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An RFID-based digital warehouse management system in the tobacco industry: a case study

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This paper proposes a digital warehouse management system (DWMS) in the tobacco industry based on radio frequency identification (RFID) technology. The DWMS helps warehouse managers to achieve better inventory control, as well as to improve the operation efficiency. In this system, a set of basic events and storage/retrieval rules are defined as event-condition-action (ECA) rules to improve the feasibility and flexibility of DWMS. By using RFID technology, the DWMS enables a plane warehouse to achieve visualised inventory management, automatic storage/retrieval assignment and high accuracy of inventory control as an automatic warehouse. A case in the tobacco industry is studied to illustrate the feasibility and rationality of the proposed system. Based on the ECA rules, a storage/retrieval methodology is proposed to improve the storage/retrieval operations. The results of this case study illustrate that RFID-DWMS can help a plane warehouse to improve operation efficiency, enhance the utilisation of warehouse capacity, increase inventory accuracy and reduce manpower and loading time significantly.

Keywords: radio frequency identification; digital warehouse management system; storage/retrieval assignment; event-condition-action; digital pallet; digital shelf

1. Introduction

Inventory management is a critical component of efficient supply chain management that, in turn, can be the fulcrum for success in a business. It is well-known that supply chain inventory management decisions depend on inventory data gathered from automated or manual control systems (Uçkun *et al.* 2008). Therefore, in the past, automatic warehouses have played an important role in inventory management, as they integrate multiple functions and possess advantages, such as a faster turnover speed, a low rate of product dilapidation, and the ability to store more products in a smaller area. However, few enterprises can afford automatic warehouses, mainly because they require a large investment and a high level of technological and management capabilities. In addition, they have to be designed for the long term.

Therefore, most of the enterprises in China still adopt the plane warehouse, which is defined as a normal warehouse without high racks or automatic equipment (e.g., robotic arms, automated guided vehicles). Traditionally, in such a plane warehouse, the products

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are randomly placed on the floor without pallets, and the operation performances mostly depend on the operator's memory and experiences, which results in more operation time and mistakes (Hausman *et al*. 1976). With the increasing types of products and more and more complex customer orders, the warehouse managers have been facing a dramatic challenge on changing the traditional mode of manual operation. In a plane warehouse, the significant questions faced by the managers may be concluded as follows:

- How to identify a storage/retrieval assignment strategy for fast moving products?
- How to help the operators to pick the products more rapidly and accurately once the assignment decisions have been made?
- How to improve the operational efficiency of the warehouse as customer orders become more complex?
- How to improve inventory visibility in the supply chain, so as to better synchronise material and information flows and reduce inventory discrepancies?

In order to address the above questions, we invest in the emerging and innovative wireless technology, namely, radio frequency identification (RFID). In this paper, we present an RFID-based digital warehouse management system (RFID-DWMS) to improve the warehouse operations. This system benefits from the advantages of RFID in data collection, such as wireless object identification, multi-object identification and more storage space. Especially, RFID allows objects to communicate information about themselves automatically without human intervention.

In the RFID-DWMS, we define a set of basic events and storage/retrieval rules using an event-condition-action (ECA) mechanism to improve the feasibility and flexibility of RFID-DWMS. Based on the ECA rules, a storage/retrieval assignment methodology is proposed in a case study to accelerate the turnover velocity of products. The contribution of this paper is that, by building on the intuition of the advantages of an automatic warehouse, we design an RFID-DWMS to improve the operations in a plane warehouse, by integrating RFID, computer and wireless communication technology. The proposed system enables a plane warehouse to achieve the functions of automatic storage/retrieval management, real-time inventory management, and accurate shelf management, which usually belong particularly to the automatic warehouse. Furthermore, the implementation of RFID-DWMS is more feasible with much lower investment than building an automatic warehouse.

The rest of this paper is organised as follows: in Section 2, the supportive literature and related studies are reviewed. The system architecture of RFID-DWMS is proposed in Section 3. Section 4 discusses the basic events in RFID-DWMS, and describes how they compose complex events. Section 5 describes a set of basic storage/retrieval rules and the application of ECA rules for storage/retrieval management. In Section 6, a case study is presented to show how RFID-DWMS is used in improving the warehouse operations and inventory control in a tobacco industry warehouse in China. We summarise the lessons learned from this case study in Section 7. Finally, we conclude with a summary of the main results and discussions of future research in Section 8.

2. Literature review

2.1 *Warehouse management*

The main warehousing operations consist of inventory storage, order product mixing, cross docking and customer service (Coyle *et al*. 2003). The most important of them is inventory management, including storage/retrieval management and inventory control. Ballard (1996) addressed that efficient utilisation of space and resources in a warehouse will result in higher accuracy and better customer service. Thus, a vast amount of literature focuses on the use of the warehouse management system (Cormier and Gunn 1992, Hokey and Sean 1994, Berg and Zijm 1999, Nynke *et al*. 2002, Chow *et al*. 2006, Li and Kuo 2008), especially on automatic warehouse management, which can be organised into the following two categories: optimal order-picking (Gibson and Sharp 1992, Koster *et al*. 1999, Petersen 2000, Ho and Tseng 2006, Chang *et al*. 2007), and modelling as a job shop scheduling problem (Vis 2006, Oliveira 2007, and references therein). Most of these studies depend on the assumption that the inventory record is accurate. However, this assumption does not actually hold. The traditional way of identifying and remedying for the inventory deviations is doing costly audits by manual checking.

In the past decade, a new technology, radio frequency identification (RFID), has become popular in the fields of business and industry, particularly in the logistics and supply chain management (SCM) domain. Thus, more and more managers take into account the adoption of RFID to balance the operating cost against the requirements on building an automatic warehouse and manual checking.

2.2 *RFID technology*

Academic research on RFID has proliferated significantly over the last few years. The recent academic literature review from 1995 to 2005 on RFID technology was worked by Ngai *et al*. (2008a). The authors organise it into four categories: technological issues, applications areas, policy and security issues, and other issues. Recently, more and more organisations have moved to RFID to improve the efficiency of material and information flows both within and between organisations. Alongside this industry interest, Atali *et al*. (2005) investigated the value of RFID under imperfect inventory information. Delen *et al*. (2007) conducted a case study using actual RFID data collected by a major retailer from the goods shipped by one of its major suppliers. The authors discuss how supply chain partners find information about themselves valuable to each other, and argue that RFID can help to eliminate the delay in information sharing. Similarly, Parlikad and McFarlane (2007), and Zhou (2008) also discuss how RFID-based product identification technologies can be employed to improve information visibility. Thiesse and Fleisch (2008) were concerned with the impact of RFID on the value of location information to lot scheduling in complex manufacturing processes. For more research on the information technology and system, we refer the interested reader to the literature review by Gunasekaran *et al*. (2006). In this paper, we not only focus on improving information visibility, but also on increasing the inventory accuracy.

To illustrate the impact of RFID technology on reducing inventory discrepancies, most researchers take into account three main sources of inventory incorrectness: shrinkage, misplacement of products and transaction errors in their work and indicate that the inventory discrepancies can be detected in time and reduced efficiently (Heese 2007, Kok *et al*. 2008, Rekik *et al*. 2008, 2009). Uçkun *et al*. (2008) model as a single-period newsvendor-type problem to conclude that if the market is characterised by highly uncertain demand, making an investment in the RFID technology to decrease inventory inaccuracy may not be reasonable. Most of these studies are based on the assumption that the accuracy of RFID is 100%. However, from our case study, we illustrate that this assumption does not hold in practice.

Most of the existing literature on RFID discusses the value of RFID through case studies. A part of these case studies focuses on the application of RFID in tracking and tracing (Ni *et al.* 2004, Goodrum *et al.* 2006, Chen *et al.* 2007, Ngai *et al.* 2007a, 2007b, Fisher and Monahan 2008 and Martínez-Sala *et al.* 2009). To research the impact of RFID on the service industry, Ngai *et al.* (2008b) design an RFID-based management system to improve a sushi restaurant's quality of service. Lee *et al.* (2008) implement a customer-facing diffusion model in the service sector to improve the organisational performance. From five case studies, Tzeng *et al.* (2008) point out the business value of RFID to encourage more organisations to implement it. Our research focus is different, with an emphasis on the impact of RFID on improving warehouse operations, as well as inventory management.

There is vast literature on the use of RFID to better manage inventory and improve the operations in a supply chain. Kärkkäinen (2003) apply RFID tagging at the transport-unit level (i.e., recyclable transport containers), and combine item-level barcode to improve the information visibility and increase efficiency in the supply chain for short shelf life goods. By applying RFID at the item level, Lee *et al.* (2004) focus on analysing the effects of inventory accuracy, shelf replenishment policy and inventory visibility. Gaukler (2004) analysed the benefits, roll-out strategies and cost sharing agreements for item-level RFID implementation in a retail supply chain. Doerr *et al.* (2006) analysed the costs and benefits of RFID technology for the management of ordnance inventory. They used the factorial structure for the non-cost related benefits of the implementation and the traditional ROI (return on investment) analysis to assess the value of implementing RFID. Gaukler *et al.* (2007) show how the cost of item-level RFID should be allocated among supply chain partners such that supply chain profit is optimised.

Moon and Ngai (2008) study the views of fashion retailers on RFID applications and analyse the added value to be gained by adopting RFID. Wang *et al.* (2008) show that the RFID-enabled pull-based supply chain can be effectively achieved with 6.19% decrease in the total inventory cost, and 7.60% increase in the inventory turnover rate. Szmerekovsky and Zhang (2008) study the affect of attaching RFID tags at the item level on manufacturers and retailers in a vendor managed inventory (VMI) system, and conclude that RFID is a revenue generating technology as opposed to a cost saving technology, by comparing the case of an RFID enabled and a non-RFID enabled VMI system. Considering the capital investment, we adopt the way from Kärkkäinen (2003) by tagging RFID at the transport-unit level instead of the item-level.

The work of Chow *et al.* (2006) is the one closest in spirit to our research. They present a design of an RFID-based resource management system (RFID-RMS) for use in a warehouse operations environment. The goal of the system is to formulate a resource usage package to enhance the effectiveness of resource operations by integrating RFID, case-based reasoning (CBR) technologies, and the programming model for forklift route optimisation. The results of applying RFID-RMS to the GENCO Distribution System illustrate that the utilisation of warehouse resources is maximised while work efficiency is greatly enhanced. The authors extend their work in Choy *et al.* (2009), and Poon *et al.* (2009).

However, with an emphasis on building a digital warehouse with multiple functions as an automatic warehouse, our study is quite different from Chow's work. First, in order to enhance the warehouse capacity, we consider the situation of adopting the drive-in racks (also called passage racks) to store the products. The character of drive-in racks, last-in-first-out (LIFO) goods rotation, is incompatible with our objective, first-in-first-out (FIFO) rule. Hence, we propose a methodology to apply the FIFO rule in the drive-in racks situation in the case study. Second, instead of order-picking operations, we palletise boxes of same products onto a pallet embedded with an RFID tag. Thus, the products are transported in the form of pallet units. In addition, how to improve the visibility of inventory information in the whole supply chain by the introduced RFID technology is also the concern in our paper.

