every person. It is the same case with the passive RFID tags used to identify food product cartons. The SGTIN is adopted, since the cartons also need to be uniquely identified.

As for the active RFID tags used to identify the logistics units, such as the pallets and containers, the Serial Shipping Container Code (SSCC) is used. For the active RFID tags to identify the vehicles, the Shipment Identification Number (SIN) is used. What's more, since the active RFID tags often have memories, additional logistics information is stored in the tag memories according to the specific applications.

The EAN-128 barcode is used in the last three phases of the module to identify the packaged food items. The Global Trade Item Number (GTIN) is printed on the barcode label for all three phases to identify product type. Other types of information to be added depend on the specific application requirements. For example, in the processing phase, the birth country id, the cultivation country id, the cultivation farm id, the approval number of the slaughterhouse, and the leg ring tag number is added. In transportation and storage phase, the shipment consignment id, the consigner id and the receiver id is added. In retailing phase, the birth country id, the cultivation country id, the cultivation farm id and the slaughter house id is printed. The Application Identifiers (AI) are used to identify different types of information on the label. Corresponding information is also printed on the label in the form of text for people to read. If EAN-13 barcode is used for packaged food items in retailing phase to minimize the impact to the original barcode system, the Global Trade Item Number (GTIN) is used as other common EAN-13 barcode labels to identify the type of the product.

The following table summarizes encoding mechanisms adopted for the RFID tags and barcode labels.

Phase	Traceable item	AIDC adopted	Encoding
Cultivation phase	Poultry	Passive RFID	GTIN + batch
	Feeding stuff	EAN-13 barcode	GTIN
	Operators	Passive RFID/ Manual	SGTIN
	Logistics units	Active RFID	SSCC
	Vehicles	Active RFID	SIN
Processing phase	Packaged food items	EAN-128 barcode	GTIN etc.
	Flavoring stuff	EAN-13 barcode	GTIN
	Operators	Passive RFID/ Manual	SGTIN
	Cartons	Passive/Active RFID	SGTIN
	Logistics Units	Active RFID	SSCC
	Vehicles	Active RFID	SIN
Storage & transportation phase	Packaged food items	EAN-128 barcode	GTIN etc.
	Operators	Passive RFID/ Manual	SGTIN
	Cartons	Passive/Active RFID	SGTIN
	Logistics Units	Active RFID	SSCC
	Vehicles	Active RFID	SIN
Retailing phase	Packaged food items	EAN-128/EAN-13 barcode	GTIN etc.
	Operators	Passive RFID/ Manual	SGTIN
	Cartons	Passive/Active RFID	SGTIN
	Logistics Units	Active RFID	SSCC
	Vehicles	Active RFID	SIN

Table 4.3. Summary of encoding mechanism in chicken supply chain

4.3. Mechanism to Achieve the Nested Visibility

This section first analyzes the reason why we implement the nested visibility in the module. Then our mechanism to achieve the nested visibility is presented, while there are no existing guidelines to achieve it.

In a typical supply chain, lower level traceable items are often wrapped into higher level traceable items, i.e. individual trade items are put into cartons, and then the cartons are put onto pallets, and then the pallets are put into containers. The identification reading of lower level traceable items, which are inside a higher lower traceable item, is inconvenient or sometimes impossible. For example, when some pallets are put into a container, the vehicle is required to stop and the container is required to be unlocked for the reading of the RFID tags on the pallets, because the metal container blocks radio frequency signals from outside. We tackle this problem by implementing the nested visibility, by means of which we can get the identifications of its aggregated lower level traceable items when we read the identification of a higher level traceable item.

The nested visibility is of great significance because achieving the nested visibility will undoubtedly lead to the achieving of real time visibility of products in the item level and at that time we will be able to monitor efficiently the item level products that are inside the higher level traceable items such as the cartons and containers etc. Furthermore, since the traceable item sources and traceable item recipients only need to be recorded in the same level of traceable item within their respective systems, the data flow is simplified. Additionally, the nested visibility is the precondition for product security and environment monitoring of containers and their product contents, because it is impractical both physically and financially to install environment monitoring sensors for all item level products. The sensors should be installed on the higher level traceable items, and the application systems use the nested visibility to get environment data of the item level products. Lastly, real time reading of the item level data makes more informed decision possible based on the accurate and timely information.

Our works to develop the methodology of achieving the nested visibility includes two parts. The first part is the pilot runs of nested AIDC technologies adoption. As stated in the last section, we have made selections to the appropriate AIDC technologies and the frequencies for RFID tags to the traceable items. Actually, we have already made the nested use of AIDC technologies. In the cultivation phase, there are aggregations between the passive RFID tags on poultry and active RFID tags on logistics units, and between the active RFID tags on logistics units and vehicles. In the following three phases, there are hierarchy relationships which from bottom to the top are barcode on packaged food items, passive or active RFID tags on cartons, active RFID tags on logistics units, and active RFID tags on vehicles. The pilot runs make sure the selected AIDC technologies and RFID frequencies are feasible to work together.

The second part of our works is to develop a communication standard between traceability partners, which is suitable in both technical aspect and adoption aspect. In the communication standard, when a traceable item is aggregated within another traceable item, the traceability partner who makes the traceable item aggregation keeps the links of traceable items. Other traceability partners only keep records of movements and locations of the higher level traceable item. When they need information about its content, they send a request to the upstream traceability partner along the supply chain. The following figure illustrates the sequence of dealing with such the request by the traceability partners.

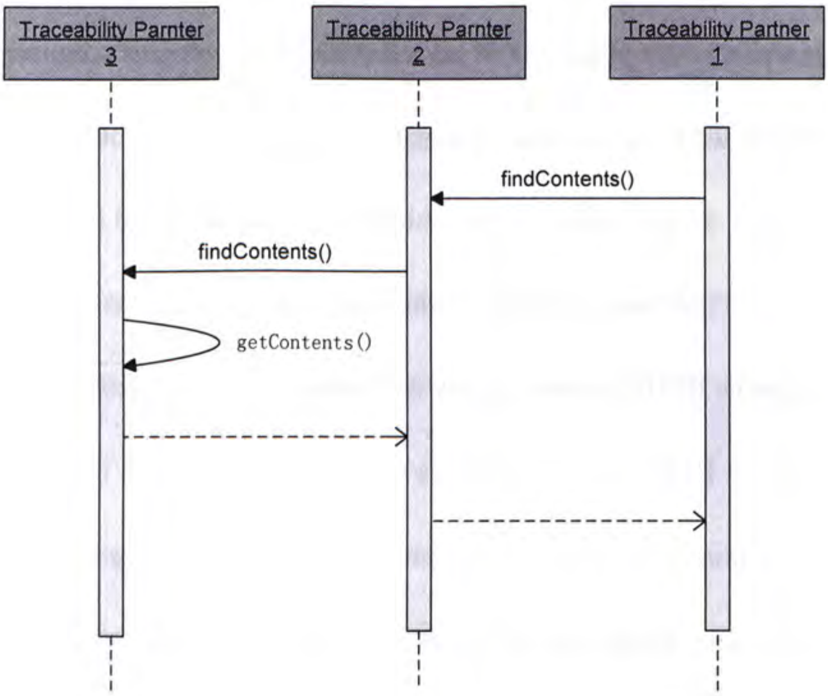


Figure 4.2. Sequence of high level traceable item content query

As shown in the above sequence diagram, when the traceability partner 1 receives a higher level traceable item, such as a container, and he want to know the content inside the traceable item, he sends out a request of "findContents" to its source, the traceability partner 2. Since the traceability partner 2 still does not know its content either, he forwards the "findContents" request to his source again until the request reaches the traceability partner 3 who makes the traceable item aggregation. Since the traceability partner 3 makes the aggregation, he is responsible for keeping record of the links between the traceable items. As soon as the traceability partner 3 identifies the content of the higher level traceable item, he sends the information back along the request chain.

Also, the following figure illustrates when a traceability partner finds some contaminated items, how the contamination is reported and how the other contaminated items are found in the supply chain.

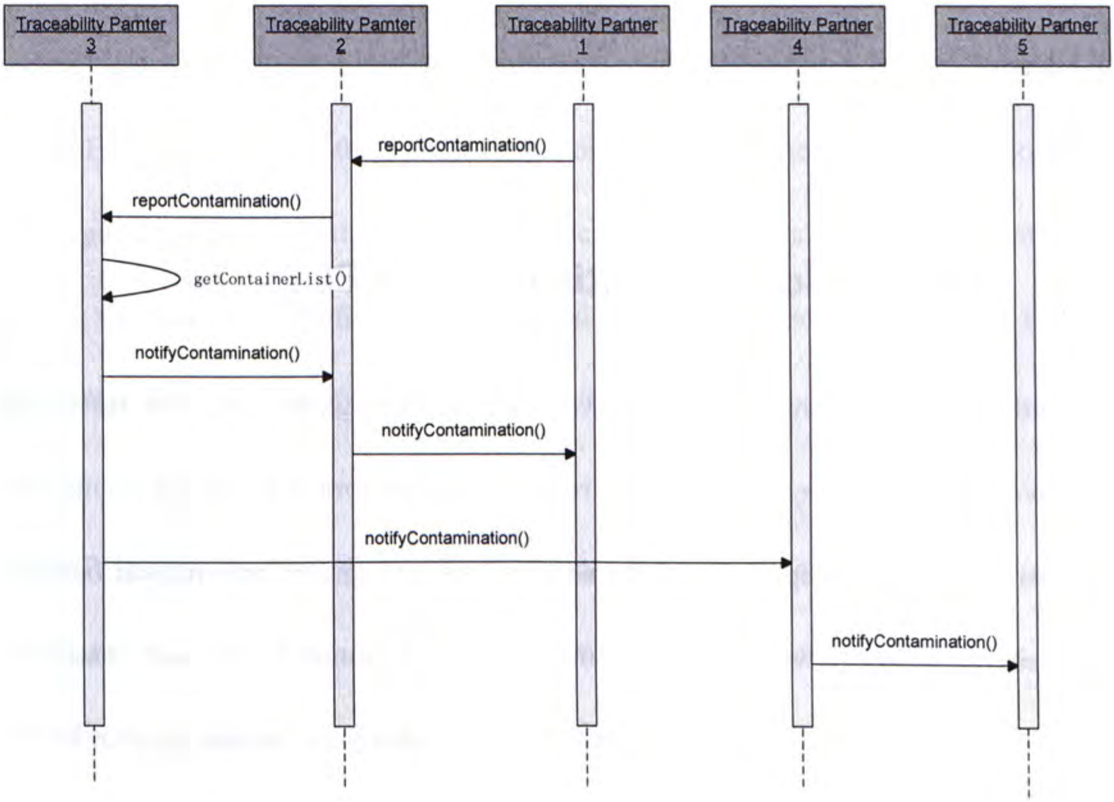


Figure 4.3. Contamination reporting and tracking with the nested visibility

As shown in the above sequence diagram, when the traceability partner 1 finds a contaminated item, he reports the contaminated item id and its higher level traceable item id, i.e. a container id, to its source, the traceability partner 2. Then the traceability partner 2 continues to forward the information towards along the supply chain until the information reaches traceability the partner 3 who makes the traceable item aggregation. Since the traceability partner 3 keeps the aggregation information, he finds out the list of higher level traceable items, i.e. containers, which contain other potentially contaminated food items, i.e. the food items produced in the same batch. After that, notifications are sent out to the downstream traceability partners who received the higher level traceable items which contain the potentially contaminated food items.

