Encoding, Application and Association of Radio Frequency Identification Tags on High Speed Manufacturing Lines

by

Herbert Moreti Fonseca
Electrical Engineer (1997)
Escola Politécnica – Universidade de São Paulo

Submitted to the Engineering Systems Division
in Partial Fulfillment of the Requirements for the Degree of

Master of Engineering in Logistics

at the

Massachusetts Institute of Technology

June 2004

Signature of Author________________________________
Engineering Systems Division
May 07, 2004

Certifyied by________________________________
James B. Rice Jr.
Director, Integrated Supply Chain Management Program
Thesis Supervisor

Accepted by________________________________
Yossi Sheffi
Professor, Engineering Systems Division
Professor, Civil and Environmental Engineering Department
Director, MIT Center for Transportation and Logistics

Encoding, Application and Association of Radio Frequency Identification Tags on High Speed Manufacturing Lines

by

Herbert Moreti Fonseca

Submitted to the Engineering Systems Division
in Partial Fulfillment of the Requirements for the Degree of

Master of Engineering in Logistics

at the

Massachusetts Institute of Technology

June 2004

Abstract

One of the entry points of radio frequency identification technology in supply chain applications is at the manufacturing line, after production, as packaged goods leave for the next link of the network of suppliers, carriers, distributors and retailers. To RFID-enable packaged products, an RFID device needs to be attached to the packaging and an identification number needs to be generated and stored accordingly. Today, a few early adopters of the technology already started to apply RFID tags to some of their cases and pallets and to collect and store the information. These processes however, are still to a large extent done at a slow pace, manually or in an experimental mode, and that may not be suited for large scale applications. To address this issue, this research document focuses on the implementation of an RFID enabled process under strict time and performance constraints, for case packaged goods and pallets. This document reviews the currently published information on the topic and the Auto-ID technology standards. It analyses system integration challenges, proposes a process for case and pallet level encoding, application and association and discusses some of information systems requirements for the implementation. It proposes a framework of options with the requirements and considerations the author believes to be most relevant.

Thesis Advisor: James B. Rice Jr.
Director, Integrated Supply Chain Management Program
Massachusetts Institute of Technology

ACKNOWLEDGMENTS

Coming to MIT after working for over 5 years at a manufacturing site was certainly a great challenge, but it is the realization of a dream. Been able to develop this research thesis and to interact with the people from the MLOG program, from the different companies and from the Auto-ID center was one of the high moments of this realization.

There is a special group of people I want to thank for their support in the development of the thesis. My advisor Jim Rice and the people that helped me in the investigation, discussion and revision of all my ideas: Paul Rieger, Joyce Muha and Tom Sharfeld, Dale Hanson, Lukasz Weber, Gustavo Riestra and my classmates at the MLOG, with special thanks to Nathan Roost, who helped me a great deal with the revision process.

Thanks also to the people who helped me with the MIT application process, Juliana Clemente, José Jaime Cruz and Sergio Perez.

Finally, I wanted to thank my parents Herbert and Solange, for always providing me with everything that I needed in every possible way, and my wife Helena, for making my life so much better.

TABLE OF CONTENTS

1. Introduction 6
 1.1. Motivation 6
 1.2. Methodology 7
2. Literature Review 9
 2.1. Technology Overview – Auto-ID standard components 9
 2.2. Overview of bibliographic reference 15
3. System Integration 20
 3.1. Introduction 20
 3.2. Challenges and issues to address 20
4. Case Level 23
 4.1. The Process 23
 4.2. Time Considerations 25
 4.3. Material 28
 4.4. Equipment Performance 30
 4.5. Procedures 33
5. Pallet Level 35
 5.1. The Process 35
 5.2. Time Considerations 39
 5.3. Material 39
 5.4. Equipment Performance 40
 5.5. Procedures 41
6. Information systems 42
 6.1. Network bandwidth 44
 6.2. Data volume and storage 44
7. Observations and conclusions 46
 7.1. Future work 47
8. Bibliography 48

TABLE OF FIGURES & TABLES

Figure 1 – Tag Classes [51] 11
Figure 2 - GTIN example – [18] 13
Figure 3 - EPC Network Overview – [18], [59] 14
Figure 4 – Case level application overview 23
Figure 5 – Tag writing process flow 24
Figure 6 - Tag writing with shielding material 27
Figure 7 - Case level time process flow 28
Figure 8 – Corrugated case 28
Figure 9 - EPC tag position 29
Figure 10 – Alternative case level time process flow 30
Figure 11 - Reader to tag relative position 32
Figure 12 – Pallet level application overview 35
Figure 13 – Pallet level process flow 35
Figure 14 – Pallet building and Encoding 36
Figure 15 – Verification, tag application and writing 37
Figure 16 – Association, aggregation and final verification 38
Figure 17 - Loaded pallet with EPC tag 39
Figure 18 - Information system infrastructure 42

Table 1 - SGTIN-96 10
Table 2 - SGTIN-96 Partitions – [18] 10
Table 3 - SGTIN-96 Example – [18] 13
Table 4 - Data volume per second example 44

1. Introduction

This thesis document analyzes the implementation of Radio Frequency Identification tags on pallets and case packaged products operating on high speed manufacturing lines. It follows the standards developed originally by the Auto-ID Center at the Massachusetts Institute of Technology and the definition that a high speed line is the one that is capable of producing one case per second.

It comprehends an analysis of the following processes:

- Encoding, or the formation of the EPC – electronic product code
- Programming of the EPC chip
- Automatic application of tags to cases and pallets
- Validation of tags applied
- Association of product code with individual unit
- Data management and storage

It also includes reflections on:

- System integration
- Response time, performance and reliability for different components of the system

The comprehends an assessment of the challenges involved on doing it in high speed production lines, where the issues tend to scale up and a higher degree of automation is usually required, comparing to the current test pilots and experimental setups. The goal is not to exhaust all different alternatives but to propose a framework of options with the requirements and considerations the author believes to be most relevant.