3. RFID-based digital warehouse management system

The system architecture of RFID-DWMS consists of three modules as illustrated in Figure 1. The first module is the Digital Warehouse Management System (DWMS), which is the core component of RFID-DWMS. This module is designed to provide a platform for inventory visualised management as well as to improve the storage/retrieval operations. Similar to the automated guided vehicle (AGV) system, we design a

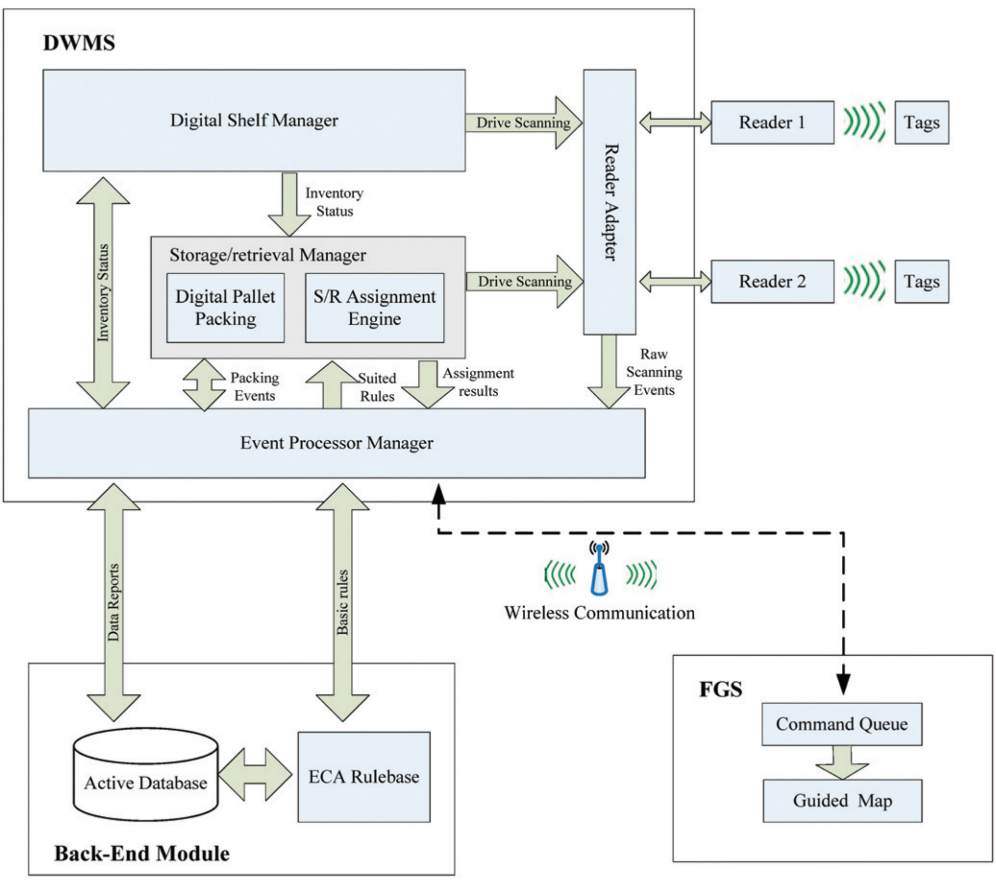

Figure 1. System architecture of RFID-DWMS.

Forklift Guided System (FGS), as the second module, to guide the forklift drivers to the exact location to perform the relevant operations. Then, the FGS will feed back the performance results to DWMS by wireless communication. The Back-End Module, as the last one, is composed of an active database and an ECA rulebase. The module's primary function is to recognise specific situations and react to them by storing or providing the required data and rules.

The design of a framework with the three modules is based on the following three considerations. First, since the forklift must move around in the warehouse, the forklift guided subsystem must be separated from the DWMS, and communicate with it via a wireless network. Second, in order to facilitate the development and management of the system, the main functions of warehouse management are designed in the DWMS module, so as to simplify the information sharing between different functions. Finally, considering the need to run a background thread for the active database to monitor events, the design of a separated back-end server can effectively reduce consumption of system resources. In addition, it is convenient for database management and maintenance.

3.1 *DWMS*

The DWMS, as illustrated in Figure 1, is composed of four core components: Digital Shelf Manager, Reader Adapter, Storage/retrieval (S/R) Manager, and Event Processor Manager.

3.1.1 *Digital Shelf Manager*

As the core component of DWMS, the Digital Shelf Manager is designed to monitor the inventory events in the warehouse and provide a platform for operators to manage the inventory visually. Before we describe how it works, we would like to give the following definitions.

Definition 1: digital pallet We define the pallet embedded with an RFID tag as a digital pallet, which records all the information of the products on it, such as amount, specification, production date, etc. The status of a digital pallet may be full, half or empty, as shown in Figure 2.

Definition 2: digital shelf A digital shelf is a storage space identified by a predefined ID number, namely, shelf ID (SID), which is bound to the tag ID (TID) of the digital pallet

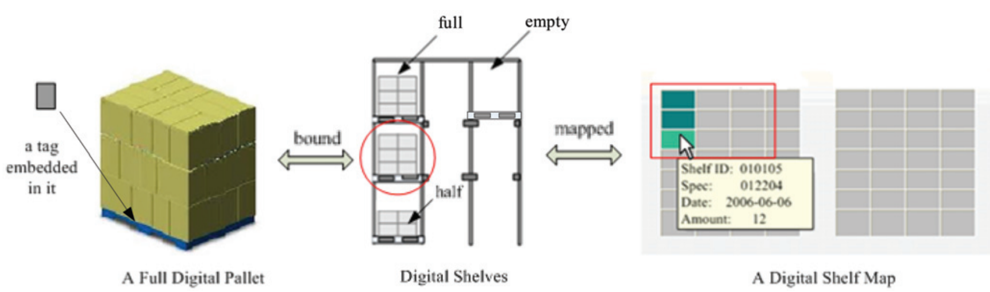

Figure 2. The illustration of a digital pallet, digital shelf, and digital shelf map.

placed on it. Similar to a digital pallet, the status of a digital shelf could be full, half or empty, see Figure 2.

Definition 3: digital shelf map We can picture a digital shelf as a piece of a square figure on a map on the computer screen, and regard the information of corresponding products as the attributes of the figure, which can also be denoted on the map, then we call this map a digital shelf map, see Figure 2.

Compared with the traditional pallet, a digital pallet has many advantages. It can be identified by its own unique ID of the tag. Thus, all the digital pallets will be easily identified, monitored and tracked when they are transported in the supply chain, while the normal pallets are often mixed and transported by mistake. On the other hand, a digital pallet can be operated as a basic unit and the detailed information of the relevant products can be easily obtained in milliseconds with an RFID reader.

By defining a digital shelf map, the real-time inventory information is clear when observing the map. Furthermore, the Digital Shelf Manager provides a query interface for managers to focus on the special inventory information on variant customised query conditions. If a query event occurs, the digital shelf map will trigger the Event Processor Manager to notify the active database to provide the query results, which satisfy the query conditions. As soon as the results are returned to Digital Shelf Manager, the locations of them will be shown on the digital shelf map, and marked with different colours. In addition, the Digital Shelf Manager provides a shelf adjustment platform for the requirements of adjusting the locations of digital pallets. Then, the adjusted pallet tag ID will be scanned and rebound to the new SID by this component. As a result, the Digital Shelf Manager realises a visualised management in the traditional plane warehouse without depending on human beings' memory. Therefore, the inventory mistakes made by human beings can be reduced efficiently.

3.1.2 *Reader Adapter*

Since there are many kinds of RFID readers which have been used in various environments, a reader adapter is significant to enhance the flexibility of our DWMS. It performs as a bridge of the relationship between DWMS and physical RFID readers. In fact, the adapter specifies a virtualised API, which contains a set of interfaces to support common RFID reader functionality. Hence, the new adopted reader can be registered by installing its driver in the adapter, and build a connection to DWMS. Then, the raw scanning events created by readers are gathered by the adapter, and transported to the Event Processor Manager for advanced procession.

One may argue that the set of functions specified in the adapter are impossible to support any kind of RFID readers. Indeed, this is a limitation. We try to select a set of the most general functions from as many kinds of readers as we have met, in order to minimise the effort required for adapting to a new reader platform to our system. A more flexible adapter for all kinds of RFID readers will be one of our future researches.

3.1.3 *Storage/retrieval Manager*

In our DWMS, the Storage/retrieval (S/R) Manager is designed to improve the traditional warehouse operation procedure as well as to improve the storage/retrieval assignment.

The S/R Manager consists of two core components, namely, Digital Pallet Packing and S/R Assignment Engine.

Before the storage operation begins, the Digital Pallet Packing component will help the operators to gather the barcodes of the palletising products and write these barcodes into the corresponding pallet tags with an RFID reader. Furthermore, when parts of products have to be dispersed and depart from a digital pallet, the information recorded in the pallet tag is also updated by this component. After completing a digital pallet packing, a packing event is generated and triggers the Event Processor Manager to store the bound information (TID and products data) in the database for further usage.

The S/R Assignment Engine is designed to improve S/R assignments. Since the assignment decision depends on different racks and customised requirements, the S/R Assignment Engine actions are based on a set of basic storage/retrieval rules, which are predefined and stored in the ECA rulebase. The suited rules will be retrieved and transported by the Event Processor Manager when requirements have been specified. After the assignment decision has been made, S/R Assignment Engine will lock the assigned digital shelves, and generate relevant commands for dispatching to FGS. The assignment results trigger the Event Processor Manager to update the status of these corresponding digital shelves in the database.

3.1.4 *Event Processor Manager*

The Event Processor Manager (EPM) is a key component in our DWMS, which enables the DWMS to observe and detect the generated events and take corresponding processions in real time. As mentioned above, massive raw events are generated by various performances and transported to the EPM. The raw events can be divided into two types: basic event and high-level event (HLE). Generally, the basic events are generated by the hardware devices (e.g., readers), while the HLEs are generated by the high-level applications. In the construct of the Event Processor Manager, the input events are accepted in the events buffer, and then move through a series of components with specified functions including decomposing, grouping, filtering, and complex event processing (CEP) construction, as shown in Figure 3.

The structure of EPM is quite similar to that in Dong *et al.* (2006). However, an additional component, namely decomposer, is designed in our EPM. The raw events

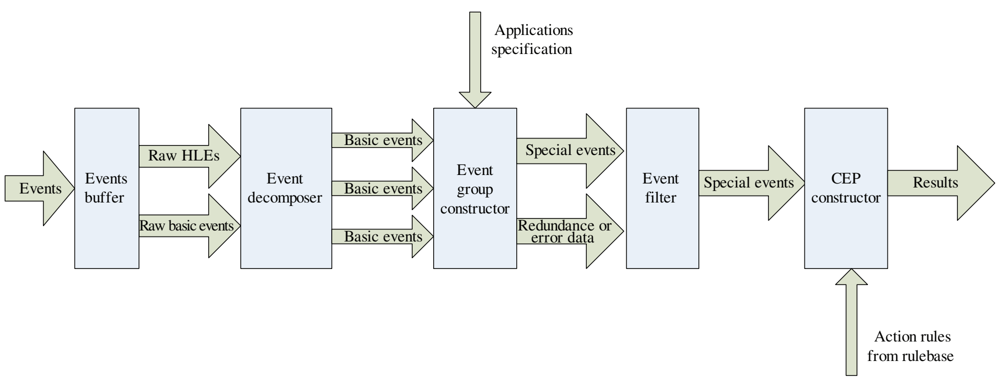

Figure 3. Event Processor Manager structure.

will be decomposed into basic events (defined in Section 4) by the decomposer when they enter into the EPM. Then all the basic events are grouped for special processing (e.g., assignment or information updating) when passing by the event group constructor. Sequentially, with the action of filter, the redundant events and error data are removed from the special event flow. Finally, with the action of the CEP constructor, the processing results are returned to the corresponding applications.