4.4. Information Integration in the EPCIS

According to the architecture framework of the EPCglobal [4], the RFID tag observation data is stored in the EPCIS repository in the format of EPCIS events. The data in each EPCIS Repository is shared to exchange logistics information between business partners. However, the existing EPCglobal standards are only based on passive RFID technology and how to integrate the heterogeneous data into an EPCIS Repository is not specified in the current EPCIS specifications, while in the tracking and tracing management module we adopt multiple AIDC technologies, including passive RFID, active RFID and barcode. Developing a methodology to integrate the heterogeneous data into an EPCIS is also very important for the upper two modules, because we will further integrate data from sensors into the EPCIS. We think the most suitable way is to basically follow the existing EPCIS standard but make necessary extensions. In that way, we will minimize the impact to the existing users of the EPCglobal architecture framework. This section talks about how we model and store data gathered by different AIDC technologies into the EPCIS Repository.

In our EPCIS Repository, the Uniform Resource Identifier (URI) representation is used in the object id fields. In the tracking and tracing management module, multiple AIDC technologies are adopted, including passive RFID, active RFID, and barcode technologies. Identification detection data from all the above three sources is recorded in the EPCIS Repository for a permanent storage. Though the barcode detection data are typically input directly from the application software's graphic user interface (GUI), the barcode identifications are sent to the EPCIS Repository from the GUI to facilitate the further use of the application software.

The EPCglobal Tag Data Standards [7] defines the URI representation of the passive RFID tag id, namely the EPC code, as reviewed in Chapter 2. But since [7] is exclusively designed for the passive RFID technology, we extend the URI representation to also represent the active RFID id and barcode id. Since id of an active RFID tag or a barcode label is a string of numbers, the prototype of the extended URI representation is:

urn:generic:id:type:typeSpecificPart

The "urn" section means the URI representation is a Uniform Resource Name, which is constant in all URI representations. The "generic" section specifies the technology used to carry the id, i.e. the passive RFID, the active RFID, the EAN-13, and the EAN-128 etc. The "id" section means the URI representation is an id number, which is also constant. The "type" section specifies the encoding mechanism of the id, such as the SGTIN, the SSCC, and the SGLN etc. The last part is the specific identification numbers.

To fulfill the EPCglobal EPCIS specification [17] reviewed in Chapter 2, we design the following data schema for the EPCIS data repository.

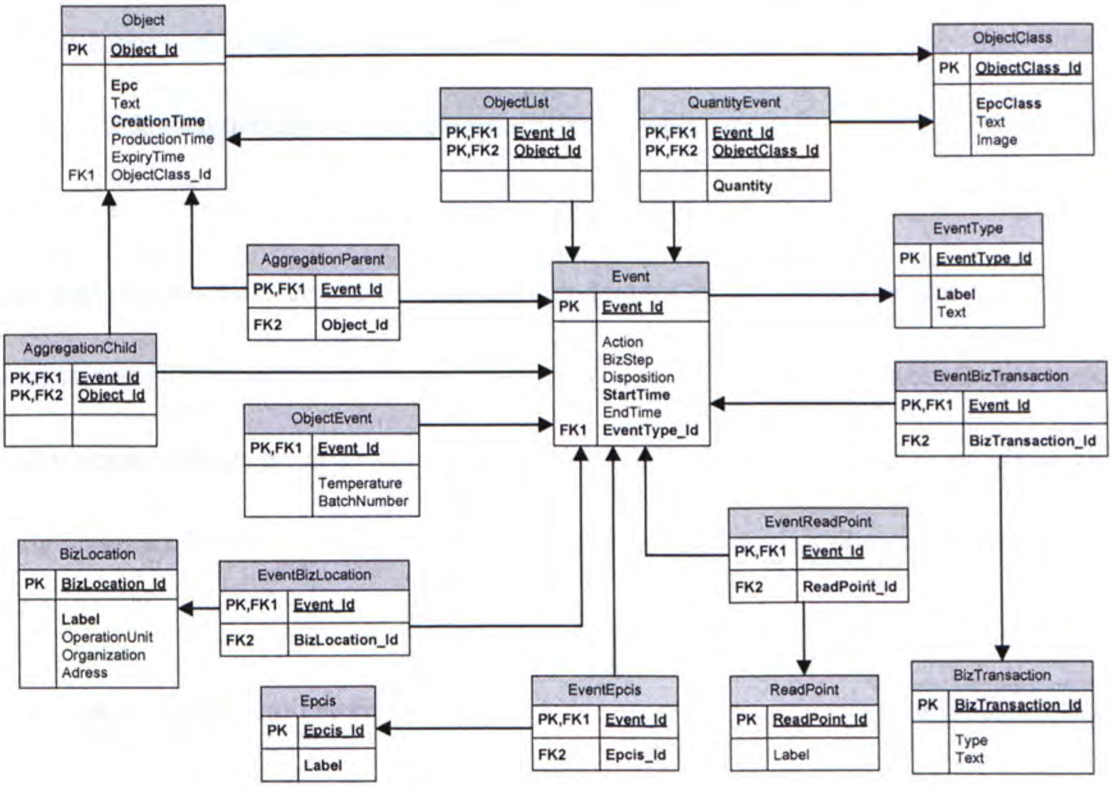


Figure 4.4. Data schema for the EPCIS repository

In the data schema, there are four basic EPCIS event types: object event, quantity event, business transaction event, and aggregation event.

When an object is observed by a RFID reader, a new object event is created with the information such as object id, event time, and logical RFID reader etc. A logical RFID reader represents more than one physical RFID reader. Both class level static data and instance level static data is able to be represented by an object event. There is an "action" attribute in an event. If we want to add a new record of class level static data, we create a new object event of the object class with action "add". In the same way, if we want to add a new record of instance level static data, we create a new object event of the object with action "add". If we want to delete the class level or instance level static data, we create a corresponding event with action "delete". The record is not actually deleted in the data repository for the purpose of future data retrieval.

A quantity event happens when a number of objects of a particular object class are observed. Once some objects with the object class are observed by a RFID reader in a given period, a new quantity event is created with the information such as object class id, starting time, ending time, and logical RFID reader etc.

A business transaction event happens when business transaction related objects are observed. Some configuration that some objects going to be observed by a particular reader are related to some business transaction must be defined previously. When the observation happens with the help of particular reader, a new business transaction event is created with the information such as business transaction id, event time, and object list etc.

An aggregation event happens when there are aggregations between higher level and lower level traceable items. When the aggregation happens, an aggregation event is created with the information such as aggregation parent id, aggregation child id list, and event time etc.

Our design of the EPCIS data schema is flexible to add new EPCIS event types for specific applications. We define a generic type of event in the database schema. All the four event types are derived from the base type. As a result, we are able to extend the database schema by adding new event types with minimum impact on the original design. For example, in some applications of tracking and tracing management module, we need to keep a record of the events about the mappings of the raw material identifications and the finished goods identifications. We define a new type called transformation event. In the following figure, we illustrate how we extend the data schema by adding a transformation event type.