1.1. Motivation

For over 25 years companies have used bar codes to identify products across their supply chains. They are used at the pallet, case and item level and applications range from identifying products at the manufacturing site to checking out at a retail store. Radio Frequency Identification is a technology that has being used for some time as well, but the costs involved usually limited the use to a few applications, like for example tracking of high value assets. RF identification technology advantages over the barcodes are primarily the elimination of the line-of-sight or contact requirement and the capacity of storing specific information about the item in its chip memory. That allows a great number of new applications like for instance automatic inventory control.

The creation of the Auto-ID Center at MIT was crucial for the promotion and for the development of a new set of standards and technologies in RF identification. The research developed there and at the other centers created in the UK, Australia, China, Switzerland and Japan enabled significant technological improvements and cost reductions, especially in tag manufacturing costs and network infrastructure design. Those improvements allowed companies to identify financial benefit in introducing RFID to a greater number of products and applications.

Over the past three to four years, these companies have started test piloting RFID technologies in their warehouses, distribution centers and manufacturing facilities. Their primary goal with this implementation strategy was to be able to learn and understand the capacities and limitations of the technology and evaluate how it interfaced with their products and processes. Over the past six months, the technology gained a new level of attractiveness when large US and European retail chains, and also a central US military organization required their top suppliers to adopt RFID on products shipped to their warehouses and distribution centers.

Today, several large corporations that have high-speed manufacturing capabilities are facing the challenge of implementing RFID into their manufacturing sites, either to take advantage of the potential of this technology or to comply with customer's mandates.

The motivation for this research is to address some of these challenges, focusing on the first steps of the RFID implementation process – the point where the information is generated. Code formation, tag application and information association are elementary parts of the process to manufacturers and can influence the results of the entire system.

1.2. Methodology

The analysis process involved a comprehensive review of articles and books published by research centers, vendors, system integrators as well as the specialized press on the topic of RFID technology and project implementation. Data collection also included several interviews with experts in the field of radio frequency identification, manufacturing processes, logistics engineering and quality assurance from one major multinational CPG company in the US. Interviews were also conducted with system integrators, RFID hardware manufacturers and researchers from the Auto-ID laboratory at MIT. It included people that were involved in the development of the technology and/or on the deployment effort.

With this collection of information, the analysis process that followed explored the identification of the current state of the technology, capacities and limitations as well the system integration challenges involved. With the observations drawn from this assessment done in chapter 3, it was possible to define the research scope and to outline a process and a set of considerations that were identified as most relevant. Chapters 4, 5 and 6 include the analysis for case level, pallet level and information systems' considerations.

The selected focus of research is on processes involving radio-frequency "friendly" products and packaging. That stands for products and packaging that do not interfere with the propagation of UHF radio frequency waves. It includes products and packaging with high percentage of air space, low presence of metallic particles and low water content. The reason for restricting the analysis to these classes of products and technologies is strategic and it is meant to remove from this analysis some of the complexity already identified on field trials developed by CPG companies. It serves the purpose of establishing the grounds to enable early adopters to learn as much as possible from the introduction of this evolving technology.

The suggested process for case and pallet level applications constitutes a sequence of steps that addresses the questions on how and where to execute tag encoding application and association. The relevant considerations were defined to be the time constraint, the influence of the materials (excluding the interference effect), equipment characteristics and the operating procedures involved. To address the Information Systems considerations, an estimation exercise was done in order to analyze some of the network and data management requirements.

Chapter 7 summarizes the observations and conclusions, as well as proposes future work on topics related to the subject studied here.

Here the author assumes that in the case and pallet level application, what we are identifying is the container and the product/items it holds. This relationship is unique and is valid only as long as the package continues to be at the condition it was at the time the association occurred. In order to maintain identification uniqueness, the principle that needs to be followed is that at any time, there will be only one valid EPC association.

2. Literature Review

In this chapter the goal is to review the published material on topics surrounding the implementation of RFID tags on high speed manufacturing lines. It includes an overview of the technology and its elements and the summary of some of the main sources of information used for this research document.

2.1. Technology Overview – Auto-ID standard components

By Auto-ID compliant technologies one should understand technologies that follow the standard developed by the Auto-ID center at the MIT. It consists of the electronic product code - EPC, the tags classified into classes, PML language and the network of Savant and EPC-IS servers, with information hosted on an ONS server.

Note that the EPC Global, the standards body that succeeded the Auto-ID center, does not set standards for all technical pieces of the implementation and therefore it is the adopter's responsibility to decide what criteria to follow. Aspects including data security and privacy, memory type and size and frequency range will have to be included, bearing in mind the need for system interoperability across the entire supply network.

Large early adopters in the US and in Europe have already started defining these additional aspects. Based on the field trials performed and on their initial implementation tryouts, they have defined their requirements for these parameters. To build on these past experiences, this analysis will focus on these specifications and requirements.

2.1.1. EPC tag data standards

The original electronic product code was a 96 bits number, consisted of a header (8bits) that is intended to identify the coding used, a Manager Identification number (28 bits) to identify the manufacturing ID, Object Class (24 bits) to identify the product and the serial number (36 bits). Is was designed in a way that the scheme is capable of accommodating growth over time and, with the introduction of the serial number, it introduced the possibility to identify products one level above the current level used for bar-codes.

Recent developments are defining an EPC data set that can be related to current EAN/UCC encoding systems used for barcodes. It consists of a header field followed by one or more Value Fields. The difference it that each portion of the code is no longer fixed in size, but it is a function of the header that defines the value fields that follows.

Although EAN/UCC numbering systems and EPC are different, it is possible to convert from one format to the other. Following the set of rules defined by the standard body it is possible to generate a encoding and a decoding rule that converts EAN/UCC numbers to EPC and vice versa. That allows systems to interpret both numbers allowing interoperability and facilitating any transition from one coding to the other.