For example, if a packing event is generated by the S/R Manager component, the event is decomposed into two types of basic events: RFID scan events and barcode scan events, where the RFID scan event contains the tag ID data and the barcode scan event contains the barcode data. With the application specification (i.e., pallet packing), the RFID scan events and barcode scan events will be gathered from the basic events flow and grouped in a set of special events. However, there must be much invalid data (e.g., rereading data or misreading data) in these special events. Hence, the event filter has to remove this invalid data and only output the valid data to the CEP constructor. According to the compress rule from the rulebase, the CEP constructor compresses this valid barcode data into a new data format (specified in Section 6.5) and returns it to the Digital Pallet Packing component for writing into the RFID tag.

3.2 *FGS*

The Forklift Guided System (FGS) is developed as a separate subsystem installed in a touch screen computer fixed on the forklift. This is one of the main differences between our system and the other existing systems. To the best of our knowledge, most of the existing systems proposed in the literature are developed as a centralised system installed in a fixed computer, instead of on a moving object (e.g., forklift). The system developed in Chow *et al*. (2006) must be the one most similar to our FGS. However, their forklift system only provides the order of picking sequence without any guided map. In our FGS, based on the development of a digital shelf map, we provide a guided map to enhance the operation accuracy of the drivers. With the help of a guided map, FGS plays the role of an automated guided vehicle (AGV) system to execute the commands dispatched by the S/R Manager in DWMS.

As shown in Figure 1, the FGS contains two components. A command queue component is designed to cache the series of received commands, and sort them in descending priorities order. The other component, guided map, is designed to guide the forklift driver to the operation location according to the command being executed.

When a command from the command queue is executed, the command queue component will trigger the guided map to show the drivers a digital shelf map, on which the corresponding locations have been marked with different colours. With the help of the guided map, forklift drivers can find out the locations immediately. When the forklift passes by the readers with a digital pallet, the tag data will be collected automatically. After transporting, FGS will feed back the execution results to DWMS. Then, DWMS will bind the tag data to the corresponding digital shelf, and update the inventory information and command state in real time.

For the sake of the safety of the forklift operation, a forklift transports digital pallets one at a time. It means that a forklift could only execute a new command from the command queue after it has finished the pre-transportation and is available again. In addition, in order to avoid a command being executed by two forklifts at the same time,

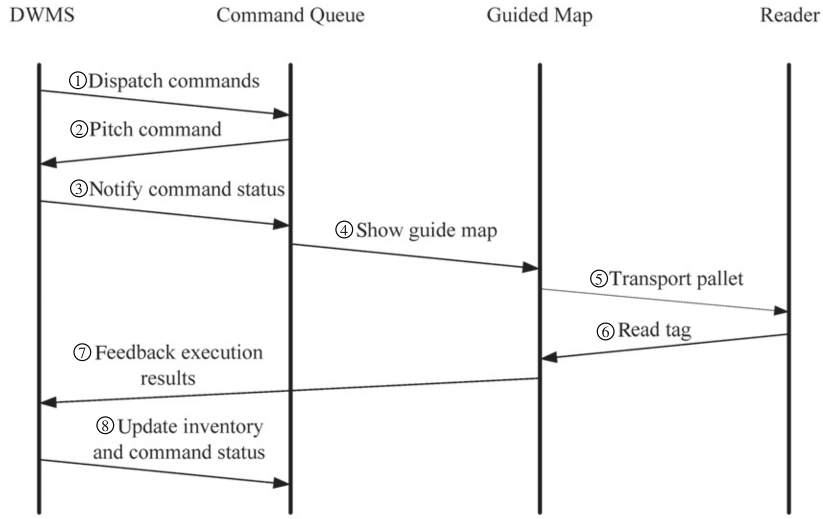

Figure 4. Sequence diagram for a transaction process of FGS.

after a forklift chooses a command, FGS will communicate with DWMS that the command has been chosen. Then the corresponding command state will be updated and notified to all of the forklifts in real time. The transaction series mentioned previously can be described in a sequence diagram that is shown in Figure 4.

3.3 *Back-End Module*

The back end of the DWMS consists of an active database and an ECA rulebase. The active database can recognise specific situations and react to them without direct explicit user intervention or applications requests. Therefore, it can enable a system to have reactive processing and autonomous response to an event that occurs inside or outside the system (Tan and Goh 1999b). The ECA rulebase contains all the basic rules in ECA forms. As a trigger mechanism, ECA rules are well established in the active database. The main advantage of ECA rules is that they can be specified dynamically and independently of application programs. Therefore, the users can easily add, modify, and delete rules in the rulebase to adjust to different application requests. This will, in turn, greatly enhance the system's flexibility.

An ECA rule has the general form as:

On event **If** condition **Do** actions

The event part specifies when the rule will be triggered, the condition part is a query which determines if the database is in a particular state, and the action part states the actions to be performed automatically (Poulovassilis *et al.* 2006). Hence, the ECA rules can be recognised by the active database, and then the relevant reaction will be triggered automatically without application intervention. Whenever an event occurs, the corresponding rules will be retrieved from the ECA rulebase and send to EPM in DWMS for evaluation and reaction. For more details on the foundations of ECA rules in active databases, interested readers could refer to Widom and Ceri (1995), and Tan and Goh (1999a, 1999b).

4. Events in RFID-DWMS

According to the description in the above section, the practice of storage/retrieval assignment is based on a set of basic ECA rules, which are triggered by a series of events. To be useful in a wide spectrum of applications an ECA rule has to satisfy the properties that events can be complex ones, resulting from several basic ones relying on special algebra (Alferes *et al*. 2006). In this section, we will give our classification and definitions of the basic events used in our DWMS, and illustrate how they compose complex ones using logical operators and trigger the other ones to occur.

Following Nagargadde *et al*. (2005), and Dutta *et al*. (2007), an event can be formalised as a tuple <L, S, T>. L is the label dimension to categorise them, containing details of the events that occur. S is the location dimension to denote where the event occurs, and T is the time dimension at which the event occurs. The granularity of the location dimension depends on the user's requirements. For example, from the perspective of a warehouse manager, the location can be an area in the warehouse such as the entrance, or a digital shelf location which can be expressed by the shelf ID. On the other hand, from the perspective of a supply chain, the location may be a node of the supply chain, such as a supplier, distributor or retailer. Similarly, the time dimension can be a time point defined in hours or days, or a time-interval. Take the formalisation of events for example, considering a database event that 'the production date of the cigarettes on digital shelf A is 22 August 2008' can be expressed as:

E1 = < L = Shelf_Status,
    L.Shelf_ID = 'A'
    L.Shelf_Date = '2008-08-22',
    L.Shelf_Type = 'cigarettes',
  S = 'Active Database'
  T = t1 >

Where t1 is the time at which E1 is detected and reported by Active Database.

As discussed in Section 3.1, we classify the generated events into two types: basic events and high-level events. A basic event is an event that can be monitored directly by readers, clock monitor, active database or other sensors, and cannot be decomposed any more. Contrarily, a high-level event (HLE) is a combination of multiple basic events or multiple HLEs, which cannot be monitored directly but can be decomposed to basic events. According to the analysis of the EPM, the basic event is the processing unit in the processor. Hence, in order to facilitate the complex event processing in EPM, it is necessary to propose the classification of the events in our system, in particular, the basic events.

Different from the classification in Dutta *et al*. (2007), we provide a more detailed classification in our DWMS, where a basic event can be generated in the following six ways, instead of four ways:

- **RFID scan:** it is generated by the RFID readers when they communicate with an RFID tagged object, such as a digital pallet. It contains information about the actual RFID data as well as reader-related information (e.g., event timestamps, reader name). Two typical RFID scan events are called RFID_Read and RFID_Write, which occur respectively when the readers read the recorded data from the tag or write data into the tag successfully.
- **Barcode scan:** the barcode scan events are similar to the RFID scan events while it can only be the reading events generated by the barcode scanner.

- **Clock:** clock events are raised at some point in time when the active database is monitoring a specified clock time event (Tan and Goh 1999a). The clock time may be absolute (e.g., 22 August at 17:00 PM), relative (e.g., the next day before operation), or periodic (e.g., every day at 23:59 PM).
- **Database:** a database event is mostly raised by the applications (Tan and Goh 1999a). Whenever an application requires the attention of special information, it will trigger the active database to present the event reports. In DWMS, the typical database events are the inventory information reports, such as the above example E1.
- **Update:** the update events are mostly generated by the program internal in response to the results of former events. For example, consider the transaction in FGS, when a command has been executed, it will trigger an update event to notify the DWMS to change the command state and broadcast to all of the FGS.
- **Confirm:** a confirm event occurs when an operation result requires a confirmation from the user to cause the subsequent events (e.g., update events). The confirm event occurs frequently in our DWMS. For example, when a transportation of a digital pallet has been finished, it requires the FGS to feed back a confirmation to DWMS to trigger the Command_Update events.

According to the above definitions of the basic events, they almost cover all types of the smallest event units in an RFID system. Therefore, with the adoption of the following operators, the classification of events can be flexible to adapt to different applications.

We borrow the expression of operators as proposed in Dutta *et al.* (2007), and Tan and Goh (1999b) to link the events, and combine them into HLEs. The operators can be one of the following set:

- **AND (∧):** conjunction of two events E1 and E2, which occurs when both E1 and E2 occur (the occurrence order could be ignored), can be denoted as $E1 \wedge E2$.
- **OR (∨):** disjunction of two events E1 and E2, denoted as $E1 \vee E2$, occurs when either E1 or E2 occurs.
- **SEQUENCE (→):** sequence of two events E1 and E2, denoted as $E1 \rightarrow E2$, occurs when E1 occurs first followed by E2.
- **PERIOD (P):** an event E which occurs periodically with specified frequency within a specified time interval I can be denoted as P (E, I).
- **NOT (!):** contrarily, if event E does not occur within a specified time interval I, it can be denoted as! (E, I).
- **Closure (C):** a closure event occurs whenever an event E occurs at least once during a specific time interval I, denoted as C (E, I).

With the help of these operators, a high-level event (HLE), attaches more importance by applications, can be expressed by multiple basic events linked by specified operators. As for example:

E1= < L = Shelf_Status,
  L.Shelf_ID = 'A',
  L.Shelf_Date = '2008-08-22',
  L.Shelf_Type = 'cigarettes',
 S = 'Active Database',
 T = t1 >

E2 = < L = Shelf_Status,
L.Shelf_ID = 'B',
L.Shelf_Date = '2008-06-14',
L.Shelf_Type = 'cigarettes',
S = 'Active Database',
T = t2 >
E3 = < L = Shelf_Status,
L.Shelf_Type = 'cigarettes',
L.Shelf_Rule = 'FIFO',
L.Shelf_B.Priority > L.Shelf_A.Priority
S = 'Active Database',
T = t3 >
= E1∧E2.