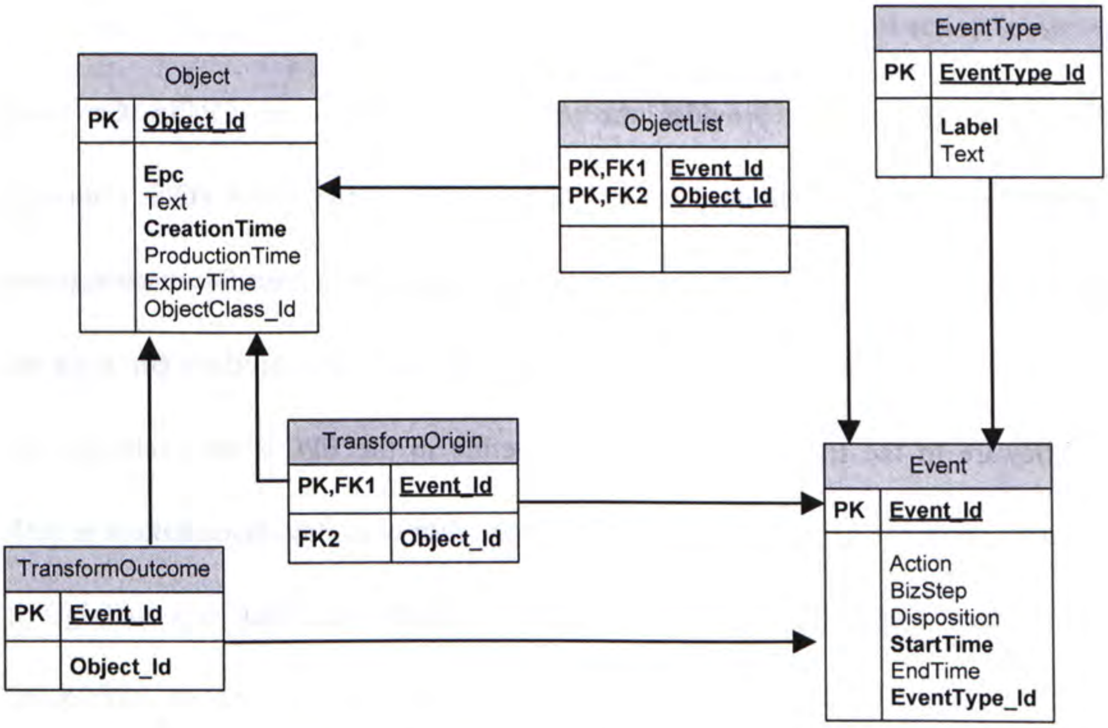
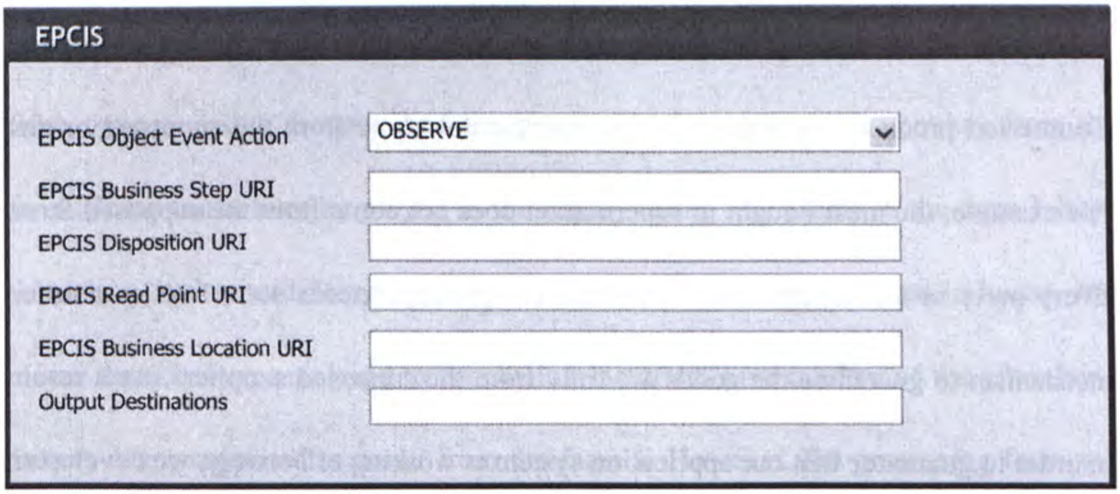


Figure 4.5. Data schema of transformation event

A transformation event happens when some object identification(s) are transformed to become some other object identification(s). For example, chicken wings in the same package are from several chickens. So, several poultry identifications become a packaged food item identification. Since we define table "event" as a generic event type, it is easy to define a new event type. We only need to add a new event type to the "EventType" table, and then add corresponding tables of the transformation event without affecting other tables for other event types. From the example, it is shown that the methodology to extend new event types to the existing event types is a technically feasible way to allow us to integrate new content of data into the EPCIS, and thus is a technically feasible way to integrate different sources of data from active RFID and barcode into the EPCIS.

The RFID middleware provides the ALE interface for the EPCIS Capturing Applications to get data that we are interested in. After the EPCIS Capturing Application receives the data from the middleware, a data workflow management module built in the EPCIS Capturing Application converts the data get from the middleware to the EPCIS events that we define in the EPCIS data schema. The following figure is a sample user interface of the data workflow management module that generates EPCIS object events from the RFID middleware data.



EPCIS Object Event Action: OBSERVE
EPCIS Business Step URI
EPCIS Disposition URI
EPCIS Read Point URI
EPCIS Business Location URI
Output Destinations

Figure 4.6. GUI of generating object EPCIC events

As shown in the figure, to generate an EPCIS object event, the event action (observe, add, or delete), the business step URI, the disposition URI, the read point URI, the business location URI, and the output destinations are configured. After the configuration, the data workflow management module generates object events with the specified attributes when receiving the data from the RFID middleware.

The workflow management engine is not an architectured component by the EPCglobal. But it is a technically feasible and useful component to reduce the complexity to convert the data from the RFID middleware to EPCIS events, especially when we extend many new EPCIS events types.

4.5. Anti-counterfeit Mechanism

It is not new to hear that customers buy counterfeit food products in the market.

Especially in developing countries such as China, this phenomenon is serious. Counterfeit products are those products that do not come from the supposed origin. For example, the meat bought in supermarket does not come from the supposed farm. Every party in the supply chain who receives products needs some anti-counterfeit mechanism to guarantee the goods are truly from the supposed suppliers. As a result, in order to guarantee that our application system is working effectively, we develop an innovative anti-counterfeit solution enabled by the AIDC technologies, which is suitable to the food supply chains in developing countries such as China. In this section, the counterfeit tricks in developing countries such as China are introduced with the sample of chicken supply chain. Then, our anti-counterfeit solution is put forward.

The following figure shows some common counterfeit tricks in the sample chicken supply chain.

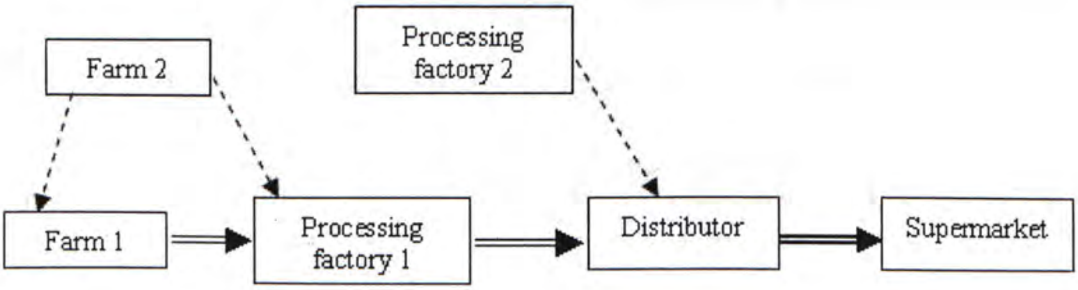


Figure 4.7. Demonstration of counterfeit tricks in a food supply chain

As shown in the above figure, in the chicken supply chain, the supermarket gets packaged food items from the distributor. The distributor gets packaged food items from the processing factory. And the processing factory gets live poultry from the farm. Some tricks may be played in the supply chain. For example, the farm 1 buys some live poultry with lower quality and lower price than those raised in house, and mixes them before supplying to processing factories. Live poultry of the processing factory 1 are supposed to come from the farm 1. However, the processing factory 1 buys some lower quality live poultry from the farm 2 with lower price, and mixes the packaged food items before sending them to the distributors. Meanwhile, the processing factory 1 pretends that all of his live poultry are bought from the farm 1 with high quality. The counterfeit trick of the processing factory 1 lowers its total cost, which is a temptation to some factories. Similarly, the distributor may buy some products from processing the factory 2 with lower quality and lower price.

Authentication of suppliers is a critical part in anti-counterfeit mechanisms and technologies. Without the authentication of suppliers, the supply chain partners may receive counterfeit products without knowing the products are counterfeit.

The anti-counterfeit solution demonstrated by the EPCglobal whitepaper [11], which is reviewed in Chapter 2 is not suitable to implement in the food supply chains of developing countries that we are targeting at. The situation in developing countries is different because even the origin of the food supply chain, i.e. the cultivation farm, may also provide counterfeit live poultry bought from other farms. In the anti-counterfeit solution of [11], we send a request to the farm asking whether these live poultry are really shipping out from the farm. But if a farm wants to interfuse live poultry from other farms, they are able to dishonestly maintain the identifications and shipping orders of the live poultry bought from other farms in their database, pretending to have brought up the poultry by themselves. Thus, the anti-counterfeit solution becomes ineffective.

In our anti-counterfeit solution, upstream suppliers are authenticated in every goods reception. Here is our anti-counterfeit mechanism in the sample chicken supply chain.

First, we implement authentication of live poultry to confirm the live poultry's origin. Since the Global Trade Item Number (GTIN) plus a batch number are recorded in the leg ring tags, if we confirm that the batch number really comes from some particular farm, we authenticate that the batch of poultry are really raised in that farm. So we propose the related government bureau in charge of food sanitation to provide an authentication code generation service to the public. The government bureau uses different one-way algorithms to generate authentication codes from batch numbers for each farm. The authentication codes must be carried by the AIDC technologies when sending the poultry to processing factories. When the processing factories receive the poultry, they read the authentication code and the batch number by the AIDC technologies, and send the batch number to the authentication code generation service. The service returns the generated authentication code. If the authentication code they received from the service is exactly the same with the authentication code they collect by the AIDC technologies, then the poultry are authenticated to be from that farm.

This mechanism works effectively because of the following reasons. The authentication code generation algorithm is one-way algorithm, which means we are able to get authentication code from batch number, but we can not get batch number from authentication code. And the algorithm for each farm is different. So, if the farm 1 buys some poultry from the farm 2, and if they still use the authentication code generated for the farm 2, the poultry receiver will find out the counterfeit situation, because the authentication code generated by the farm 1's algorithm is different from the one generated by the farm 2's algorithm. Additionally, the government bureau keeps information about the size of each farm and keeps records of how many authentication codes the farms apply for every day. And the size of a batch is restricted, i.e. 100 poultry at maximum. So, if the farm 1 buys some poultry from the farm 2, and if they apply for more authentication codes than allowed, the government bureau will find out the counterfeit situation when the number of poultry shipped out from the farm significantly exceeds the farm's capacity.

Since the leg ring tags use ISO 11784 encoding mechanism, only 38 bits are available for free definition. The 38 bits are full for the Global Trade Item Number (GTIN) and a batch number. And the authentication code needs to be at least 6 digits in length to be effective. So, the authentication code and batch number mapping are stored in the active RFID tags attached on the logistics units, i.e. cages. Typically, we assign one logistics unit as one batch.

Then, we implement authentication for the packaged food items shipped from processing factories to confirm that they are really made in the supposed processing factory and they are really made of the meat of the poultry that come from the supposed farm. So, both authentication codes for the poultry batches and the packaged food item batches are carried by the AIDC technologies. If one processing factory buys live poultry from the farm 2 instead of the farm 1 as they are supposed to, since they can not generated correct poultry batch authentication code for poultry from the farm 2, the counterfeit situation will be found. Also, if the processing factory produces significantly too many packaged food items from one poultry batch, people can find that they have interfused poultry from other farms. Since the processing factories typically do not buy packaged food items from other factories to interfuse with their own products, the packaged food item batch authentication code generation algorithm is managed by each processing factory, in stead of by the government bureau.