In this document, we will focus on the SGTIN-96 encoding scheme, but all examples can be easily adapted to any of the other numbering schemes. The SGTIN-96 is currently a 96 bits version of the GTIN and it is the one of the first proposed industry standards for low cost passive tags. It consists of:

EPC = Header (8bits) + Object Type (4bits) + Partition (4 bits) + Company Prefix (Manufacturer ID) (37-20 bits range) + Item reference (7-24 bits range) + Serial Number Serial Number (36 bits) + Lock code (8 bits) + CRC (16bits)

	Header	Filter Value	Partition	Company Prefix	Item Reference	Serial Number	Lock Code	CRC
SGTIN-96	8 bits	3 bits	3 bits	24 bits	20 bits	38 bits	8 bits	16 bits

Table 1 - SGTIN-96

Partition table for the GTIN-96 follows the table below. According to the Company Prefix number of digits (L), you define the partition value (P), the number of bits of the Company Prefix (M) and the Item Reference number of bits (N).

Partition Value (P)	Company Prefix		Item Reference and Indicator Digit	
	Bits (M)	Digits (L)	Bits (N)	Digits
0	30	12	4	1
1	37	11	7	2
2	34	10	10	3
3	30	9	14	4
4	27	8	17	5
5	24	7	20	6
6	20	6	24	7

Table 2 - SGTIN-96 Partitions – [18]

Last two components of the code (Lock Code and CRC) are not standard and depend on the technology that is going to be used. They represent added functionality that vendors could use to take advantage of the tags' memory capacity.

Note that if the EPC structure is preserved, adding functionality and enhancing the code does not interfere with the integration between different users when data needs to be read outside the enterprise. On the other hand, additional information interferes with reading and writing timings and need to be considered on high speed applications.

2.1.2. Tags

Tags are composed by a chip that includes a CPU and memory – that will store the EPC, an antenna and the substrate. Each case or pallet will have one tag attached and that makes the tags one of the most critical components of the Auto-ID infrastructure. The very large number of tags required for all cases and pallets will represent the major portion of the total RFID system costs. The cost/performance factor is the major tradeoff that needs to be considered and physical aspects (antenna size, substrate type and size) will have to be suited to the product and application. In this document, the author uses the words tag interchangeably with the concept of a smart-label, which includes a printable area and an adhesive substrate to the before mentioned components of the RFID tag.

Tags that include an energy source are called "active" tags. If they use the power available on the electromagnetic waves coming from the readers they are called "passive" tags. The first type has a selling price higher than the latter. Functionality for reading and writing can also vary and the combination of all these factors defines the tag reading performance. Another important characteristic of the tags is the type of coupling used. It can be inductive or capacitive and to operate properly, it has to match the reader's coupling type.

From Sarma et all [51], lecture notes we have the representation of the layered philosophy behind the tag's classification, as it can be seen in Figure 1 below. Tags are compatible between classes and as more functionally is added, class layer increases.

Classes 0 and 1 are what is considered generation 1 technology and between then there is not only a distinction on memory writing capabilities, but also a distinction in communication protocol or "air interface". Recently, the release of a Class 0+ enhanced tag, introduced writing functionality to the Class 0 layer. A second generation of Class 1 tags is under development and it is expected that it will merge the passive tag's protocols by the way of a common air interface. Infrastructure investment and tag selection risks can be mitigated with the use of multi-protocol / agile readers that can support future requirements. [43], [49].

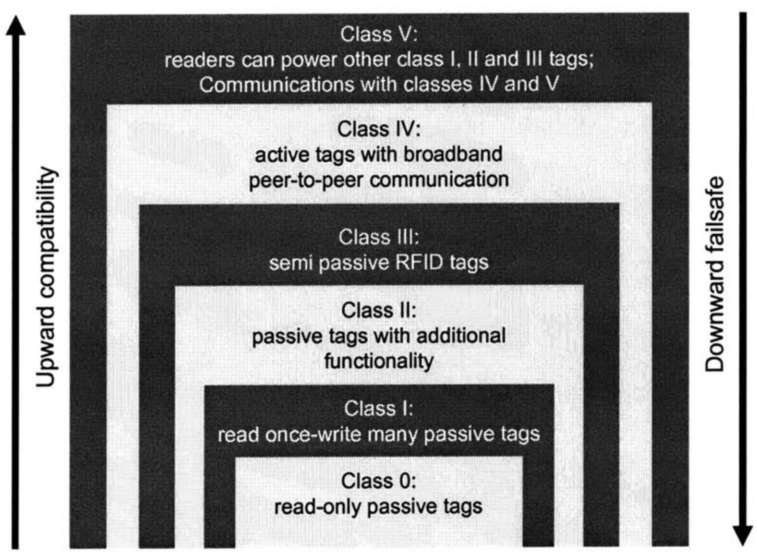

Figure 1 – Tag Classes [51]

In our case, following the same logic behind the selection of the EPC-96 SGTIN, we will focus on Class 0+/Class1 generation 1, passive, write-once/read-many, UHF tags.

2.1.3. Readers (writers) and antennae

Readers (and writers) can be viewed as the highest available class of tags, Class5. The functionally they perform is equivalent since they are both transponders of electromagnetic waves and likewise, one reader can operate with several different tags simultaneously. This analogy helps us define a similar criticality from the one used for tags. This type of equipment is high regulated to prevent interference with existing devices and the several power constraints are key on the definition of the system reading range.

Most common operating frequencies ranges are around 13.56 KHz (HF) and 900MHz (UHF), and recently there is a trend to the use of the UHF band, although this range is not standard across different regions of the world. For example in the US the range is 902-928 MHz, in Europe it is 868-870MHz and in the Asia/Pacific region it is 950-956MHz. This difference is critical and although some tags can operate at different ranges, their performance can be different on each frequency. That means that this should be considered and tested on field trials of international companies. Class1 tags are specified to operate at UHF frequencies [47].

In addition to frequency of operation, the other critical characteristics of the reading/writing equipment are air interface protocol and the power it is capable of emitting and receiving. The power the device is capable of emitting defines the reading range and the speed the information can be read and written. Standard bodies like the FCC in the US regulate the levels of power RF devices can have and therefore this capacity is always constrained by such regulating limits [51].