Where, E1 and E2 are basic database events, and E3 is an HLE composed of E1 and E2. The t1, t2 and t3 are the respective times when they occur. By this approach of combination, a more complex event can be composed of multiple HLEs, termed as the event part of ECA to trigger the corresponding reactions. As to the examples of combinations using the other operators, one can refer to Tan and Goh (1999b).

5. Storage/retrieval rules

To maintain competitive advantage and meet customer demands in today's challenging environment, more and more organisations focus on the storage/retrieval assignment for the benefits of reduced picking travel time, less congestion and enhanced space utilisation (Mansuri 1997, Tang and Chew 1997, Chew and Tang 1999, Dial 2006, Muppani and Adil 2008, Roodbergen and Vis 2009). However, most of the research in the literature focused on solving the specific problems with an invariable environment (e.g., specific racks or specific goods). When the environment has been changed, their algorithms and methods will not adapt.

Considering the limitation of existing systems, we define a set of basic rules for storage/retrieval assignment, in order to improve the flexibility and adaptability of our DWMS. In our system, the practice of storage/retrieval assignment is based on a set of basic ECA rules, which are triggered to evaluate conditions and perform relevant actions automatically. For different requirements in practice, the storage/retrieval assignment rules must be accordingly various. In order to achieve that, we conclude 10 of the most common rules used in practice, and illustrate that, with combinations of different ones, our system can flexibly adapt to different requirements.

Rule 1: random. Means that any available digital shelf is equally likely to be an assignment. This rule is mostly used in the traditional warehouse by manual operation, for the reason of easy-to-perform.

Rule 2: closest. It is widely used in various warehouses, especially in an automatic warehouse with high racks. The assignment strategy follows the principle that an available digital shelf, which is closer to an I/O point, has the higher priority to be assigned, regardless of its velocity of turnover.

Rule 3: velocity. It is quite similar to the 'closest' rule except that it takes into account the velocity of turnover. The shelf closer to an I/O point will be available for higher velocity of turnover.

Rule 4: weight. For safety reasons related to the fixedness of racks, the heavier goods should be placed on the lower digital shelf on the racks. It is an important rule of the assignment for high racks.

Rule 5: comparability. It means that similar products should be placed separately to avoid mistakes.

Rule 6: identity. This rule denotes that the same products should be placed together for convenient to manage inventory.

Rule 7: balance. Distribute velocity across zones as evenly as possible for reduction of congestion.

Rule 8: shape. An item with a special shape should be placed in a special space to enhance the space utilisation.

Rule 9: first-in-first-out (FIFO). The rule means that when there are more than two units, the first unit making its way into inventory will be assigned first for delivery. It is a significant rule for management of items with short lift cycle time.

Rule 10: last-in-first-out (LIFO). Contrary to FIFO, it means that the first unit into inventory will be delivered last.

In the above set of rules, the last two rules (i.e., Rule 9 and Rule 10) are usually used when a delivery assignment event is triggered, while the former eight rules are usually used when a storage assignment event is triggered. Using these basic rules or combination of some rules, the DWMS can provide an extensible set of storage/retrieval strategies to help managers to achieve a specific assignment goal. An example of using the ECA mechanism for storage assignment with the above rules is shown in Figure 5. Assume that there is an item required to be placed on the rack, which contains four digital shelves, denoted as A1, A2, A3 and A4. Assume that shelves A2 and A3 are closer to an I/O point than A1 and A4. When a Storage_Confirm event has been generated, it will trigger the database to retrieve the relevant rules from the rulebase. Based on the Random rule, the database verifies the condition that 'Shelf_State = "empty" for the four shelves, then generates three new events (Event 6, Event 7 and Event 8) as shown in Figure 5. Combining Random rule with Closest rule, the database generates new events subsequently by verifying the corresponding condition. In this way, the results of the storage assignment using the rules, composed by Random, Closest, Identity and Balance, are reported by the database as follows: the item will be placed on shelf A2 if shelf A1 placed the same item, or else, placed on shelf A3.

From the analysis of the above example, it is clear that the combination of different rules enables the system to provide the different assignment results, so as to satisfy the different users' preferences. In other words, the result depends on the rule's priority specified by the users before assignment. If the Balance rule takes priority over the Identity rule according to the specification, the above example results in shelf A3. Otherwise, it results in shelf A2 or A3, according to the products placed on shelf A1.

It is clear that the above set of rules can be flexible to different requirements of different products and users. However, one may argue that if the layout of shelves has been

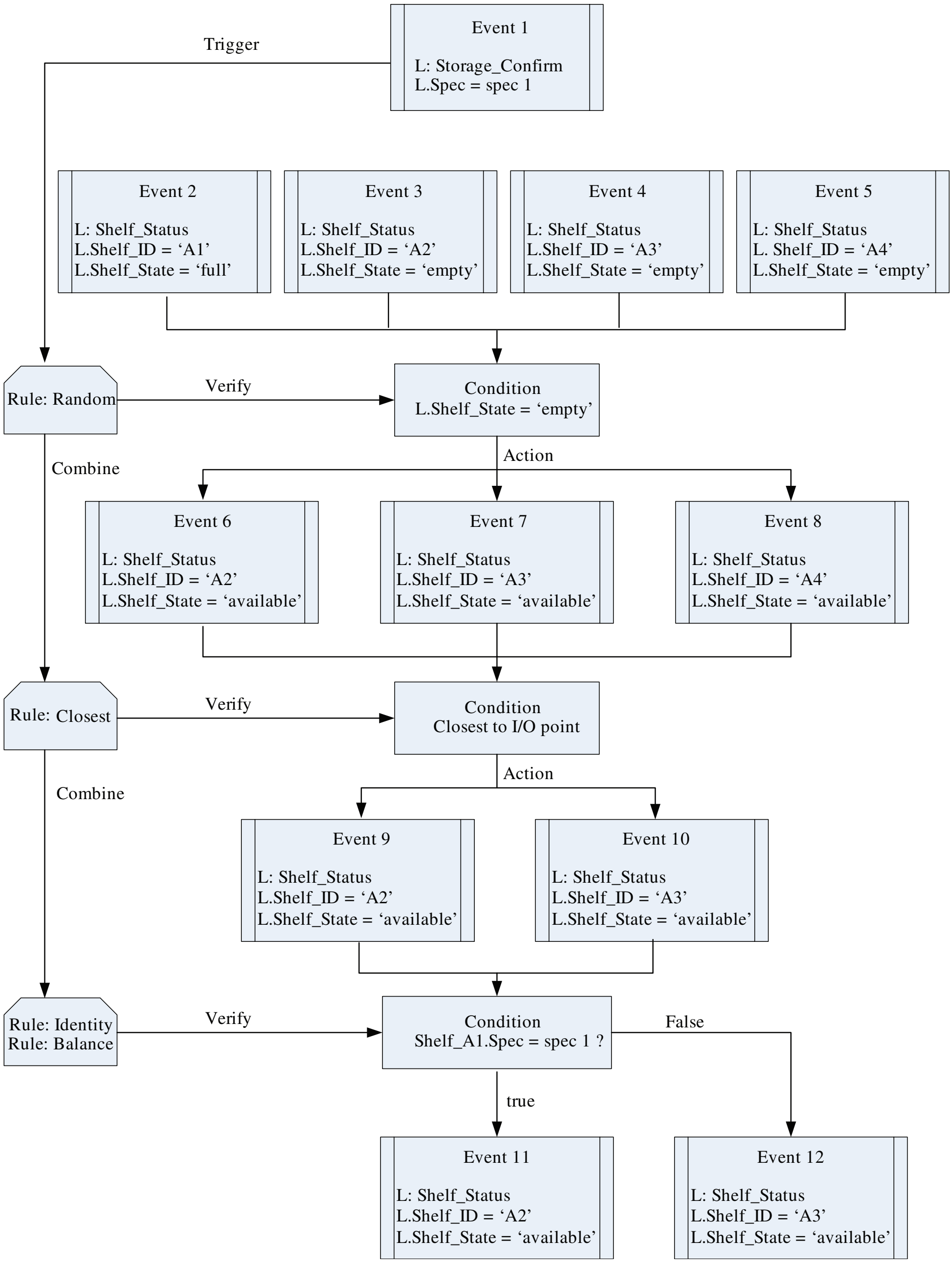

Figure 5. An example of events procession using ECA rules.

changed, the above rules may not adapt to the new racks any more. This problem can be solved by a few modifications of the corresponding rules. As discussed in Section 3.3, with the help of ECA implementation, the modifications can be easily accomplished by modifying the condition part of the ECA rules dynamically. Therefore, a flexible and adaptable storage/retrieval assignment is achieved.

6. Case study

Wuhan Tobacco Corporation (WTC) is the third biggest tobacco corporation in China. It has more than 100 warehouses with thousands of different products in different areas. To examine the proposed RFID-DWMS, we implemented this system in a distribution centre warehouse of WTC. We used a six-stage structural development method to describe this research design: warehouse process analysis, requirement analysis, warehouse layout design, system design, system implementation, and results and discussion. We describe each stage below.

6.1 *Warehouse process analysis*

In China, to control tobacco production, the Chinese government requires that all tobacco products on sale should be affixed with a barcode and that the combined barcode information should be sent to a government database. Therefore, in this warehouse, all incoming products are in the form of boxes with a pasted barcode to identify them uniquely. Before the products leave the warehouse, the operators scan them one by one to collect the barcode data for keeping records. However, the original barcode scanning system is a simple system without any management functions. The management is mostly performed by manual operations and the products are placed on the floor without any racks.

In a typical flow of a warehouse operation, when new products are received, an operator makes a storage assignment decision depending on his memory and experience, and four carriers carry them to the appointed place. When a delivering task arrives, an operator makes a retrieval assignment decision depending on his memory and experience. Then, four carriers carry these products to the delivering space. At the exit, two operators take charge of scanning the corresponding barcode one by one when the products pass through the door. Since there maybe some mistakes happening when scanning, there also is a need for one person to stay at the front of the computer, so as to monitor the results and make sure that the obtained barcode information is correct. Every day, after all operations are finished, the operators should make an inventory of the products in the warehouse by manual checking. After our process analysis, we identified some of the core business processes that could be improved, in particular, the storage process, delivering process, scanning barcode process, and inventory management process. We describe how to improve the efficiency of these processes in the requirement analysis stage.

6.2 *Requirements analysis*

Having had discussions with the warehouse managers and operators concerned, we analysed and summarised their key functional requirements for an RFID-DWMS system, as shown in Table 1.

After analysis of their requirements, an RFID-DWMS system was proposed. In order to enhance the utilisation of the space in the warehouse, we used the drive-in racks and selective racks to store the products. The drive-in rack is not divided by passages but unitary, so that it is very suitable for large quantities of the same product in a distribution centre warehouse. In order to improve the operation procedures, the products are transported in pallet units. The RFID tags are tagged only on the pallet level rather than product level, for the reason that it is the most beneficial mode of RFID adoption in industry (Bottani and Rizzi 2008). We proposed a digital shelf map to provide a visual

Table 1. Requirements for RFID-DWMS.