The poultry batch and packaged food item batch authentication code are printed on the EAN-128 barcode labels on each packaged food item. Or they are recorded on active RFID tags on logistics units, such as pallets.

Lastly, the poultry batch and packaged food item batch authentication code are carried by the AIDC technologies in storage and transportation phase until the packaged food items reach the retailers.

The following table is a summary of the encoding mechanism and the AIDC technologies adopted for each traceable item in all of the four phases when our anti-counterfeit solution is implemented.

Phase	Traceable item	AIDC adopted	Encoding
Cultivation phase	Poultry	Passive RFID	GTIN + batch
	Feeding stuff	EAN-13 barcode	GTIN
	Operators	Passive RFID/ Manual	SGTIN
	Logistics units	Active RFID	SSCC + authentication code
	Vehicles	Active RFID	SIN
Processing phase	Packaged food items	EAN-128 barcode	GTIN etc.
	Flavoring stuff	EAN-13 barcode	GTIN
	Operators	Passive RFID/ Manual	SGTIN
	Cartons	Passive/Active RFID	SGTIN
	Logistics Units	Active RFID	SSCC + authentication code
	Vehicles	Active RFID	SIN
Storage & transportation phase	Packaged food items	EAN-128 barcode	GTIN etc.
	Operators	Passive RFID/ Manual	SGTIN
	Cartons	Passive/Active RFID	SGTIN
	Logistics Units	Active RFID	SSCC + authentication code
	Vehicles	Active RFID	SIN
Retailing phase	Packaged food items	EAN-128/EAN-13 barcode	GTIN etc.
	Operators	Passive RFID/ Manual	SGTIN
	Cartons	Passive/Active RFID	SGTIN
	Logistics Units	Active RFID	SSCC + authentication code
	Vehicles	Active RFID	SIN

Table 4.4. Summary of anti-counterfeit solution implementation plan

Our conclusion for the anti-counterfeit mechanism is that it is admitted that it's practically impossible to fully prevent the suppliers in providing counterfeit products if the suppliers have vicious intention to do so. But our anti-counterfeit mechanism is a cost effective way to prevent the suppliers in providing significantly large amount of counterfeit products comparing with their normal production capability.

Chapter 5. The Storage and Transportation Monitoring Module

5.1. Overview

The storage and transportation management module provides monitoring capability in the storage and transportation phases. Active RFID tags integrated with sensors are tagged to the storage units and transpiration units, i.e. cartons. The sensors monitor the storage and transportation environment, such as temperature and humidity, and the conditions of the food, such as color and smell. Check points are typically deployed in entrance and exit points of warehouses or distribution centers. Active RFID readers are installed in the check points to collect the data from the active RFID tags and sensors. The data is then analyzed by shelf life prediction models. When the data indicates potential food contamination problems, alerts are triggered through web services to corresponding operators. The motivation to build this module is: first, the strong need to establish monitoring to food products as food safety and quality problems arise seriously in recent years; second, despite of recent development of the

AIDC technologies, the standards and specification to establish environment monitoring with AIDC technologies have not been matured.

The storage and transportation monitoring module is developed on the basis of the tracking and tracing management module. A significant technology development in this module is the innovative sensor integrated active RFID tags. The sensors are used to monitor storage and transportations environment, while the active RFID tags provide identifications to the traceable items. When the sensors are integrated with the active RFID tags, the sensor data is stored in the active RFID tags' memory. When the active RFID tags integrated with sensors pass through pre-designed check points, the active RFID tags' identifications as well as the sensor data stored in the tags' memory are read and transmitted to a central repository. Thus, the storage and transportation monitoring module provides in situ monitoring of the environment during the storage and transportation phase of food products. The use of the responsive warning mechanism provides high-level confidence of food safety and quality status.

Since there are no existing standards and specifications on how to manage the data collected from the sensor integrated active RFID tags, our work illustrates the encoding, filtering, compression, capturing, and accessing of the data. The data encoding involves the selection of compression algorithms to reduce the required memory size in the active RFID tag. With the data capturing capability in active RFID tags, a communication protocol for the active RFID reader to read tag and sensor data as well as to write text information to the active RFID tags is developed. The application program interfaces and data structures employed in the RFID middleware and the EPCIS is extended to deal with the sensor data. Furthermore, the data inquiry services for information sharing and exchange in the supply chain are augmented with the capability to inquire the sensor data.

Enabled by the sensor integrated active RFID tag technology, we develop a responsive warning mechanism to support the analysis of food safety and quality during storage and transportation. When the food products with the sensor integrated active RFID tags pass through the pre-designed check points, the food product information and the corresponding cumulated environment data is read and transmitted to a central repository. If the environment data shows any sign of abnormality such as refrigeration malfunction, continuous rising of the temperature or temperature deviations from operational regulation, the responsive warning mechanism in the storage and transportation module provides timely alerts to field operators to immediately deal with the abnormal situation to stop further losses. In addition, the evaluation of the environment information and the prediction of product shelf life are achieved by analyzing the collected sensor data with the knowledge of mathematics models between the food quality and the environment parameter.

The following sections cover the discussion the compression of the sensor data in the active RFID tags, the management of the sensor data in the RFID middleware and the

EPCIS, and the implementation of the responsive warning mechanism.

5.2. Compression of the Sensor Data

The sensor data can not be unlimitedly cumulated and stored on the active RFID tag memory, because the memory size of the tags is limited. A encoding and compression mechanism must be used to reduce the data amount stored on the active RFID tags. In this section, we firstly analyze why we can not use existing compression algorithms to compress the sensor data on the active RFID tags. Then we present a new and suitable sensor data compression algorithm developed according to the sensor data characteristics.

Compression algorithms fall into two categories, as reviewed in Chapter 2. One is the lossy compression algorithms. The other is the lossless compression algorithms. In the lossy compression algorithms, the exact original data are not allowed to be reconstructed from the compressed data. On the contrast, in the lossless compression algorithms, the exact original data are allowed to be reconstructed from the compressed data. Since one objective of the storage and transportation monitoring module is to judge whether there are any exceptions in the environment according to the environment data collected by the sensors, the compressed sensor data must be extracted to form the exact original data. Otherwise, the judgment to the storage and transportation environment is not reliable. Therefore, only lossless compression algorithms are suitable. But we can not use existing lossless compression algorithms, because the microprogrammed control units (MCU) on the active RFID tags have too limited computing resources. As a result, new compression algorithms with good compression rate but low computing resource requirement must be developed.

We develop our new compression algorithm according to the following two important characteristics of the sensor data. One characteristic is that the sensor data series is a markovian signal source. A markovian signal source has the following characteristics: for signals with memory, the sensors of the signal generates a time series S = $(U_1, U_2, \ldots, U_{t-1}, U_t)$, such that the variable $U_t \in$ A. If condition distribution P(U_t | $U_{t-1}, U_{t-2}, \ldots, U_1$) only depends on the variable U_{t-1}, that is P(U_t |$U_1, U_2, \ldots, U_{t-1}$) = P($U_t$ | $U_{t-m}, U_{t-m+1}, \ldots, U_{t-1}$). Then the signal source represented by set A is markovian. So, we model the sensor data as a markovian process. The other characteristic is that the sensor measurement usually changes slightly or steadily. For example, the temperatures in frozen containers usually keep constant in normal situations, and change slowly and steadily during freezing and thawing process. Light intensities in containers are constantly low when the containers are closed. After the containers are opened, light intensities become constantly high.

By considering of the two characteristics of the sensor data, we develop a new compression algorithm to only record the changes to the last data. Moreover, since one active RFID tag may integrate with several sensors, the data captured from different sensors is separated in the decompressed data. The corresponding decompression algorithm is implemented on the application software that makes use of the sensor data, while the compression algorithm is implemented on the chips of the active RFID tags.

5.3. Management of the Sensor Data

The first part of section talks about the necessary tuning of the sensor data transmission from the active RFID tags to the RFID readers. The second part talks about the extension to the current EPCglobal standards to manage the data collected from the sensor integrated active tags. Since the current EPCglobal standards only focus on passive RFID technology and do not deal with the management of the sensor data, we think the most suitable way to implement our system is to make necessary extensions to the current standards so that the impact to other existing RFID applications is minimized. The necessary extensions discussed in this section include the extension of the middleware ALE interface and of the EPCIS.

As for the sensor data transmission from the active RFID tags to the RFID readers, two parameters are considered for the active RFID reader and tag system. One is the Tolerable Maximum Upload Time Interval. The other is the Tolerable Maximum Data Sample Amount.

The Tolerable Maximum Upload Time Interval is the maximum time interval for the active RFID tag to upload the sensor data to the reader. Since there is size limitation of the tag memory, if the sensor data cumulated in the tag memory is not uploaded to the reader in time, new sensor data will take the place of the old data in the tag memory and the old data will be lost. We guarantee that the sensor data is uploaded to the active RFID reader within every Tolerable Maximum Upload Time Interval.

Suppose the Sampling Interval (SI) is the time interval for the sensors to record environment data, s is the Memory Size of the active RFID tag and r is the Compressed Sample Data Rate (how much memory one sample of compressed sample environment data occupies). The Tolerable Maximum Upload Time Interval (MTI) is calculated according to the following equation:

$$\mathrm{MTI} = \mathrm{SI} \times (s / r)$$

For example, if the Sample Interval is 10 minutes per sample, the Memory Size is 1 KByte, and the Compressed Sample Data Rate is 4 byte per sample on average, then the Tolerable Maximum Upload Time Interval is around 2560 minutes. So, according to the calculated Tolerable Maximum Upload Time Interval, we adjust the Sample Interval to a reasonable value. If the Sample Interval is too high, the environment monitoring preciseness is too low; if the Sample Interval is too low, it is difficult to guarantee that the sensor data is uploaded to the active RFID reader within every

Tolerable Maximum Upload Time Interval and the sensor data may be lost because of the limitation of the tag memory size.