This analysis will consider the use of multi-protocol UHF readers, which allow reading the different types of tags available today.

2.1.4. Savant

Savant is the component from the original Auto-ID infrastructure that was designed to hierarchically share the load of data flow over the network. It can categorized into Edge Savants - to be located at stores, warehouses and manufacturing sites; and Internal Savants to be located in regional or national data centers and include the information from their descendants.

In the different levels they will reside, they will be responsible for executing three different types of tasks [40]:

- Event Management System: Implemented on the ES to collect tag read events. It includes the reader's interfaces and adapters that allow different types of reader to be read. It is responsible for smoothing (correct positive and negative reading errors), coordinating (multiple readers reading the same tag) and forwarding the filtered and logged data.

- Real Time In-Memory Event Database: As the name suggests, it is an optimized database designed for performance that is memory resident. It is responsible for logging events in a dynamic database, containing multiple snapshots of data.

- Task Management System: It was designed to help the maintenance of multiple systems and is the link on the distributed product management framework. The communication is done using SOAP and XML. Tasks are stored on a persistent database so in the case of a crash the task can be restored. Sample tasks include SQL queries, batch event report, data migration, ONS/EPC IS lookup and memory snapshot logger.

2.1.5. PML

Physical Markup Language - is a collection of standardized vocabularies based on XML– the extended markup language. It is used to describe objects and data captured from EPC enabled objects. It defines the interchange format for the exchange of data between components within the EPC network. It is not used as a storage format and it is also not a product markup language. It includes a core portion, used to describe data directly generated by the EPC infrastructure and an extensions portion, used to provide information describing the objects [51].

Examples of such contents include the data read by the reader from the tag or e-commerce documents featuring EPC data. Although content my diverse, by using the common PML schema, it will be possible to exchange this data over the network using XML messages. It includes the elements that are already defined in existing business standards such as UBL, EAN.UCC and RosettaNet, and was designed to operate in under these standards [13], [18].

One example of an EPC tag read, taken from the EPC Global Inc standards [18] for a GTIN 10614141007346 code looks like:

(01) 1 0614141 007346 (21) 2

Figure 2 - GTIN example – [18]

	Header	Filter Value	Partition	Company Prefix	Item Reference	Serial Number
SGTIN-96	8 bits	3 bits	3 bits	24 bits	20 bits	38 bits
	0011 0000 (binary)	7 (decimal)	5 (decimal)	0614141 (decimal)	100734 (decimal)	2 (decimal)

Table 3 - SGTIN-96 Example – [18]

(01) is the Application Identifier for GTIN and (21) is the application identifier for the serial number. Application Identifiers are used in certain barcodes. The header fulfils that function in EPC.

- Header for GTIN-96 is 00110000
- The filter value is part of the SGTIN pure entity, but it is additional data that can be used for fast filtering and pre-selection of basic logistics types (Item, Inner Pack, Case, Pallet, other). Since is not yet defined, we arbitrarily select 7.
- Since the Company Prefix is seven-digits long (0614141), the Partition Value is 5. This means the Company Prefix has 24 bits and the Item Reference has 20 bits.
- Indicator 1 is repositioned as the first digit in the Item Reference
- Check digit 6 is dropped

The PML core code that represents the observation is:

```
<pmlcore:Sensor>
   <pmluid:ID>urn:epc:1:4.16.36</pmluid:ID>
   <pmlcore:Observation>
       <pmlcore:DateTime>2003-11-06T13:04:34-05:00</pmlcore:DateTime>
       <pmlcore:Tag>
         <pmluid:ID>urn:epc:tag:sgtin-96:7.0614141.100734.2</pmluid:ID>
       </pmlcore:Tag>
   </pmlcore:Observation>
</pmlcore:Sensor>
```

Note that the information above includes only the reader ID, the timestamp and the EPC number read.

This example allows us to estimate the minimum information size that will be used to evaluate the information technology requirements in chapter 6 - Information Systems.

2.1.6. EPC Network

EPC Network, as shown in Figure 3, can be viewed as an intra and inter company information sharing structure that, using the Internet as infrastructure, allows the EPC and the related data to be shared across the supply chain.

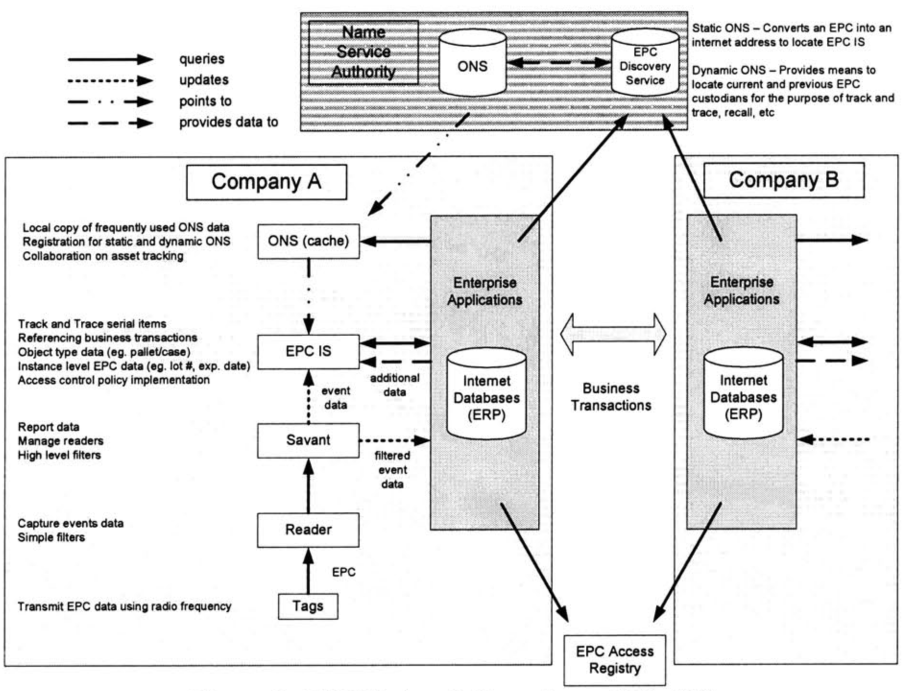

Figure 3 - EPC Network Overview – [18], [59]

Intra-company components are the ones described previously, ranging from the hardware (tags and readers), the middleware (savant and EPC IS) and the enterprise applications (ERP, WMS, etc). Inter companies, there are another 3 components: EPC Information Services (EPC IS) that stores information on a product, distinguishing it at all points of the supply chain; EPC

Discovery Services, that maintains a list of each EPC IS containing information about a given product and Object Name Service (ONS), that routes the requests for information to the appropriate EPC IS [59].