Stakeholders	Requirements for RFID-DWMS
Warehouse manager	• Using racks to increase warehouse capacity • Using RFID tag to store the barcode information and improve operation procedure • To maintain operator records • Provide a visual view of the entire warehouse inventory information • Record the inventory in and out situations • Provide inventory reports
Warehouse operators	• Provide an automatic decision for storage/retrieval assignment • Provide a guide map for storage/retrieval operations • Provide a reminder and alert of the inaccurate operations

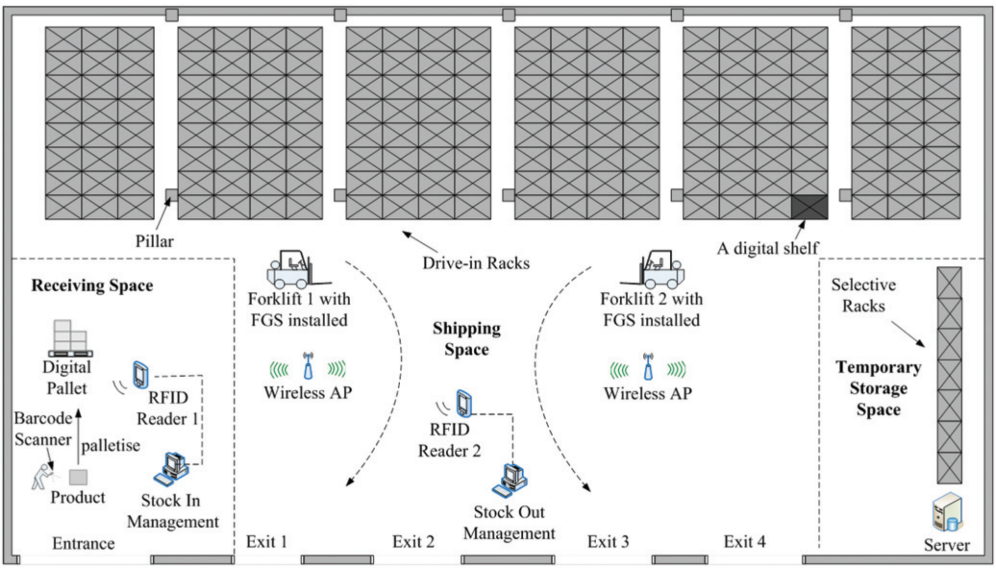

Figure 6. The warehouse layout.

view of the real time inventory information, as well as to provide a guide map for warehouse operators. Based on the design of drive-in racks, a storage/retrieval methodology was proposed in this system to improve the storage/retrieval operations. Since the inventory in and out information are recorded in the system, the real time inventory statistics can be printed accurately. In addition, the system provides a reminder and alert to the operators when inaccurate pallets are transported.

6.3 *Warehouse layout design*

Since there are no racks in the warehouse, a good design of racks is significant before implementing the RFID-DWMS. The layout of drive-in racks and the relevant equipment in the warehouse is shown in Figure 6, where the racks actually have two layers. The depth of the racks is designed to be the length of eight shelves, based on the capacity of trucks, which makes a truck capable of holding 16 shelves. As shown in Figure 6, in the temporary storage space, we use a selective rack containing 14 digital shelves to store a small part of special products which are required to be handled first.

Different from Chow *et al.* (2006), in order to avoid crashes when forklifts drive in the aisles of racks, we do not fix RFID readers on the forklifts but fix them in the receiving space and shipping space linked with a DWMS installed computer separately. The products required to be stored are palletised onto digital pallets in the receiving space, and the operations of data collection and tag writing are performed by a barcode scanner and RFID reader simultaneously. Similarly, the shipping space is designed for delivery operations. The information of the delivered products will be collected in real time by Reader 2 when forklifts pass by the scanner. Since the RFID scanner is not fixed on the forklift, we adopt the UHF RFID facilities to make sure that the transported pallets can be read at a certain distance. On the forklift, a touch screen computer installed FGS has been fixed, as shown in Figure 7. In addition, the database server is allocated in the temporary space, which consists of various specific databases like inventory information, human resources, storage/retrieval rules and RFID information.

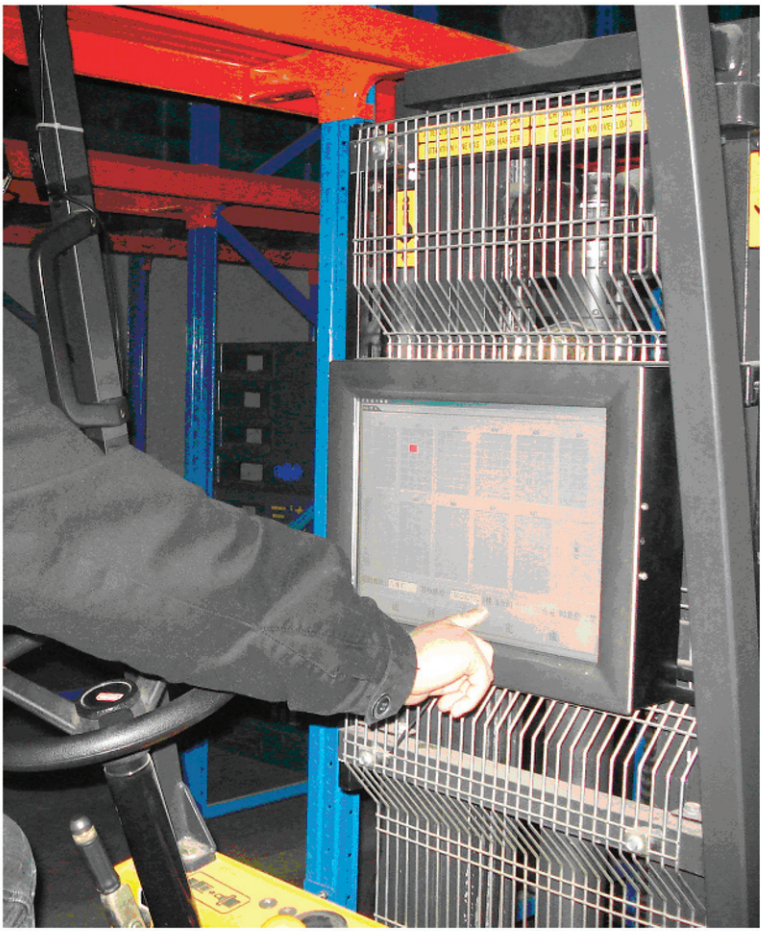

Figure 7. A touch screen computer fixed on forklift.

6.4 *System design*

According to the analysis of the requirements and the proposed RFID-DWMS architecture, we divide this system into six subsystems based on functionality, which are human resources subsystem, stock in subsystem, stock out subsystem, digital shelf management subsystem, forklift guided subsystem, rules management subsystem. Their functionalities and relationships are shown in Figure 8.

The functionalities of each subsystem are described below.

(1) Human resources management subsystem

This subsystem enables a warehouse manager to maintain the operator record information, including personal information, training arrangement, checking attendance and appraisal evaluation.

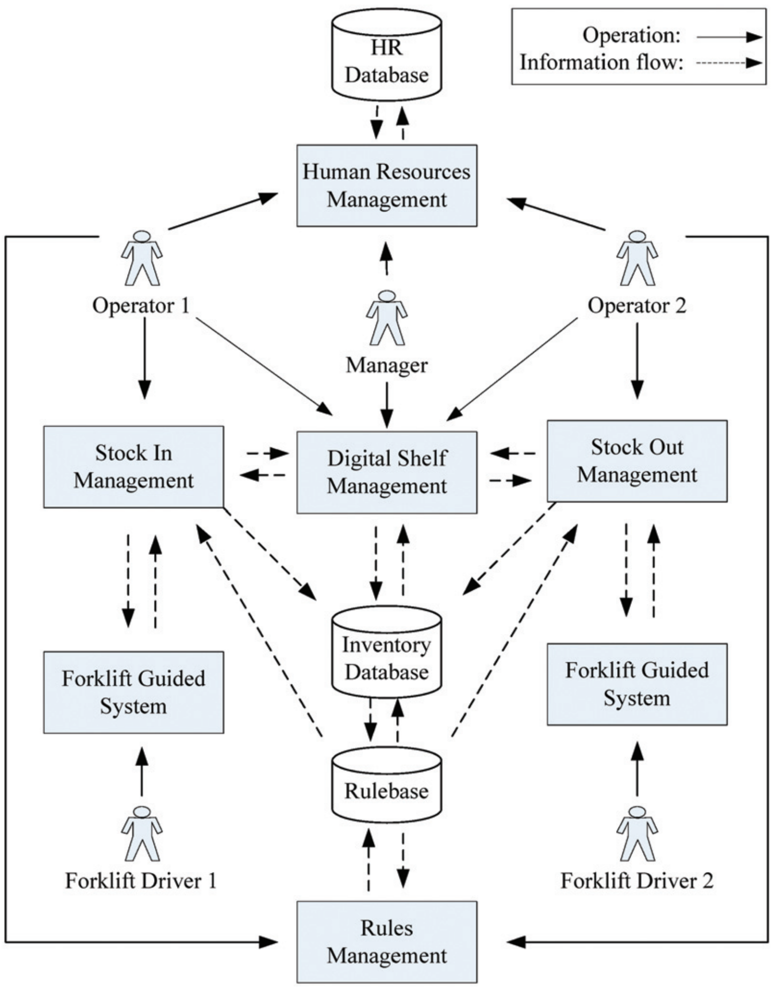

Figure 8. The functionality of subsystems in RFID-DWMS.

(2) Stock in subsystem

This subsystem has four main functions. First, based on the real time inventory information, it provides an automatic storage assignment function for the incoming products. The storage assignment decisions are made depending on the storage rules specified in the rulebase. Second, the operators can use this subsystem to generate the corresponding storage commands, and dispatch to the forklift guided subsystem for drivers to execute them. Third, since all the products should be palletised on the digital pallets before storing them on the shelves, this subsystem helps the operator to compress the corresponding barcodes into a new data format, and drives the reader to write it into the RFID tags (the detailed format will be discussed in the next subsection). Finally, after it receives the confirmation from FGS, the corresponding information (e.g., inventory information, commands status or shelves status) is updated by this subsystem.

(3) Stock out subsystem

Similar to the stock in subsystem, this subsystem is designed for stock out procedures. It provides an automatic retrieval assignment decision, helps to generate the retrieval commands, dispatches them to FGS and updates the information. When the RFID scanner detects the transported digital pallets, this subsystem also helps to decompress the barcodes from the RFID tags. In addition, if a wrong pallet has been transported, this subsystem can discover it by matching its tag ID with the relevant shelf ID. Then this subsystem will give an alert to warn the drivers.

(4) Digital shelf management subsystem

This subsystem provides a digital shelf map for the manager to have a visual view of the entire warehouse inventory information in real time. Furthermore, a real time precise inventory statistical report function is also provided in this subsystem. The report contains the beginning inventory data, store in and out quantities, corresponding specifications of products, operators' names, operation time and closing inventory data. In addition, this subsystem provides a shelf adjustment function to assist monitoring the racks situation. If there are only a few pallets in an aisle of drive-in racks and the selective rack has enough spare shelves, it provides a reminder and alert for adjusting the remaining pallets to the temporary storage space, so as to enhance the utilisation of drive-in racks. The corresponding shelf adjustment command can also be generated and dispatched in this subsystem.