The Tolerable Maximum Data Sample Amount is the maximum sensor data amount for the active RFID tag to upload to the reader. Since there is a physical constraint in the data transmission speed between the active RFID tag and reader, if the active RFID tags pass through the detection range of the readers too quickly, the uploading of the sensor data is likely to be disrupted before it is completed. We guarantee that the sensor data is uploaded to the active RFID reader before the sensor data amount reaches the Tolerable Maximum Data Sample Amount.

Suppose we know the time t taken for the active RFID tags to go through the detection range of a particular reader and the Effective Data Transmission rate (EDT) per second. The Tolerable Maximum Data Sample Amount is calculated by the following equation:

$$\mathrm{MDS} = \mathrm{EDT} \times t / r$$

For example, suppose it takes 10 seconds for the active RFID tags to go through the detection range of a particular reader, and the Compressed Sample Data Rate is 4 byte per sample on average. The typical maximum data transmission rate between active RFID tags and readers is 2.7Kbit per second. But there is setup time between the data transmission of different tags, the Effective Data Transmission rate actually is approximately half of the maximum value. So, the Tolerable Maximum Data Sample Amount is 432, which means if there are 4 tags passing through the reader simultaneously, only around 100 samples are allowed to store on each active RFID tag on average. So, according to the calculated Tolerable Maximum Data Sample Amount, we further adjust the Sample Interval to a reasonable value. If the Sample Interval is too high, the environment monitoring preciseness is too low; if the Sample Interval is too low, it is difficult to guarantee that the sensor data is uploaded to the active RFID reader before the data transmission is corrupted before it is completed.

After the sensor data is transmitted to the active RFID readers, the data is first managed by the RFID middleware. The EPCIS Capturing Application typically controls the middleware through the ALE interface. The EPCglobal ALE interface specification [12] targets at passive RFID systems, while we use the active RFID tags to integrate with the sensors. Thus, there are no existing methods to deal with the sensor data in the ALE interface defined by [12]. As a result, we extend the ALE interface by providing a means to read and write the data in the active RFID tag's memory.

In the extension of the ALE interface, we add the following method to request the active RFID tag to upload the data in the tag's memory, on matter it is the sensor data or other text data that is written to the tag memory before.

byte[] ReadData(data: DataSpec)

Here the DataSpec specifies the parameters for the data collection. It has 4 members: the TagID is the active RFID tag ID that need data collection, the formatID specifies different format of organizing the tag's data memory and addressing scheme, the address specifies the start address of current read operation, and the length is the number of bytes to read. When formatID=1, a simple sequential addressing scheme is used. When format=2, an addressing scheme with page numbers is used. And the reading always starts from the beginning of a page. The return value of the method is the byte array read.

In addition, we add the following method to write text data in ASCII encoding into the memory of the active RFID tag.

int WriteData(data: DataSpec)

In addition to the 4 members in the above mentioned DataSpec, a byte array of data bytes is provided as the data to write.

In our implementation of the ALE interface extension to read and write the active RFID tag, the RFID middleware tries to read or write only once. The reader to read and write the tag is not specified the methods, while the middleware requests the reader that has the latest detection of the target tag to do the tag reading and writing.

After the RFID middleware receives the active RFID tag ID and the sensor data, the EPCIS Capturing Application captures the information through our extended ALE interface to the EPCIS Repository for a permanent storage. Consequently, the data schema in the EPCIS must be able to accommodate the sensor data. In the EPCIS data schema that we design for the tracking and tracing management module, we add a temperature field in the ObjectEvent table for flexibility, because in some applications, people may keep record of the current temperature when an object event happens. But the temperature field is of "float" type, and the sensor data may contain more data bytes than a typically "float" type record. Moreover, since the sensor data is still not decompressed when they are stored in the EPCIS Repository, the compressed data may even contain control characters which can not be stored in database systems. In addition, the extended ALE interface allows storing text information into the active RFID tag's memory, while the text information can not be stored as a "float" type data. Owing to these reasons, it is not suitable to store the sensor data to the temperature field. Thus, we make corresponding extension to the EPCIS data schema.

We have two methods for the extension. One is to replace the temperature "float" field with a "character" type field. But this method exerts an impact on the application software in the tracking and tracing management module, because the application software reads the temperature field as of "float" type.

The other method is to add a new EPCIS event type called Environment Event. As we design a generic event type in the EPCIS data schema of the tracking and tracing management module, the extension of a new EPCIS event type is flexible. The generic event type is regarded as the base type of all event types and has the common attributes. The new event type derives from the common fields by inheriting the base type, and adds new attributes according to its particular usage. The following figure is the data schema for the Environment Event.

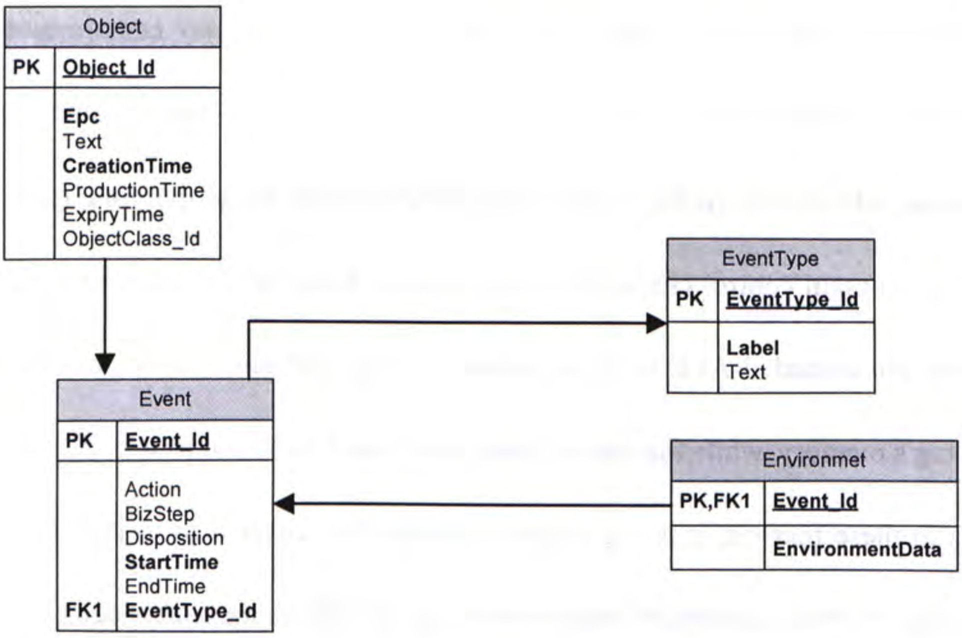


Figure 5.1. Data schema for the Environment Event

For an Environment Event record, we create a record in the generic Event table, link the record to the EventType table indicating the event type is the Environment Event, and maintain other necessary data in the Object and the Environment table. The Object table maintains information about the active RFID tag, while the Environment table maintains the data cumulated in the tag's memory. The EnvironmentData field in the Environment table is defined to be of "character" type with sufficient length according for the data read from the active RFID tag's memory. The compressed data is stored in the field. And the application software that makes use of the data is responsible for the data decompression.

5.4. Responsive Warning Mechanism

In the storage and transportation module, we develop a responsive warning mechanism. In the responsive warning mechanism, when the data about logistics activities from the AIDC facilities is collected by pre-designed check points, the application software accesses the data through the EPCIS Accessing Application, analyzes the data and makes business decisions in response to the supply chain situation according pre-defined rules. This section discusses the system architecture to implement the responsive warning mechanism. There are two major developments. One is the Event Processing System (EPS) implemented in the application software. The other is the Service Oriented Architecture (SOA) adopted as the application software architecture.

The Event Processing System (EPS) is a crucial part of the application software in the storage and transportation monitoring module. Its overall architecture is shown in the following figure.

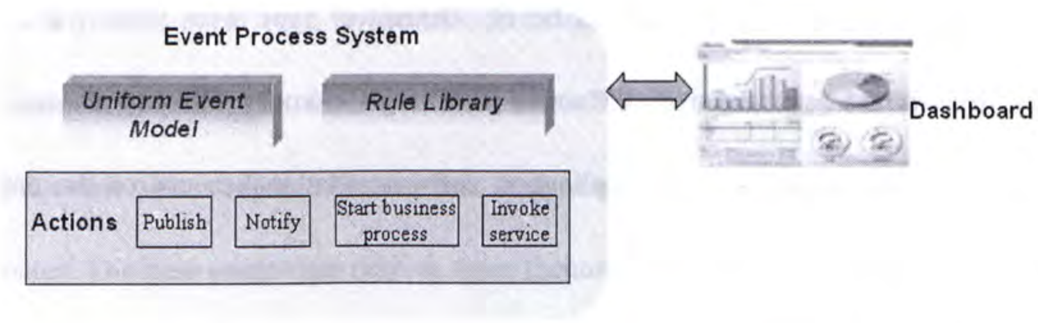


Figure 5.2. Architecture overview of the Event Processing System

The EPS system accesses the EPCIS Repository through the EPCIS Accessing Application, then analyzes the data and takes corresponding actions. The data retrieved by the EPCIS Accessing Application is in the format of EPCIS events. The EPS system maintains a Uniform Event Model, which adds more business context to the EPCIS events. A transformation engine is developed to transform the data from the EPCIS Repository to the Uniform Event Model format. The EPS system also maintains a Rule Library, to which we plug-in business rules of generating actions from business events. The plug-in mode means the system scans the available business rules that are configured to use when the system starts up, which ensures the flexibility of defining rules. The actions to be taken include publication, notification, starting business process, service invocation. Publication means conveying the information to the subscribers. Notification means notifying related personnel through e-mail, short message service (SMS), or system message etc. Starting business process means initiating a particular predefined business process. Service invocation means starting a pre-programmed web service. Besides, a dashboard is also provided for the monitoring of supply chain status.

The Service Oriented Architecture (SOA) is adopted in the application software. The following figure illustrates the overall application software architecture enabled by the SOA.