The ONS/EPC DS schema is designed to be the equivalent of what the Domain Name Service is for Internet web services addresses. It is a central database that will relate the electronic product code to an Internet address that will contain information about the product (static) and provide the means to locating current and previous EPC custodians for additional functionality like tracking and tracing (dynamic). Locally inside the companies, ONS caches can be used to speed up the process of searching for frequently used ONS data and will provide registration for the upper level ONS.

EPC Global Inc is currently in the process of developing such standards, and a name service authority has recently being selected, again following the idea behind the Internet structure. It is expected that the final proposed structure will change and adapt, but the framework presented here is likely to be maintained.

2.2. Overview of bibliographic reference

The bibliographic reference used for this research project can be classified into four different categories:

- Academic research publications
- Business / Company publications
- Product analysis
- Lecture notes

The goal of this review is to provide an overview of what the author found to be most relevant to the research question in each of these categories.

2.2.1. Academic research publication

Into this category the author included four previously published master thesis documents related to RFID technology and a series of technical and instructive publications from the Auto-ID centers.

From [12] - Carayannis-Pararas, J., we have a case study on Unilever's Home and Personal Care, North American division. It outlines potential applications of RFID technology on the company's Supply Chain and it surfaces the field tests and trials on RFID technology used for pallet identification. It highlights the partnership with the pallet supplier and describes some of the issues identified during the test trials.

From [29] - Joshi, Y., we have a systemic analysis of the effect of visibility in supply chain dynamics and a proposed framework to achieving information visibility with the use of RFID technology. It discusses the evolution of production and operations management software over the past decades and analyses some of the impacts RFID data will have on such systems, highlighting for example the importance of data accuracy for the proper operation of the system.

From [35] - Koh, R., we have an analysis of the impact of the use of unique item identification and RFID in the capabilities of supply chain and how they are designed and managed. The analysis is done in the context of the product, its related processes and the overall supply chain and it uses the Supply Chain Operating Reference (SCOR) model to assess supply chain utility under this different scenario.

From [53] Sharfeld, T., we have an explanation and analysis of the fundamental constraints and their fundamental trade-offs of the application and configuration dependant specifications that affect system performance, including range, speed, integrity, compatibility and costs. It includes a comprehensive discussion about the design requirements and constraints of passive RFID systems, including electromagnetics, communications, regulations and the limits of physical implementation.

Key publications include:

[2] – Albano, S. A technical report that summarizes the execution, the learnings and the results from the phase 1 field tests of the prototype Networked Physical World system, which integrates standard EPC, ONS, Savant, PML and RFID tags. The goal of the test was to use the system to locate pallets anywhere and anytime in the supply chain. Highlight the issues and needs identified at the time to improve overall system performance.

[13] – Chang, D. et all. The paper provides guidelines for the introduction of Auto-ID provided information into existing Business Information Systems. It also helps users prepare for business processes and to identify which systems may accompany Auto-ID provided information. Main insights: Effort will heavily involve the company's IT organization. After current/future IT architecture is studied, define the scope relating to the expected benefits. The integration should follow the information chain (CS -> MES -> SCM / ERP) and there is a need of determining weather the system has the functionality to receive that information or not. The expectation is that EPC and PML will improve data quality and enhance planning and execution quality of systems but that will require modifying current BIS.

[16] – Eberhardt, N. Document describes some of the equipment available to read tags, setting conditions, considerations and presumptions to a benchmark performance evaluation. The following types of reading were evaluated: pallet reader (portal and rack did not consider reading at the wrapper), conveyor reader – for pallets and cases, forklift reader – for pallets, portable reader (handheld, shopping cart) – for pallets, cases and items, shelf reader – for items and checkout counter reader – for items. First it is necessary to define the user's requirements (needs, issues, concerns and expectations), them set test performance targets accordingly.

[36] – Lo, J. This paper discusses the key considerations in executing a successful Auto-ID transformation management program. Managing transformational change correctly will fulfill the original business objectives, decrease disruption to current business processes, and increase cooperation and collaboration of all those involved. Success is measured by achievement of business benefits, increased performance and sustainability. A transformation is not complete until incorporated into the company's culture.

Installation = RFID technology + process reengineering + systems improvements

Implementation = Installation + change management that will enable the organization to complete its transformation.

[46] – Richards, H. Framework with tools and techniques for formulating a manufacturing strategy and performance measurement. It includes a brief summary of several decision support tools that can be used to help companies that will implement RFID technology.

[54] – Scharfeld, T. The paper reviews the elements of an RFID implementation (focusing on challenges of being able to read the tags inside the 4 walls across and on the supply chain) and how they pose problems to RFID interoperability. It also proposes process for testing, compliance and certification.

2.2.2. Business / Company publications

Key publications include:

[1] – Association for Automatic Identification (AIM) & [49] – Rommel, J. articles about the initial performance and standard requirements from Wal-Mart, one of the main drivers for many companies evaluating the implementation of RFID today.

[14] – Chappel, G. et all. A business case analysis on the impact of RFID on manufacturing operations. Highlights of potential benefits and uses company examples for illustration.

[15] – Dempsey, M. et all. Presentation that took place at the Global Supply Chain Conference. It includes perspectives from RedPrairie and Unilever on applications and considerations for the implementation process. They include the focus on compliancy to mandate and on the middleware functionality in order to allow the system to grow, risks of obsolescence, and the decision about the level of involvement a company should have, matching the company's goals and capabilities.