(5) Forklift guided subsystem

As discussed in Section 3, this subsystem is installed in the touch screen computer fixed on the forklift, which assists executing the commands. All the commands dispatched by the other subsystems are stored in a command buffer, and ordered by their priorities according to the LIFO rule of drive-in racks. In addition, this subsystem provides a guide map to assist in executing the operation commands. An example of the guide map is shown in Figure 9, where the current batch of operational locations are marked in light grey colour, and the current executing

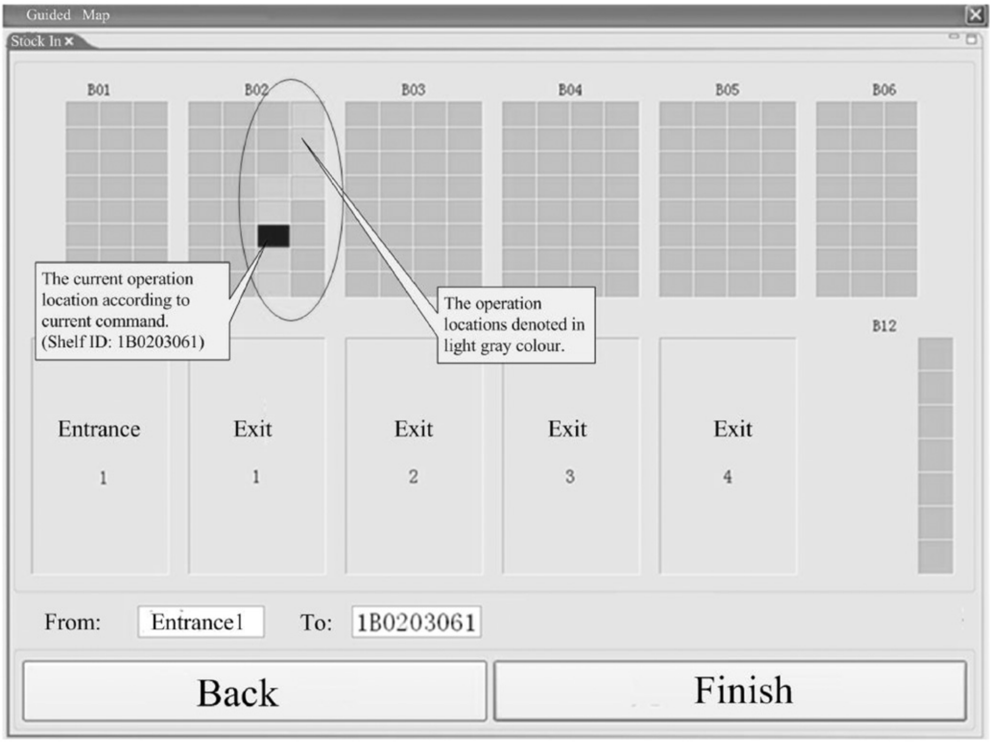

Figure 9. The guided map on forklift.

location is marked in dark black colour. From the guide map, the drivers can easily know the specific location of the destination, so that a misplacement possibility will be significantly decreased. Another important function of this subsystem is to communicate with other subsystems via a wireless network, including receiving commands, returning command status, updating inventory information.

(6) Rules management subsystem

This subsystem is designed to provide a rules maintenance platform for users to add, modify and delete rules in the rulebase, as well as to specify the priorities of rules for storage/retrieval assignments.

6.5 *System implementation*

According to our architectural and system design, the RFID-DWMS was developed and built on the Rich Client Platform (RCP), which is based on the familiar Eclipse plug-in architecture. It helps to build Java applications that can compete with native applications on any platform. Based on the wireless network technology, we use Transmission Control Protocol/Internet Protocol (TCP/IP) and Socket technology to realise the point-to-point communication between subsystems. In addition, the multithread technique is also developed in our system to solve the system resources conflicts between different applications.

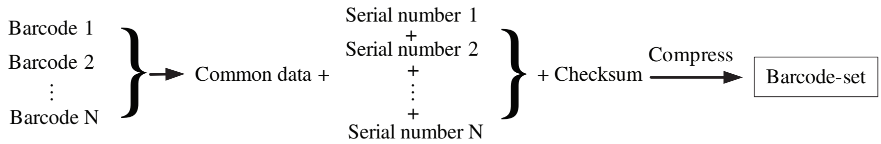

Figure 10. Compressing barcode data into a barcode-set.

However, there still exist three potential problems of implementing this system. They are how to compress the barcode data into a new data format, and what are the innovative procedures of storage and retrieval operations with the implementation of RFID technology? Now, we describe them below.

6.5.1 *Compressing barcodes*

In this case, the capacity of a digital pallet is 30 boxes. The barcode data of each box is a 32-digit number. The first 19-digit part of the number is common in a same batch of products, containing the information of company name, production area, date, and specification;. and the last 13-digit part of the number is a serial number to identify each box uniquely. In order to save the storage space of RFID tag and enhance the communication efficiency, the barcodes are compressed into a new data format (named barcode-set), as 'common data + serial number 1 + serial number 2 + ··· + serial number N + checksum', where N ($N \leq 30$) is noted the actual quantity of boxes palletised on the pallet, as shown in Figure 10. The checksum is a certain number of check bits generated by the cyclic redundancy check (CRC) method, which is a very powerful but easily implemented technique to obtain data reliability (Ansari *et al.* 2007). By determining whether or not the checksum agrees with the barcode data, the system can ascertain whether an error occurs in the communication. In the packing process, the palletising operation is used for physical combination of pallets and boxes, while writing the operation of the RFID reader is used to combine them on information aspect; and the link of TID and barcode-set will be the combination between barcodes and RFID.

6.5.2 *The innovative procedures of storage operations*

After implementing RFID-DWMS, the procedures of storage and retrieval operations are a great innovation in comparison with that of previous operations. This improvement mainly lies in that the barcode scanning operation is accomplished and recorded in the pallet tag before storing rather than loading. In the general case, the loading time is a significant part of the lead time, and the efficiency of loading products directly affects the length of lead time. Hence, the change of the barcode scanning procedure will reduce the lead time significantly. The improved storage operation procedure is shown in Figure 11, which consists of the following steps:

Step 1: When products arrive, operators input the information of warehouse voucher into the computer in the receiving space, including the specifications, quantities, date, etc.

Step 2: Make the storage assignment decision by DWMS automatically or by user empirically.

Step 3: Create the relevant operation commands and dispatch them to forklifts with DWMS.

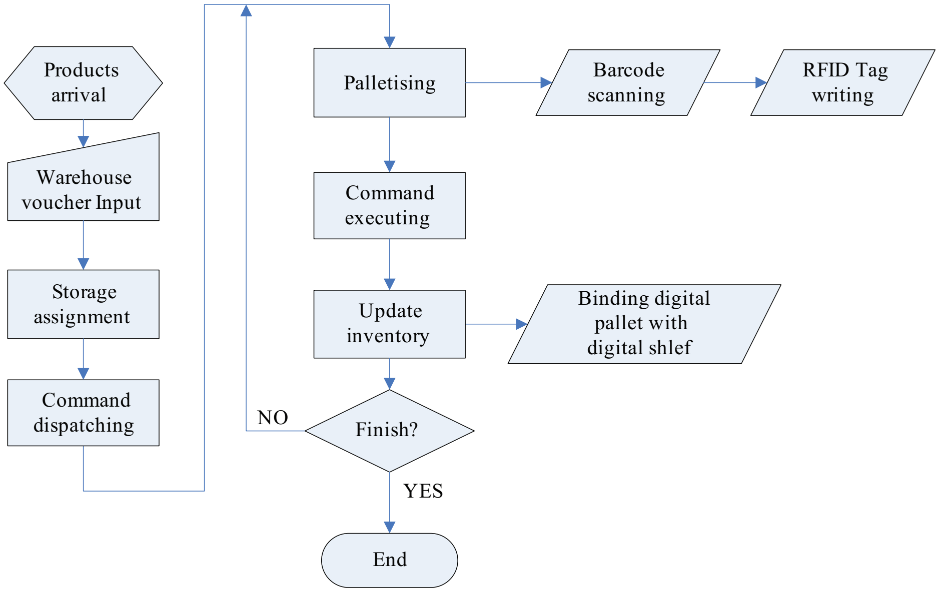

Figure 11. Flow chart of storage procedure.

Step 4: Palletise the products onto a digital pallet one by one. In the meantime, the barcode scanner collects the barcode data to the local computer. When palletising has finished, the local computer compresses these pieces of barcode data into barcode-set (shown in Figure 10) and writes it into the pallet tag with RFID Reader 1.

Step 5: FGS guides the forklift driver to transport the digital pallet to the relative digital shelf.

Step 6: DWMS updates the inventory information and binds the digital pallet information with the corresponding digital shelf.

Step 7: If all incoming products have been stored, go to the end. Else, go back to Step 4 and continue.

Since the drive-in racks are operated from the end (the other end is near a wall), the specifications of the products in the same aisle are the same, and the order picking in one aisle has to follow the LIFO rule. Thus, in our system we focus on the FIFO rule based on the aisles in racks. In order to achieve that, new batches of products are not stored in the aisles where the products with an earlier production date are stored. Contrarily, if an aisle in the racks stored the products with the same specification and production date, the residual empty shelves in the aisle will be assigned first for enhancing the utilisation of racks. Hence, we propose a methodology to determine the storage assignment for drive-in racks, which is described in the following pseudo code:

Function: Storage assignment

Input: specification and production date of the products, and the quantity of digital shelves required, denoted as S, D and Q separately.

Output: a set of empty digital shelves for storing digital pallets, denoted as E, which is initialised to null when beginning.

Let: $A' = \{a'_1, \ldots, a'_m\}$ be the set of aisles which have stored the products with the same specification S and production date D in the drive-in racks.

Let: $A = \{a_1, \ldots, a_n\}$ be the set of empty aisles in the drive-in racks.

Let: $|X|$ denote the total number of empty digital shelves in X, where X can be a'_i, a_i or E.

Let: $P_k(z_i)$ denote that a set of k empty digital shelves assigned from aisle z_i,$z_i \in A' \cup A$.

Begin
  Initialise $E = null$
  For each $a'_i \in A'$
    If $|E| < Q$ Then
      If $\left|a'_i\right| < (Q - |E|)$ Then
        $E = E \cup P_{|a'_i|}(a'_i)$
      Else
        $E = E \cup P_{Q-|E|}(a'_i)$
      End-If
    Else
      Break
    End-If
  End-For
  For each $a_i \in A$
    If $|E| < Q$ Then
      If $|a_i| < (Q - |E|)$ Then
        $E = E \cup P_{|a_i|}(a_i)$
      Else
        $E = E \cup P_{Q-|E|}(a_i)$
      End-If
    Else
      Break
    End-if
  End-For
End

Based on the above methodology, an example of the automatic storage assignment in our system is shown in Figure 12, where the shelves of the assignment results are marked with 'X'.