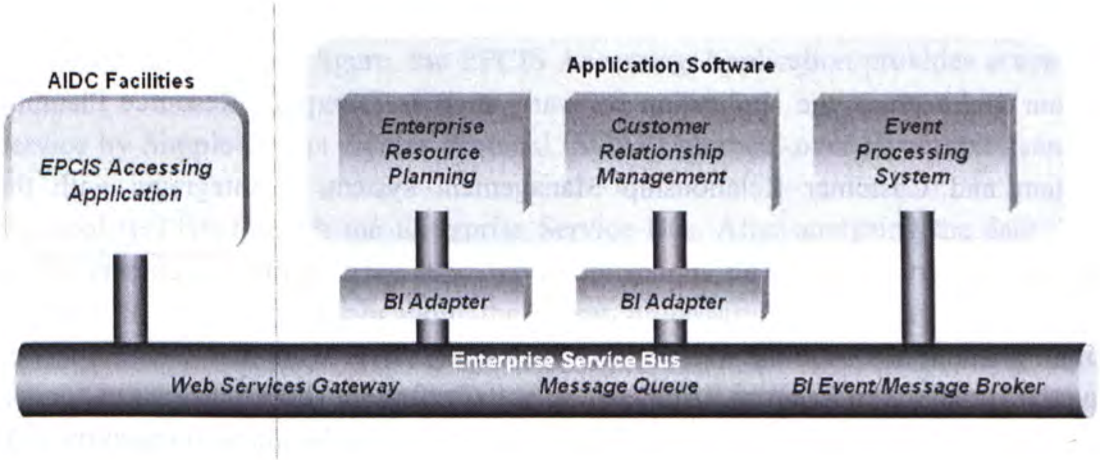


Figure 5.3. Integration with the Enterprise Service Bus

The Enterprise Service Bus (ESB) provides middleware infrastructure to facilitate communications capability which links the application software inside the corporation and the EPCIS Accessing Applications outside the corporation boundary. It consists of three major components: Web Services Gateway, Message Queue, and Business Integration Event/Message Broker. The Web Services Gateway is a run-time component, which provides configurable mapping based on Web Service Definition

Language (WSDL) documents. It maps any WSDL-defined service to another service on any available transport channel. The Message Queue is a software component used for inter-process communication. It provides an asynchronous communications protocol, which means the sender and receiver of the message do not need to connect to the message queue at the same time. The messages placed onto the queue are stored until the recipient retrieves them. The Business Integration Broker extracts data from the source node at the configured time, transforms the data, converts the schema, and routes the data to the application.

In our architecture, the application software, such as Enterprise Resource Planning system and Customer Relationship Management system, is integrated with the Enterprise Service Bus. The application software is seen as many web services of small granularities. And the web services are loosely coupled, so that when some web services change, the impact on the others is small. The Business Integration (BI) Adapter is used to convert those application software interfaces that are originally not through web services to interfaces exposed as web services.

The EPCIS Accessing Application and the Event Processing System is able to be integrated through the Enterprise Service Bus, as shown in the following figure.

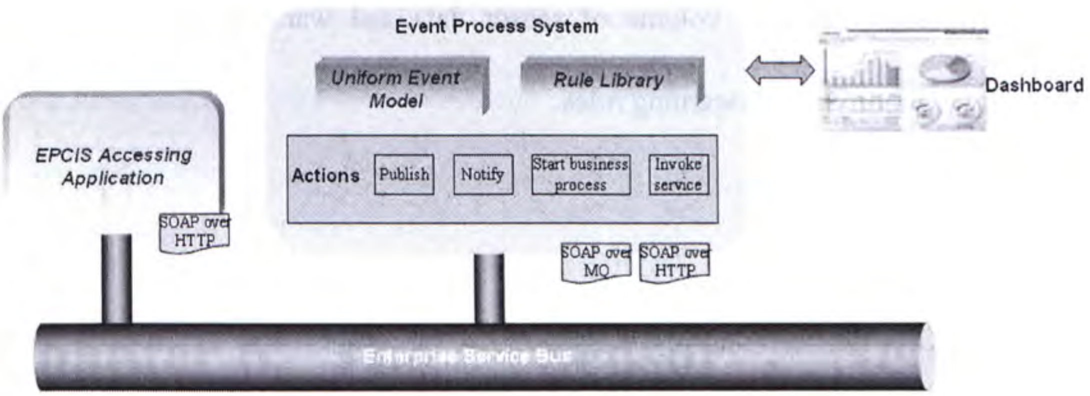


Figure 5.4. Integration of EPCIS Accessing Application and Event Processing System

As shown in the above figure, the EPCIS Accessing Application provides accessing service by Simple Object Access Protocol (SOAP) protocol over Hypertext Transfer Protocol (HTTP) through the Enterprise Service Bus. After analyzing the data from the EPCIS Accessing Application, the Event Processing System determines what actions to take and sends the information out by SOAP protocol over either Message Queue (MQ) or HTTP. To those actions we do not expect instant response from the other application software components, we use SOAP over MQ. Otherwise, we use SOAP over HTTP.

Our responsive warning mechanism is a technically feasible and effective solution to provide warnings in response to the collected sensor data. However, since we implement the Event Processing System and adopt the Service Oriented Architecture in the solution, the building cost is higher than directing modifying the existing enterprise application software by adding the warning rules. But our solution provides higher scalability to large volume of sensor data and warning rules and higher flexibility in modifying the warning rules.

Chapter 6. The Sensor Networks Enabled Assessment Module

6.1. Overview

The sensor networks enabled assessment module deploys sensor networks in different phases of the food supply chain to achieve a more compressive monitoring of supply chain activities. The upload of the data from the active RFID tags and sensor networks does not reply on fixed check point. Mobile active RFID readers integrated with GPRS communication modules are able to upload the data through GPRS networks in real time. In order to trigger more precise alerts, data mining is used to find out the patterns of sensor network data that may indicate potential food contamination problems. The motivation arise from the need to establish more comprehensive monitoring capability than the storage and transportation monitoring module and the immaturity of the technology to integrate active RFID and sensor networks.

The stability and maturity of the technologies in the previous two modules is the foundation for the development of the sensor networks enabled assessment module. A core innovation in this module is the integration of the sensor networks and the active RFID systems. The active RFID system records where a particular food product is, while the sensor networks provide a set of continuously collected sensor data about food safety and quality and different environment conditions in locations such as farms, factories, warehouses, and supermarkets to improve the monitoring capability of food cultivation, processing, transportation, storage and consumption over the entire life cycle of food products. This module enables a complete food safety and quality network solution to assess the food safety and quality by having a thorough and transparent monitoring with an active warning mechanism. The potential benefits from interoperating with sensor networks includes building advanced scientific cultivation systems, monitoring against human error or intentional sabotage, and preventing epidemic situation proliferation, etc. These potentials serve well for the public interest and enterprise to reduce risk in the food safety and quality.

Since there are no existing standards and specifications to refer to, we develop application program interfaces for the RFID middleware and the application software to support the use of sensor networks. We make use of the Sensor Model Language (SensorML) to facilitate the efficient adaptation of sensor networks and eventually ease the implementation process in different organization in the food supply chain.

Enabled by the sensor networks integrated active RFID tags, an active warning mechanism is implemented in the sensor networks enabled assessment module to achieve thorough and real time monitoring to the supply chain activities. The two key technologies in the active warning mechanism are the GPRS and data mining technologies. The GPRS technology provides real time data transmission channel. The data mining technology provides analyzing capability to find cause of food quality problems from patterns in the archived sensor data. Corresponding actions are triggered according to the discovered data patterns.

The following sections discuss how we manage the sensor network data and implement the active warning mechanism.

6.2. Management of the Sensor Network Data

The deployment of the sensor networks provides a wide range of measurement to assess the food safety and quality status in cultivation, processing, transportation, storage and consumption over the entire life cycle of food products. Meanwhile, the data captured from diverse sensors needs to be managed for analysis, but there are no existing standards and specifications to refer to. As a result, this section discusses how we make use of the Sensor Model Language (SensorML) to manage the sensor network data in the application software.

We use the SensorML to define the sensor systems in a generic way so that we are able to adapt to the varieties of the sensor systems. The following figure shows an example of a sensor system defined with the SensorML.

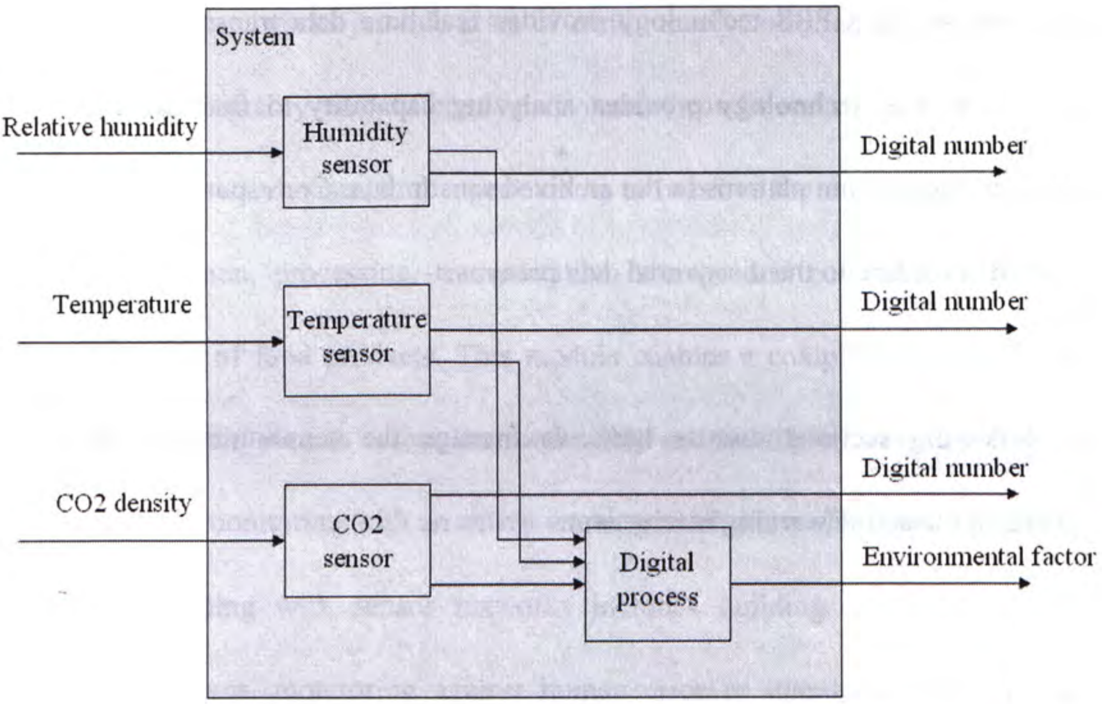


Figure 6.1. Sensor system of storage environment

As shown in the above figure, the sensor system in the example monitors the storage environment in a warehouse. There are three inputs by three types of sensors: relative humidity, temperature, and carbon dioxide density sensor. The SensorML describes the component structure, position information (location and orientation) and technical characteristics of the system. The sensor system outputs not only digital number of the three measurements, but also an environment factor affecting the food, which is calculated by the embedded digital process.