[26] – Harty, D. Framework from which you can evaluate the use of RFID technology. It makes it clear that the technology is not a silver bullet and that the implementation is complex. If suggests a "sanity check" by answering first: Why to tag in the first place? Is ROI positive? Highlights major areas of concern and defines a large list of questions to answer and considerations to make in the design phase of the project. It also discusses some of the application specific requirements, like reading range, multiple versus single antennas and how external factors can influence the operation of the system.

[31] – Kellam, L. P&G's vision of Consumer Driven Supply Network. It can be divided in – five key parts: 1- EPC, 2 – Collaborative Planning, 3 – Produce to Demand Manufacturing Systems, 4 – Dynamic Replenishment and Distribution, 5 – Superior Retail Execution.

[45] – RFID Journal article on how to access vendor's qualifications for RFID projects.

2.2.3. Product analysis

Product analysis included articles about the devices and equipments related to RFID technology currently available in the market or on their final stages of development.

It includes information from tag and readers manufactures like Alien Technology ([3], [4] and [5]), Matrics Inc ([7], [8] and [43]) and Texas instruments ([20] and [58]), covering from the fundamentals of the technology to the different standards and technical specifications of their different products. Articles from these companies also deal with applications, RFID regulations and technical solutions to problems like interference and performance. In addition to what was discussed previously in the technology overview, highlights from these publications are the existing differences between hardware provided by different suppliers. Although capable to perform the same tasks, equipment from different suppliers operate with different protocols and are not 100% compatible with each other. Some devices offer additional functionality and other devices are more cost attractive. All suppliers agree in reinforcing the importance of testing their products with their customer's products and applications as a critical procedure to improve performance results.

RFID tag application equipment solutions were discussed by Marken ([7]), Siemens Dematic ([55]) and Zebra ([62]). These documents dealt mainly with proposed solutions for the implementation of tag application to cases. Over the analysis of these products it is possible to notice that some of the currently available solutions are not suitable for high speed manufacturing. Even if the solution is capable of operating at high speed, it is likely it will still require some customization to comply with customer requirements such as tag type and position in the case. For pallet tag application the information available is scarcer but the indication is that a solution used for case application can be adapted to work with pallets.

Software solutions include articles from companies such as Oat Systems ([40] and [41]), IBM ([47]), SAP ([52]) and Sun Microsystems ([56], [57]). In addition to the highlights presented in item 2.1–Technology Overview, these articles describe the specific characteristics of the products they developed. Although the overall structure of the solutions is the same, it is necessary to evaluate which of the alternatives is best suited for the application, if the functionality is compatible with the requirements and more importantly, how the solution integrates with the existing software solutions available at the manufacturing facility were RFID is to be installed.

Additional product information used as reference is related to programmable logic controllers [48] and automatic identification using vision systems [32]. This information was used to estimate how these two elements integrate into the RFID solution and although it references to specific vendors, it can be generalized to compatible alternatives.

2.2.4. Lecture Notes

Lecture notes from two different M.I.T. graduate classes were used as reference in this research document, ESD.264 - Database, Internet & System Integration Technologies and ESD.290 - Business Impact of RFID.

From [34] – Kocur, G. - ESD.264 - Database, Internet & System Integration Technologies, key concepts of information technology applied to systems engineering were extracted, including databases, middleware and data communications and storage. This class included references to RFID and the reference model used for estimation of the volume of information to be generated, as discussed in chapter 6-Information Systems.

From [51] – Sarma, S. et all - ESD.290 - Business Impact of RFID, the author was able to have a hands on experience with the technical components of RFID systems, by building a fully functional RFID kit and experimenting with readers and tags, performing reading and writing operations and evaluating the influence of interference and different materials to the performance of the system. Lecture notes were also reference to supply chain management process analysis, policy and regulatory aspects of the technology.

3. System Integration

3.1. Introduction

It is possible to reapply learning's from the implementation of other new technologies to the implementation of RFID in manufacturing lines. In the work of Greenwood [22] on the implementation of flexible manufacturing systems, it is possible to find a few similarities to the introduction of RFID, especially regarding the justification for investment on a promising but yet evolving technology. Flexible manufacturing consisted of a technology and a group processes that were designed to improve the efficiency of batch manufacturing. By the time it was introduced, there were no standard approach to the problem and it was not simple to find suppliers and developers that had extensive experience in integrating the systems. It was also difficult to find support for the ongoing operation. Similarly to what it was then, careful attention to design and the use of sound project management practices will be essential to overcome the challenges and take full advantage of the potential RFID technology has to offer.

3.2. Challenges and issues to address

The implementation of RFID in manufacturing lines will involve more than the introduction of the Auto-ID standard elements described above. The implementation of RFID as a project can be viewed as the introduction of a new manufacturing or operation technology, in combination with the introduction of a new information system technology. Therefore, putting RFID to work can be viewed as the integration of two complementary systems. The first involves placing the tags on the product appropriately and getting data out of the system reliably. The second involves managing and integrating the data that is being generated, transforming it into information that is useful. It will require a great deal of integration between the different areas, inside and outside the companies, redefinition of business rules and processes, personal capability development and significant capital investment.

Placing the tags and getting good data reliably, include mainly the following challenges:

- Maximize system performance
  - Design alternatives that improve technical and operational overall results
- Minimizing capital investment costs
  - Reduce the risks of obsolesce with fast developing technology
- Technology Transfer and Training
  - Personal trained and qualified
  - Include RFID technologies into people's skill requirements
  - Update current operating procedures
- Reduce external interferences
  - Prevent existing RF emitting systems to interfere with RFID systems
- Data consistency and security
  - Data has to be verified and protected from interference
- Reliability of the process must not interfere with overall performance
  - Line performance must not be affected by RFID system

These challenges require the involvement from several areas within the organization including: product packaging development, industrial engineering, process engineering, supply chain, logistics and material management, procurement, quality assurance and finance.