6.5.3 *The innovative procedures of retrieval operations*

Since the products have been palletised, in the retrieval procedure, the delivery operations can be put into practice directly in the form of digital pallets rather than boxes. This leads to a two-fold benefit. First, the products are transported as a pallet unit by forklift, instead of manual carrying, which results in significant reduction in manpower and loading time. Second, with the help of the RFID reader, the product barcodes can be collected in seconds from the pallet tags instead of scanning them one by one, which results in more

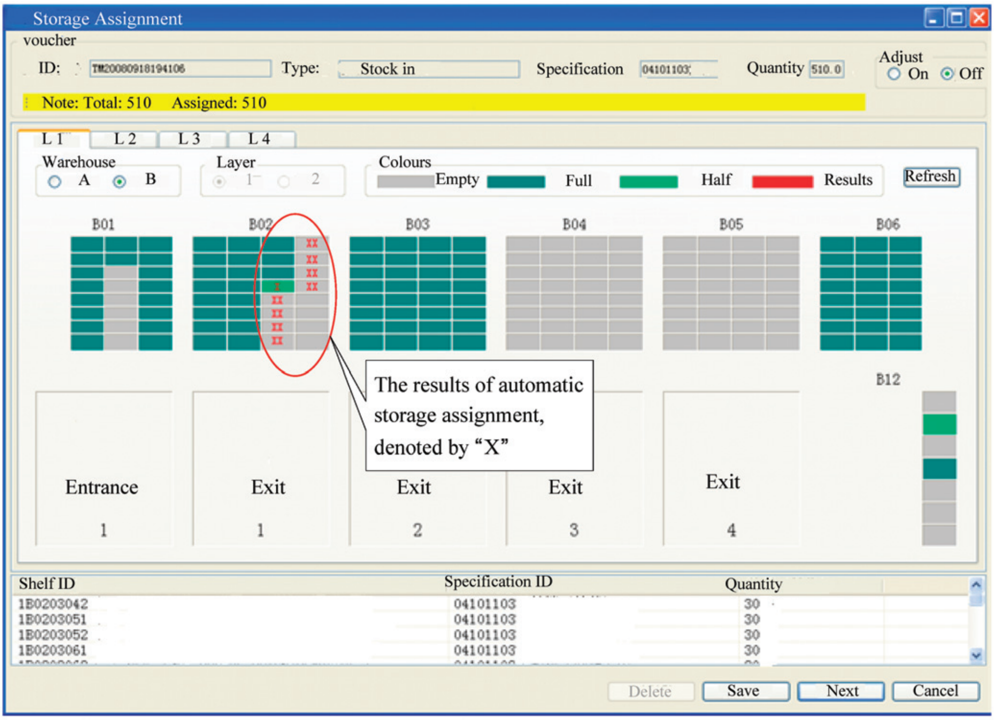

Figure 12. An example of automatic storage assignment.

reduction of loading time. The improved retrieval operation procedure is shown in Figure 13, which consists of the following steps:

Step 1: When orders arrive, operators input the information of delivery voucher into the computer in the shipping space, including the specifications, quantities, date, destination, etc.

Step 2: Make the retrieval assignment decision by DWMS automatically or by user empirically.

Step 3: Create the relevant operation commands and dispatch them to forklifts with DWMS.

Step 4: FGS guides the forklift driver to the corresponding digital shelves and transport pallets to the shipping space. The system scans the pallet tag via Reader 2 and decompresses the barcode-set to barcodes, when it passes by the scanner.

Step 5: If the current pallet does not need to be separated, then go to Step 7. Otherwise, if it does not need to deliver the whole pallet but only part of it, then separate it into boxes, and deliver parts these boxed parts. The remainder is re-palletised, and the pallet tag is rewritten by Reader 2. Then, comparing the net barcode set with the former one, the system calculates the corresponding barcode data of the delivered parts.

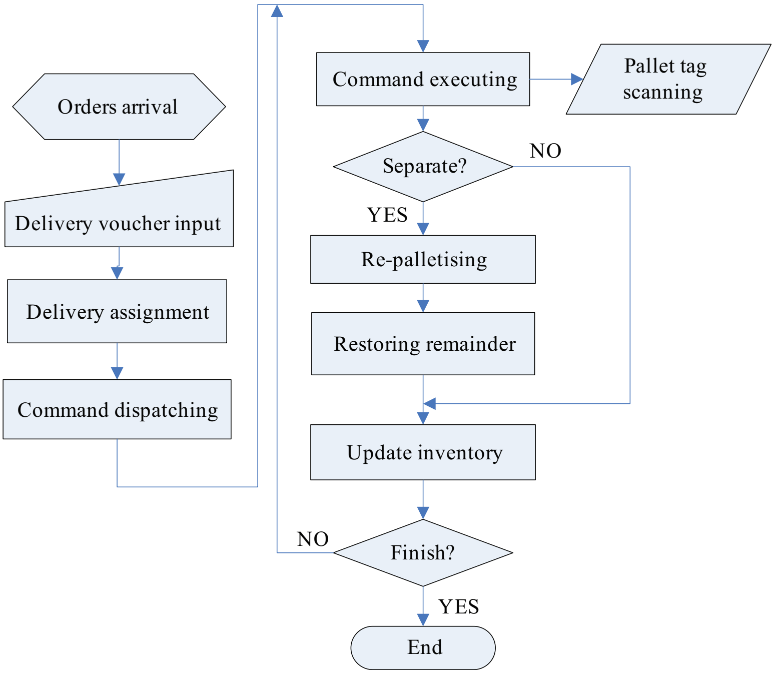

Figure 13. Flow chart of retrieval procedure.

Step 6: Restore the remaining parts on a special shelf (e.g., shelves in temporary storage space).

Step 7: DWMS updates the inventory information after receiving the confirmation from FGS, and sends the barcode data to the government database.

Step 8: If the commands have been executed completely, go to end. Else, go back to Step 4 and continue.

According to the above steps, in order to avoid overstocking, we propose a methodology to determine the retrieval assignment based on the FIFO rule. It is given in the following description.

Function: Retrieval assignment

Input: specification and quantity of digital shelves required by the orders, denoted as S and Q separately.

Output: a set of digital shelves for delivering the digital pallets placed on them, denoted as E, which is initialised to null when beginning.

Let: $L = \{l_1, \ldots, l_m\}$ be the set of digital shelves with the same specification S on the selective rack, which have a higher priority than the ones in drive-in racks.

Let: $B = \{b_1, \ldots, b_n\}$ be the set of aisles which have stored the products with the same specification S, which have been sorted in ascending production date of the products. That means b_i has stored the products with an earlier production date than b_{i+1}.

Let: $[Y]$ denote the total number of non-empty digital shelves in Y, where Y can be b_i or E.

Let: $F_k(b_i)$ denote a set of k non-empty digital shelves assigned from the aisle $b_i, b_i \in B$.

```
Begin
  Initialise E = null
  If m > Q Then
    E = E ∪ {l_1, ..., l_Q}
  Else
    E = E ∪ L
  End-If
  For each b_i ∈ B
    If [E] < Q Then
      If [b_i] < (Q − [E]) Then
        E = E ∪ F_[b_i](b_i)
      Else
        E = E ∪ F_{Q−[E]}(b_i)
      End-If
    Else
      Break
    End-If
  End-For
End
```

Based on the above methodology, an example of the automatic retrieval assignment is shown in Figure 14, where the shelves of the assignment results are marked with 'X'.

6.6 *Results and discussion*

By implementing RFID-DWMS, the operating performance in the distribution centre warehouse has been improved in the following four aspects: inventory visualised management, automatic storage/retrieval assignment, forklift automated guided and loading time reduction.

By using a digital shelf map, the detailed information of inventory is accurately shown on the map in real time. As a result, the mistakes made by management on manual memory are significantly reduced. In addition, the warehouse manager can effectively monitor the inventory change in real time, so as to monitor the operators' operations from the digital shelf map.

With the implementation of the drive-in racks, the utilisation of the space in the warehouse has been significantly enhanced. Furthermore, the products are delivered following the FIFO rule, based on the methodology for determining storage/retrieval assignment. Therefore, the overstock of overdue products is avoided effectively. In addition, comparing the discussion of the warehouse process analysis, there is no need to move around in the warehouse for making an assignment decision anymore. The assignment jobs can be easily done by the person who stays at the front of the computer via a few clicks of the mouse.

After implementing FGS on forklifts, the operators do not need to notify the carriers orally anymore, but only to dispatch the relevant commands to forklifts when

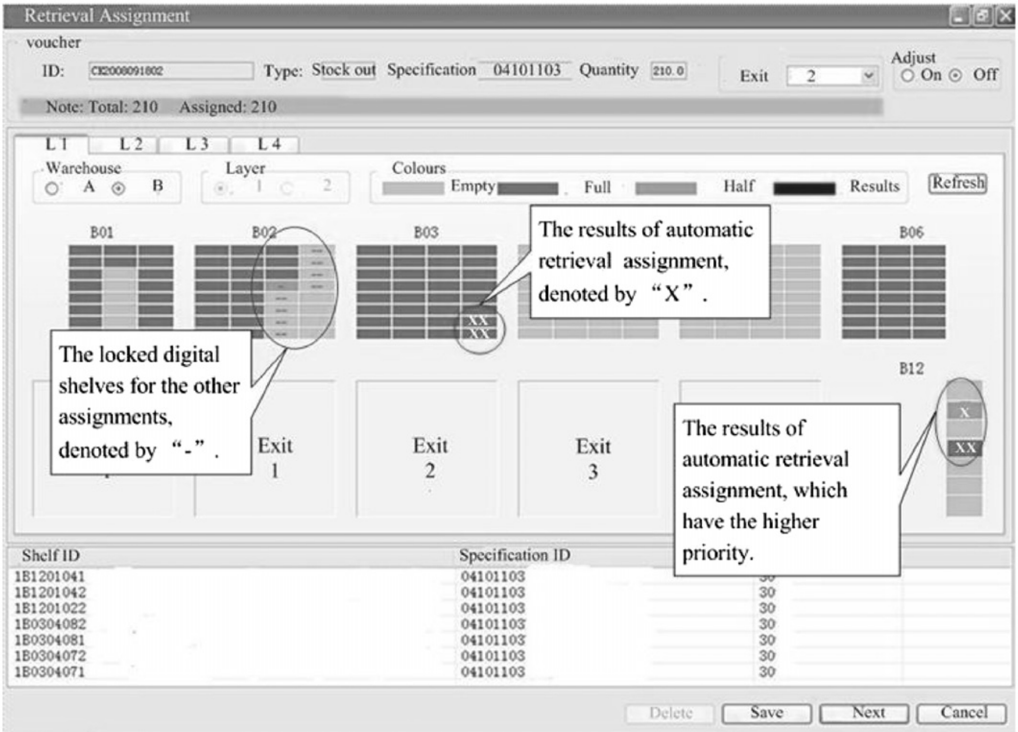

Figure 14. An example of automatic retrieval assignment.

operations perform. Then the drivers execute them and drive directly to the exact space according to the indications from the automated guided map rather than operate manually. In such a case, it results in not only less consumption of manpower, but also reduction of mis-operations.

Since the delivered products are transported in the form of digital pallets when loading, there is no need for operators to scan the barcode of products one by one and to manually verify that they have picked the right products with the right quantity, all they need is to drive the forklift with digital pallets and pass by the scanner, and the barcode data is collected automatically by DWMS, which in turn verifies the validity of the products. If a digital pallet is picked incorrectly, DWMS will give a message to FGS to warn the driver to place it back.