We further use the SensorML to define the process chains of the sensors. The following figure shows an example of a sensor process chain defined with the SensorML.

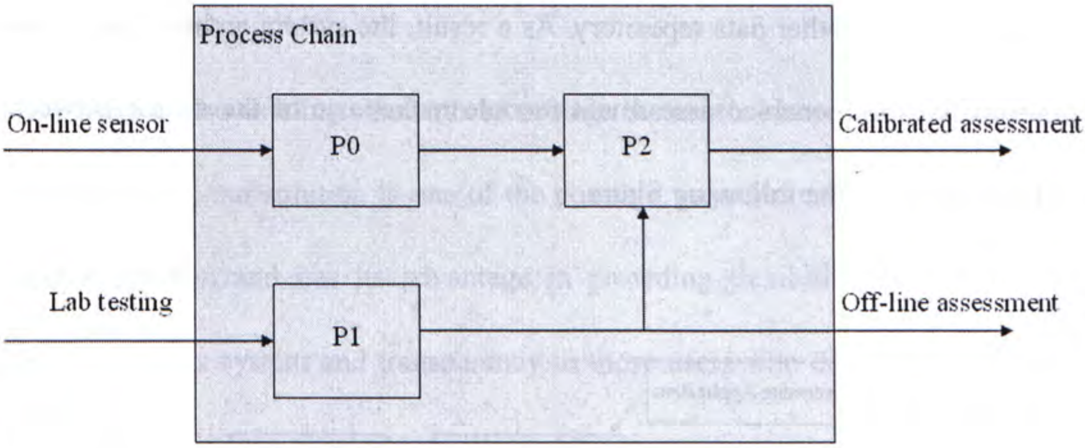


Figure 6.2. Sensor process chain

As shown in the above figure, there are three sub-processes in the process chain. The Process P0 receives data input from on-line sensor. And the process P1 receives data input from laboratory testing. Although the data input for P1 is not as frequent as that of P0, P1 provides long term data calibration parameters for the on-line assessments and the parameters are sent to the process P2, which is responsible to calibrate the data from P0 to get a calibrated on-line assessment.

In the sensor networks enabled assessment module, the sensor data is stored permanently in the EPCIS Repository and accessed through the EPCIS Accessing

Application. Since in the sensor networks enabled assessment module, the SensorML is used to accommodate the complexity of the sensor systems, an extra SensorML process library repository is used to keep record of the sensor systems and process chains defined in the SensorML. This design provides transparency to those users who do not need to analysis sensor networks data, because the sensor networks definitions are in another data repository. As a result, the system architecture of how the sensor networks enabled assessment module makes use of the sensor networks data is illustrated in the following figure.

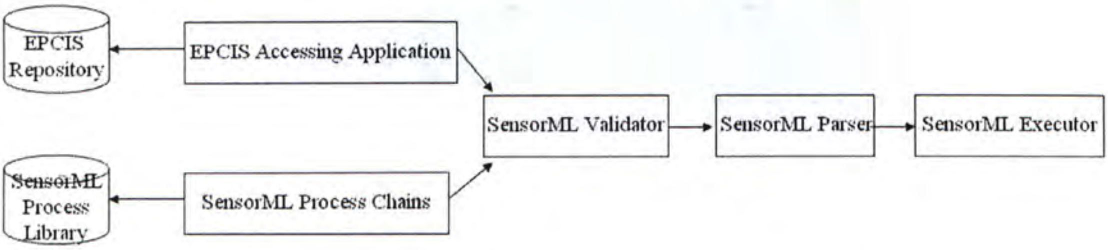


Figure 6.3. System architecture to use the sensor networks data

In the system architecture, we get the raw sensor data from the EPCIS Repository, and get the SensorML process chains from the SensorML process library. The SensorML language is XML based so that high level programming languages such as Java is able to interpret it. Therefore, a Java based SensorML validator is built to validate the SensorML instance documents according to the official XML schema. A Java based SensorML parser is built to generate Java objects after the reading of the SensorML process chain document and the sensor data. A Java based SensorML executor is built to provide a framework for executing the process chain models with the sensor data.

The application software takes corresponding actions according to the execution result of the SensorML executor. As a result, the data detected by the sensor networks and collected by the RFID facilities is analyzed by the process chains defined by the SensorML, and decisions about the supply chain activities are made by the application software.

Since there are no existing standards to manage the sensor networks data collected by RFID facilities, our solution is one of the possible ways but not the only one. It is a feasible solution and has its advantage in providing flexibilities of defining new sensor networks system and transparency to those users who do not need to analyse sensor networks data. If no standardized definitions of sensor networks systems are used, i.e. SensorML, but customized systems are built based on the adopted sensor networks, the cost of building such systems is lowered, but the flexibility is compromised.

6.3. Active Warning Mechanism

In the sensor networks enabled assessment module, an active warning mechanism is implemented to achieve more thorough and real time monitoring to the supply chain activities than the responsive warning mechanism. The two major enabling technologies are the GPRS technology and the data mining technology. The GPRS technology provides real time data collection capability anywhere within the GPRS signal coverage, while the responsive warning mechanism relies on pre-set check points to collect the data about the supply chain activities. The data mining technology provides analyzing capability to find the cause of food quality problems from patterns in the archived sensor data. This section discusses how we use the two enabling technologies to implement the active warning mechanism.

The first enabling technology is the GPRS technology. In the active warning mechanism, we make an innovation in the integration of the GPRS and RFID technologies. As the GPRS network is a public wireless network that covers nearly everywhere of major cities, we innovatively use the GPRS network as a data transmission channel to upload the data collected by the active RFID systems. The transmission through the GPRS network is actually more reliable than the one from the active RFID tag to the reader. The data includes the identifications of the active RFID tags, the sensor networks data, the text information written to the tags, and the position data from the GPS system. As a result, data about the identifications, the safety and quality status, and the positions of the food products is collected to a central data repository nearly everywhere the logistics activities happen.

We develop a prototype system to integrate a cell phone with GPRS support and the active RFID system. The cell phone is connected to the active RFID reader. The data collected by the reader is sent to the cell phone. When the cell phone receives a particular command, it sends the data out to a central data repository through the

GPRS network. The prototype system is also flexible to integrate GPS systems. When a GPS receiver is integrated to the cell phone, the position data is also sent out through GPRS network along with other data.

The second enabling technology is the data mining technology. The data mining technology is used to find the relationship between the food safety and quality problems and the archived sensor data. New decision variables in the form of sensor measurement thresholds are generated and setup in the application software for better assessment of the food safety and quality. Since the active RFID readers send out data of the sensor measurements in real time through the GPRS networks, the violation of the thresholds is found soon after the incident and thus the corresponding personnel are notified.

Our data mining procedure in the active warning mechanism includes the following steps.

First, problem analysis. This step identifies the food safety and quality problem and the potential sensor measurement that may cause the problem. A feasibility assessment about the availability of the sensor data, the data mining technology, and the deployment of sensor measurement thresholds in the application software is made in this step. If the feasibility is high, then we move on to the next steps.

Second, data preparation. We use extract tool, transform tool, and load tool for the data preparation in this step. The overview of the data preparation tools is shown in the following figure.

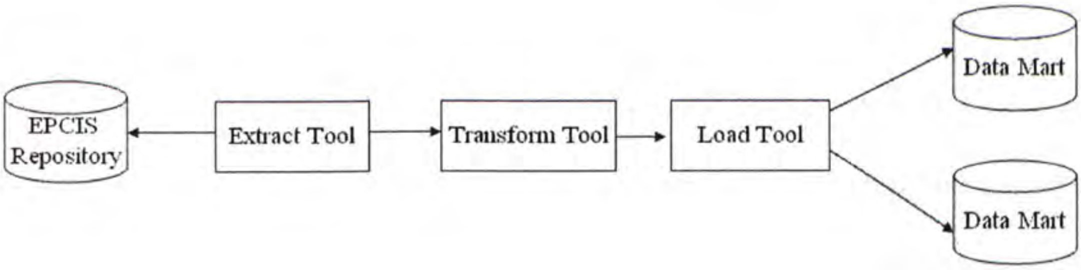


Figure 6.4. Data preparation tools

As shown in the above figure, the extract tool reads data from the EPCIS Repository. The transform tool coverts the extracted data from its original state into the form required for the data mining algorithm. The transformation involves using rules, lookup tables and combining the data with other data for data enrichment. The load tool writes the data into the target data mart for data mining.

Third, pattern generation. This step precedes the actual pattern discovery stage. The patterns are the relationships between food safety and quality problem incidents and the archived sensor data. The patterns are expressed in the form of sensor measurement thresholds. We use classification algorithms to discover the patterns. Classification is the process of assigning classes, or categories to the archived sensor data. The sensor data of each business transaction is defined as a record, which has defined a set of attributes and is expressed as a feature vector. The classification attribute is the "Is_Safety_and_Quality_Problem" attribute, which has two values: "Yes" or "No". The history data is divided into two parts: training data and testing data. In order to get the classification model, the classification algorithms are run on the training data. Then the classification model is tested on the testing data. During the testing, the value of classification attribute is calculated according to the classification model. Then the calculated classification attribute value is compared with the real value. The algorithm parameters are adjusted if the testing result is not satisfactory.

Fourth, pattern deployment. This step involves deploying the discovered patterns as designed in the problem analysis stage. The sensor measurement thresholds are setup in the supply chain activities monitoring application software. The active RFID readers send sensor data to the application software through GPRS networks. Alerts are triggered when any violation of the thresholds happen.

In order to improve the disruptive events detection, two methods are used. One method is setting up sensor profiles for different sensors. The other is association analysis of the sensor data.