Companies that have already started addressing these issues decided to proceed by selecting a sample product and location, where an in-depth analysis of the issues can be followed by a group of experts. Results from field trials have shown that the technology is capable of providing the desired functionality. However, overall performance of system still needs to be improved in order not to interfere with overall performance.

Managing and integrating the data into current information systems, include mainly the following challenges:

- Data storage, retrieval and standardization
  - Dealing with current and historical data
  - Inter systems compatibility
- Telecommunication and computational infrastructure
  - Adequate to the new volume and flow of information
- Electronic Business processes design and adaptation
  - Adequate to new information format and content
- Data and system integrity, security and reliability
  - Data has to be correct and readily available to the appropriate user

These challenges will require involvement of information technology professionals as well as process and logistics engineering groups.

As it can be found currently in the specialized press, the current stage of the implementation does not include full integration between all these systems and there is no end to end solution that could be found in the market. Field trial and experimental systems have also shown that technology is capable of providing the desired functionality. However, legacy systems, facilities management and resource planning systems are only starting to be adapted to receive the new form of information and business processes are starting to be designed.

As the adoption of RFID technology for handling electronic business processes increases, the criticality, defined as the importance of having the systems up and running, is also going to increase to very high levels, and operations will increasingly depend on the performance of the system.

Additional challenges related to the implementation include a narrow range of vendors that are experienced with the process and technology. According to experts in the field of system design and integration, it is estimated that after sales costs and efforts comprehend up to 30% of the total amount invested on such systems. Therefore, to increase in-house capabilities will be "key" to the success. Also according to such professionals, getting in house personal trained will increase implementation and costs considerably, from 2 times up to 4 times.

Details like managing products coming from overseas vendors or subsidiaries will also have to be addressed. The decision of whether to tag the item at origin or destination will represent additional logistic challenges such as the increased processing and handling time if tag application is performed off-line and also technical challenges like for example codes and data management, concerned with how and where the ID is going to be generated.

Total system reliability will be crucial to allow the introduction of new and improved business processes. First it is necessary to define the user's requirements (needs, issues, concerns and expectations). Then set test performance targets accordingly [16]. As more and more the information gets integrated into operating processes, the higher the required reliability will be. System will need to be fault tolerant and 24X7 redundant systems will be required [52]. Reliability is expected to be in the neighborhood of 99.9%, or 500 minutes of downtime per year, up to carrier-grade standards of 99.999%, or 5 minutes of downtime per year [59]

The technology will have to be operational across the supply chain, meaning that systems will be required to be flexible and follow standards. An adoption path that allows the evolution of the technology is important to preserve the functionality over time, as well as to make sure the migration from old to new systems is as smooth as possible. From the work of Lo [36], Rommel [49] and Sarma at all [51] there is evidence that the use of evolutionary implementation strategies is highly beneficial in this case. It addresses issues like building knowledge, increasing performance, reducing obsolescence and improving interoperability across different systems.

4. Case Level

Case level encoding, application and association of EPC tags is a process that can be divided into the 6 different steps described below. The time required to perform each task is considered to be the main constraint of the process and therefore it is the main focus of the analysis. The materials used during the operation, the equipment performance requirements and the procedures involved are additional considerations also explored in the following topics. The document highlights the main challenges and provides suggestions to address then.

4.1. The Process

Figure 4 – Case level application overview – suggests the process and the 6 different steps required for the case level implementation of RFID tags.

Step 1 of the process is the identification of the product coming on the line. Since we assume different cases are coming on the conveyor, this should be an automatic identification system, and it can be based on the existing bar codes, a special marker or the artwork printed on the box. At this point the system can also define if the case needs tagging or not. If it needs a RFID tag it follows to step 2. If for any reason the case doesn't need a tag, the control system identifies it and lets the case pass through, the skipping the RFID tagging steps.

After this item is identified, the control system needs to generate a product identification code – Product-ID. This product-ID code represents the object class of the EPC number, and can be the same UPC/EAN code used today. It follows the EPC manager number that is associated with the manufacturer, that can also be the same Manufacturer-ID UPC/EAN code used today. These numbers can be stored in the controller's memory.

Step 2 – the encoding rule – consists of combining these two preset numbers with the information generated at a local server. It consists of the unique serial number for that one case and the lock number, used to prevent the tag from being modified. The four pieces of data together constitute the EPC that will be written on the tag.

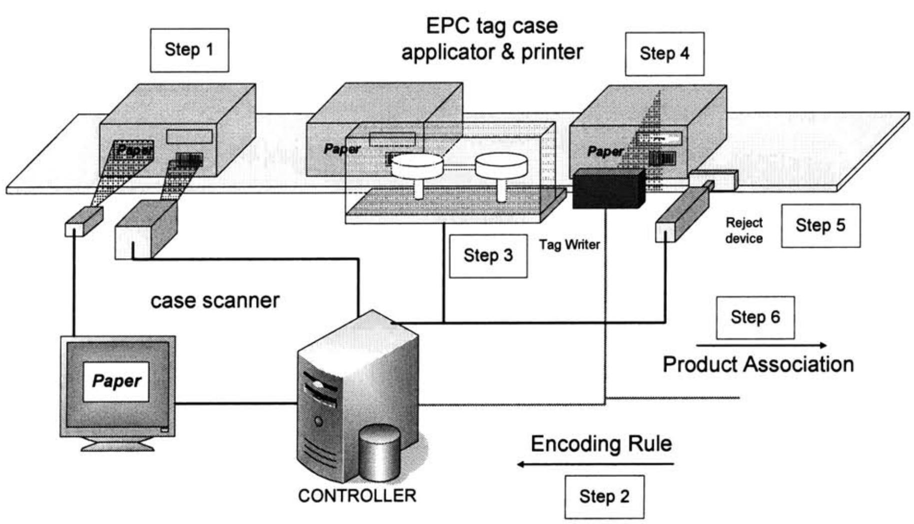

Figure 4 – Case level application overview

Step 3 of the process consists of applying the tag on the case. This step combines the action of a series of electro-mechanic devices and upon a triggering signal, the mechanical device that applies the tag to the case will be activated and by the end of the process the case will have a tag attached to it.