Table 2 compares the warehousing performance without and with RFID-DWMS in the following five ways: the warehouse capacity, loading manpower, loading time, loading ratio and inventory accuracy. We discuss these separately below.

(1) Warehouse capacity

From Table 2, it is clear that the capacity of the warehouse has been enhanced by 52.5%. This is mainly benefited by the adoption of the drive-in racks. First, the products can be stacked up higher with the help of racks. On the other hand, the drive-in racks can be more effective than any other racks to enhance the utilisation of the space in the warehouse, for the reason that the shelves are all combined together, rather than divided by passages.

Table 2. Comparison of warehousing performance without and with RFID-DWMS.

	Without RFID-DWMS	With RFID-DWMS
Capacity of warehouse	7200 boxes	10980 boxes
Loading manpower	8 persons	4 persons
Average loading time	50 minutes	18 minutes
Loading ratio	800 boxes	480 boxes
Inventory accuracy	80%	99%

(2) Loading manpower

After implementing RFID-DWMS, the number of human beings for products loading has been reduced by half. Comparing the analysis of the traditional warehouse process in Section 6.1 and the innovative retrieval operations in Section 6.5, it is clear that the reduction in human beings is mainly reflected in the following three ways: reduction of operators for walking around to determine the storage/retrieval assignment, reduction of operators for scanning barcode data and reduction of carriers for manual carrying. Therefore, it results in a reduction of half the loading manpower.

(3) Loading time

From our practical calculation, it appears that the average loading time is reduced from 50 minutes to 18 minutes. As discussed in Section 6.5, this is benefited by the implementation of digital pallets, which leads to a two-fold benefit: the greatly reduced time for collecting barcode data and the time for manual carrying.

(4) Loading ratio

Since the products are transported in the form of digital pallets, the loading ratio is only 60% of the previous one. However the drop of loading ratio can be countervailed by raising the efficiency of loading and unloading as well as truck turnover, or by adjusting the size of digital pallets or trucks (Lu *et al*. 2007).

(5) Inventory accuracy

By using RFID-DWMS, an increase of inventory accuracy is shown from 80% to 99%.

In order to illustrate this benefit, we calculate the inventory inaccuracy by two aspects: misplacement and transaction errors. Figure 15 gives the statistical data of the inventory inaccuracy caused by misplacement and transaction errors in each month of the year during our requirements analysis (as shown in Figure 15(a)), and the first year after implementing RFID-DWMS (as shown in Figure 15(b)). Figure 15(a) illustrates that, before implementing RFID-DWMS, the inventory inaccuracy was mainly caused by misplacement. This was due to two main reasons. First, since the storage/retrieval assignment was determined based on operator's memory and experience, errors would be likely to occur, especially with greater product variety and increasingly complex customer orders. Second, with the similar appearance of the products, the carriers often made mistakes after receiving the tasks from operators. However, with the help

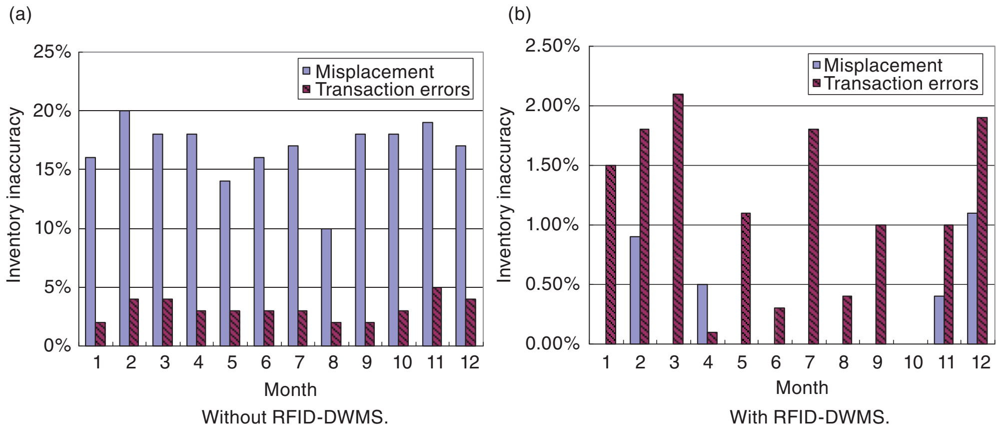

Figure 15. Comparison of inventory accuracy.

of RFID-DWMS, Figure 15(b) shows that the misplacement has been greatly reduced by the automatic storage/retrieval assignment function and the error warning function.

By comparing the transaction errors, before using RFID, the errors mainly lie on the barcode scanning errors caused by misreading, rereading or wrong reading. While using RFID-DWMS, the barcode scanning errors can effectively be detected when compressing them into a new barcode-set, exposing the rereading errors. In Figure 15(b), the transaction errors were mostly generated by misreading of RFID readers. The proposed system shows an overall 98% read rate on the pallet tags. It is believed that with the improvement of the RFID readers and tags, the inventory inaccuracy can be avoided.

7. Lessons learned

In this section, we conclude some lessons learned from the findings of the successful implementation of the RFID-DWMS in our case study warehouse. These lessons can be used as a foundation for conducting future studies on RFID applications in other areas.

(1) Secure the top management support

The top management support is the most important factor affecting the success of implementing an RFID system. In our case study, obtaining management and executive support was the first step towards success in the implementation of RFID-DWMS. Since the new system brings about significant changes in the procedures of warehouse operations, the top management support plays a pivotal role as an agent of change to make the new management standards for supporting the new system implementation.

(2) Provide a prototype system for testing

Since RFID is an innovative technology with high investment cost, it is difficult to obtain management and user commitment and understanding on the RFID system. This can be the primary problem encountered for any RFID system development. In order to give the managers an intuitive understanding on RFID technology, a prototype system should be developed to test its feasibility and advantages before starting a real trial. In this case, we first developed a prototype system and tested it in our workstation by simulating the warehouse environment. Then a real environment testing was performed in the warehouse accompanied by the WTC managers. The testing included reading and writing rate test, tag location test (in the centre or at the front of the pallet), electromagnetic interference (EMI) test, wireless network test, palletising time test and emergency test (e.g., power blackout). The managers can give their commitments only if all the testing results are satisfactory. Therefore, a prototype system is significantly necessary before a real trial.

(3) Full-scale scanning or passageway scanning

Before implementing an RFID system for tracking products in a warehouse, an important decision should be made on adopting the full-scale scanning solution or passageway scanning solution. The full-scale scanning solution provides a real time detection of the products with tags embedded, as well as the precise locations of each product. In order to achieve that, more antennae are needed for fixing in each corner of the warehouse to make sure that the effective magnetic field of antennae can cover the whole area of the warehouse. In such a case, how to distinguish the cross area between two antennae is a significant problem raised sequentially. Furthermore, there must be more electromagnetic interference for scanning when the products are placed in the metal racks. Therefore, the full-scale scanning solution calls for not only more capital investment but also a higher level of technological capabilities. Contrarily, the passageway scanning solution only needs one scanner located at each entrance or exit door to record the transported products. From our case study, it is clear that the passageway scanning solution is sufficient for a generic warehouse to manage its inventory, while the full-scale scanning solution can be more suitable for valuables holders, retailers or supermarkets to monitor them in real time.

(4) Item-level tagging or pallet-level tagging

Another problem most concerning RFID implementers is whether to adopt an item-level tagging solution or a pallet-level tagging solution. The main difference between the two solutions is the investment cost. In order to save the cost, we adopted the pallet-level tagging solution in this case, combined with barcodes to identify the products uniquely. Since the digital pallets can be returned after they have left the warehouse, the pallet-level tagging solution can significantly save the investment cost and be easily implemented in a closed-loop system. However, there also exist limitations in the pallet-level tagging solution. That is, the pallet-level tagging solution is only suitable for the regular shapes and large throughput products. If the product shapes are different, and the transported quantity is small, the time saved by RFID collection cannot balance the time cost for separating and repacking a pallet. Contrarily, the item-level solution will be much more flexible for different products. However, if the tags are not returnable, few companies can afford the item-level tagging solution.

(5) Flexible system design

A flexible system design is very important for developing an RFID system. Since most companies start RFID implementation with a small-scale trial, the managers are most likely to extend the RFID applications on a large scale if the trial brings a large number of benefits from RFID technology. Therefore, flexible design is an important prerequisite for the success of the extension. In order to improve the flexibility and adaptability of RFID-DMWS for implementing in a warehouse, a set of different storage/retrieval assignment rules is necessary to be considered and designed in the system. Based on these rules, this system can be easily extended for different rule requirements by few modifications. The result shows that the more flexibility of the system design, the fewer modifications that are needed for future extension.

8. Conclusion

Our study focused on the problem of how to improve the inventory management and operations in a plane warehouse, referring to the advantages of RFID technology. In order to achieve that, an RFID-DWMS was proposed in our paper, which achieves the real-time visualised inventory management and automatic storage/retrieval assignment in a plane warehouse. With the help of RFID technology, the digital pallet and digital shelf are implemented. They ensure that the products and their stored places can be bound together and identified uniquely. Through this case study, we have demonstrated that RFID technology can be effectively applied in a plane warehouse to help improve operation efficiency, enhance the utilisation of warehouse capacity, increase inventory accuracy, save manpower and reduce loading time significantly.

As a result, the proposed framework of RFID-DWMS enables a plane warehouse to realise most functions of an automatic warehouse. These achieved functions include automatic storage/retrieval assignment, automatic information collection, real-time inventory management, accurate shelf management and a forklift with a guided map playing a role as AGV. Furthermore, the cost of implementing the RFID-DWMS in a plane warehouse is much lower than building a new automatic warehouse. Not limited in the tobacco industry, the proposed system is feasible and flexible to be applied in other industrial environments with features of regular product shapes and large throughput operations, under which the efficiency of the digital shelf might be maximised.

The developed RFID-DWMS is distinguished from the existing systems on the following three aspects. First, based on the development of digital shelf map, a visualised guided map is designed and installed on a touch screen computer for guiding the forklift drivers to pick goods. Second, we proposed a more detailed classification of events in our system. The proposed set of basic events covers almost all of the basic events in a general RFID system. As a result, it improves the flexibility of our system effectively. Third, with the implementation of the ECA mechanism, we proposed a set of the most common rules used in storage/retrieval assignment in our system, which enables the system to provide different assignment results with different specifications. Furthermore, the advantages of the ECA mechanism effectively reduce the effort required for modifying our system to adjust to the different application environments. The case study illustrates that our system is more flexible and adaptable than the existing warehouse management systems, based on the above three improvements.

For the future study of this work, it will be a challenging but useful extension of the application of RFID-DMWS to the whole supply chain, including suppliers, distribution centres, wholesalers, and retailers. By using RFID-DWMS and network communication, the real-time inventory information could be shared with all of the supply chain members with digital shelf maps, which realises the synchronisation of information flow and material flow as well as VMI mode in the supply chain. Thus, the reduction of bullwhip effect will come true. On the other hand, since the products in the form of digital pallets could be identified uniquely, the corresponding logistics tracking system and products anti-counterfeiting system based on RFID will be a valuable future direction, which we have started exploring in our ongoing research efforts.

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