The reason for the sensor profiling is that each sensor has its own history of alerting behavior. The sensors vary in terms of alert types, alert ratios, distribution of alerts on day-of-week and time-of-day basis etc. The alerts are filtered or enhanced according to the sensor profiles that are generated from the historical sensor data. The attributes of the sensor profile include the alert volumes in each priority level, the ratios of alert volumes, the frequencies of alerts in each day of a week, and the frequencies of alerts in different time of a day.

The association analysis is first introduced to analyze the sales data in supermarkets. An association is, for example, 30% people who buy beer will also buy peanuts. Cross sales opportunities are explored by using the association relationships found by data mining algorithms. We borrow the idea to analyze the sensor data. The associations of alert types that frequently happen together within a short period of time are found. A combination of specific alert types that often appear together every a few minutes in an extended time period is less suspicious than a sudden burst of alerts with a combination seldom seen before. For example, a violation of the vehicle often causes a surge of the container temperature. The combination of a violation alert and a temperature surge alert is a less suspicious one.

Thus, the deployment of alerting strategy is shown in the following figure. Our decision engine considers the alert associations and the sensor profiles as well as the sensor measurement thresholds when the alerts are triggered.

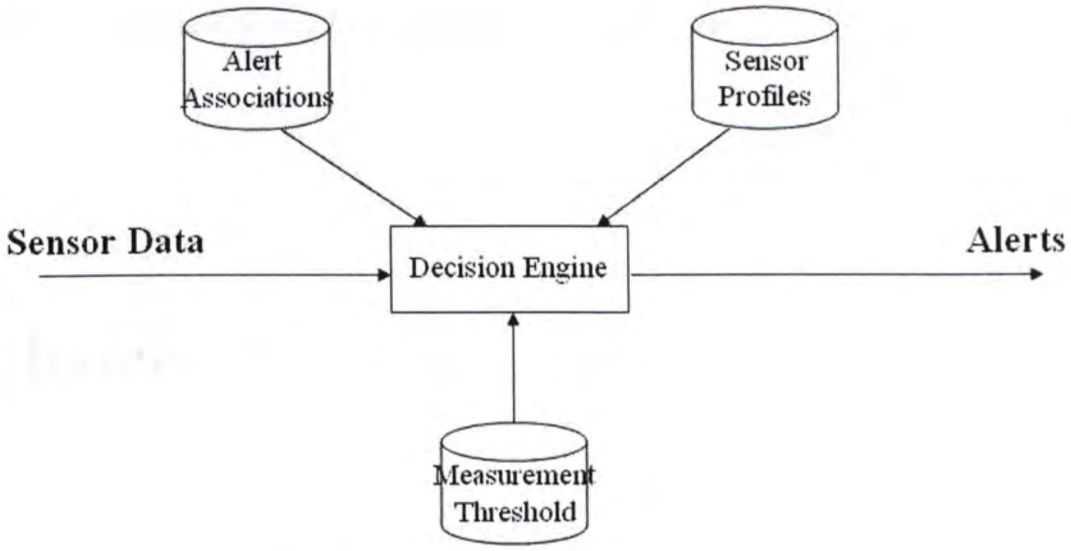


Figure 6.5. Deploy of alerting strategy

Fifth, pattern monitoring. In order to guarantee the suitability of the alerting strategy generated from the historic data, regular pattern monitoring with the new data is implemented. If the alerting strategy turns out to be unsuitable to the newly accumulated data, new data mining cycles are required to calibrate the alerting strategy. The suitability is measured by the number of the false negative and false positive cases. A false negative case is that an alert is not triggered on the occurrence of food safety and quality problems. A false positive case is that an alert is triggered when no food safety and quality problem emerges.

The active warning mechanism does make improvement to the responsive warning mechanism in providing more real time and potentially more accurate warnings, but the cost of building such solution is higher with the adoption of GPRS and data mining technologies. For similar systems, there are still many arguments about how to improve the disruptive events detection and alerting. And it is still an open research topic.

Chapter 7. Conclusions

In this chapter, we firstly present the most important contributions of the thesis. Then, there is a discussion of the further work directions.

7.1. Contributions

Current pilot projects of establishing traceability in food supply chains often involve only one or two phases in the supply chains. The scope of traceability covers tracking and tracing only and does not include monitoring of environment and food products. We define a notion of the extended traceability by adding monitoring capability to tracking and tracing. Best practice and specifications in implementing the extended traceability in a whole food supply chain, from farm to supermarket, are scarcely elaborated.

The main contribution of the thesis is our methodologies to implement the extended traceability by adopting multiple automatic identification and data collection (AIDC) technologies, including passive RFID, active RFID, barcode, and sensor technologies.

In order to achieve the extended traceability, a step-by-step approach is used. We built three layers of application modules that gradually establish the extended traceability, which are the tracking and tracing management module, the storage and transportation monitoring module, and the sensor networks enabled assessment module.

The tracking and tracing management module establishes tracking and tracing across the food supply chains. Although tracking and tracing applications are not new, this module is built in a way that provides necessary foundations for the upper two layers. A nested visibility is implemented with appropriate nest AIDC technologies to provide item level visibility to food products, while there are no guidelines for implementing it. Heterogeneous data collected from multiple AIDC technologies are integrated into the EPCIS, which is not specified in the current EPCIS specifications and thus is an innovation. Besides, an anti-counterfeit solution enabled by the AIDC technologies is put forward to tackle the serious counterfeiting situations in food supply chains in developing countries such as China.

The storage and transportation monitoring module makes use of the sensor integrated active RFID technology to provide in situ environment monitoring. Our methodology is presented to encode, filter, compress, capture and access the data collected by the sensor integrated active RFID tags; this methodology is original since there are no existing standards and specifications. In addition, a responsive warning mechanism enabled by the sensor integrated active RFID technology is developed to support the analysis of food safety and quality during storage and transportation.

In the sensor networks enabled assessment module, the sensor networks integrated active RFID systems are used to provide more comprehensive monitoring capability across phases in food supply chains. Application program interfaces for the RFID middleware and the application software are developed to support the use of sensor networks since there are no existing standards and specifications to refer to. Also, an active warning mechanism enabled by the GPRS and data mining technologies is developed to achieve thorough and transparent monitoring to the supply chain activities.

In conclusion, the contribution of this thesis covers three aspects: hardware, infrastructure, and application software. In the hardware part, a key technology innovation is the integration of sensors and active RFID tags. In the infrastructure part, the extension of the RFID middleware and the EPCIS to accommodate data collected from multiple AIDC technologies is an achievement. And in the application software part, we develop three layers of application modules that gradually establish the extended traceability, which is the third achievement.

7.2. Future Work

By using the methodology of implementing the extended traceability in food supply chains, the future direction is to establish a food safety and quality (FSQ) network that connects together all related farms, companies, government bureaus, and consumers. There are three most significant scenarios of using the FSQ network.

The first scenario is about supply chain partners. When the AIDC technologies detect some abnormities in supply chain activities, alerts are sent to all potentially related supply chain parties, no longer limited to the company responsible for those supply chain activities. For example, the message of the disruptive events in transportation is sent to supermarkets for potential additional replenishment and to manufacturing factories for potential additional producing.

The second scenario is about government bureaus. It is often heard that local government has found some contaminated food. The announcement issued by the local government often specifies the origin and the type of the contaminated food. But without FSQ network, it is difficult to make sure all the contaminated food has been recalled. On the contrast, government bureaus can broadcast through the FSQ network all the unique identifications of the contaminated food so that all the contaminated food will be found and recalled.

The third scenario is about individual consumers. When consumers buy food products, they can search the product history on web sites. Or, they can subscribe the inquiry service to cell phones so that they can obtain the information through short message service (SMS). The product history includes the history of product location, environment, and the food safety and quality status.

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Appendix 1

1. Food

1.1. Beaver Street Fisheries pallet and case USA

1.2. Target Corporation, material handling vehicles, USA

1.3. Namibia Government intermodal containers beef, Namibia

1.4. Savannah Georgia cross docking facility, trailers USA

1.5. Schwebel's Bakery, delivery monitoring, USA

1.6. Diageo pallet, case and item, UK

1.7. Moraitis, tomato tray tracking, Australia

1.8. Mercadona supermarket, pallets / cases Spain

1.9. Ballantine Produce Company, fruit tagging, USA

1.10. Horticulture Australia Ltd (HAL), perishable food tracking, Australia

1.11. Arla Foods, steel carriers tagging, Sweden

1.12. Hutchison Whampoa ,intermodal container logistics, USA, Singapore

1.13. Scottish Courage Brewing, beer keg, UK

1.14. Metro Future Store supermarkets, item level Germany

1.15. Marks & Spencer, food tracking, UK

1.16. Campofrio meat, Spain-item level

1.17. Sushi Bars, Yoshikawa item level Japan

1.18. PSA Corporation, intermodal container logistics USA China Singapore

1.19. Maruetsu Supermarkets food supply chain, Japan

1.20. Envirotainer air cargo ULDs, Europe

1.21. Air Canada food trolleys, Canada

1.22. Paramount Farms, trailers for nuts, USA

1.23. Sepang Airport, food trolleys, Malaysia

1.24. Alliant Atlantic Food, trucks, USA

1.25. foodSafe International, fruit and vegetable tracking, Botswana

1.26. Selfridges, food vehicles and containers, UK

1.27. International Professional Association of Iberian Pig, hams, Spain/Portugal

1.28. ConAgra, pallets and cases, US

1.29. Bell AG, tracking meat, Germany

1.30. Port of Tacoma/Seattle, intermodal containers, USA

1.31. Ministry of Agriculture fruit / vegetables item level Japan

1.32. Best Buy item level USA

1.33. National Computerisation Agency , beef item level Korea

2. Livestock

2.1. Klein Karoo Co-operative, ostrich tagging, South Africa

2.2. SPM Farm, automatic pig feeding, Thailand

2.3. Australian Sheep Industry and New South Wales DPI, sheep, Australia

2.4. Clyde AG Wingadee, cattle, Australia

2.5. State of Salta, cattle, Argentina

2.6. Smørfjord, reindeer, Norway

2.7. Thailand Government, pigs, cows, shrimp Thailand