Depending on the position where the tag will have to be placed, a different type of mechanical device will be necessary. Depending on the type of mechanical device, different operation speeds will be achieved. The tag position on the case will be further analyzed on 4.3 – Material considerations below. The issues involving the equipment and time considerations will also be further discussed below.

Step 4 consists of writing the EPC on the tag followed by an inspection of the tag. The tag writer will receive the EPC code coming from the network, will convert it to radio frequency waves and store the number on the tag's memory. Second part of this step is the quality inspection. It consists of reading back the tag that was just written and generating a signal to be sent to the controller the represents the result of the inspection.

Noticeably, steps 3 and 4 have a good potential for being a source of defect and process delays. Depending on the expected quality / reliability of the tags and of the tag application device, steps 3 and 4 can be combined and may even need to be inverted. By doing so it is possible to optimize yield and reduce exception handling. See further analysis at item 4.3 below.

The writing process is performed by a read/write device and the process flow is the following:

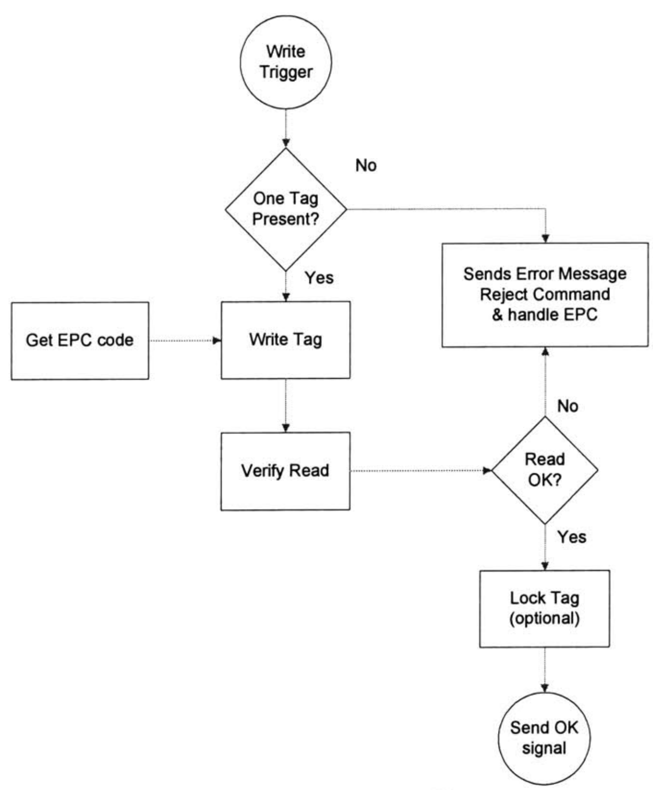

Figure 5 – Tag writing process flow

After the writing trigger signal is received from the controller, the device performs a scan to verify how many tags are present in field. For several devices available today, it is a condition to continue that only one tag is present in the reading field. If that is the case and the device is not capable of writing if more that one tag is present in his field, or if the verification result is not positive, countermeasures will need to take place as discussed in the following step.

Step 5 – Countermeasures in the case of failure of the writing and/or the verification process should consist of an action on the case and an action on the EPC that was generated initially. Action on the case may consist of an automatic rejection system like the one illustrated in Figure 4 – Case level application overview. With the indication that the writing was not successful, the system automatically rejects the case. Action on the EPC consists of the disassociation between product and EPC. The previously generated number can be stored for control purposes or discarded.

Step 6 – EPC to product association – consists of sending the EPC code resulting from a successful encoding and application to a database where the information will be stored.

4.2. Time Considerations

The constraint is that total time for executing all the steps above does not exceed 1000 milliseconds. The design of the system will define whether these steps are going to be performed in sequence or in parallel. It will be necessary to match design requirements to the current available solutions or to the capacity of developing custom devices.

According to the research sources, all these technologies can operate under timings that add up to less than 1000ms individually, but to date there are no examples of integrated systems operating under these conditions. Currently available systems operate at speeds close to 6 cases per minute - or 1 case every 16.7 seconds. Company demonstrations claim to be possible to reach 60+ full case applications per minute with cases lengths ranging from 8 to 72 inches [55].

Main time constraints and considerations that are relevant for this analysis are:

- Product identification time
- Code generations and data transfer time
- Tag application time
- EPC writing time
- Verification time

Product identification technology like machine vision systems or bar code readers already operate at speeds over a thousand parts per minute, or more than 15 readings per second. Therefore it is not expected that this component of the system will not interfere with operation time [32].

The generation of the unique serial number can be achieved in different ways. Serial number generation algorithms are fast and simple methods of generating a number that is always different from the previous numbers generated. In this case they will run o a controller like a PLC.

Programmable logic controller's running time and the communication between the different components of the system is a point that deserves careful analysis. The communication and data transfer between different systems need to be designed not to become a bottleneck. Available controllers usually operate at the speed of 1ms/K of logic or better. That means that with a typical program size of 20K, two scan times with I/O operations will take 40ms at the most [48]. For approximation purposes, if you consider the scenario were each step takes one scan of 20ms to be performed, total time for performing the 5 steps in sequence reaches is 100ms of processing time alone. This highlights the criticality of timing and illustrates the need for careful consideration on the process and equipment design. By performing tasks in parallel it is possible to gain steps in the process and by limiting the functionality of the controller it is possible to accelerate running time. Among the algorithms involved in the process, serial number generation used in the encoding rule is the most critical one. If it is necessary to include a lock key to the EPC, the algorithm may require some sort of encryption technique, and that could potentially delay the processing time. For data transfer rates requirements please see topic 6.2Data below.

Although traditional labeling machines operate today at speeds greater than 200 labels per minute, RFID tag application process include additional complexity that requires more time to complete. At a minimum, the process needs to include one attempt to write the EPC to the tag, followed by one reading for verification purposes. Current technology equipment typically performs this task in a time frame within the range of 250 to 1000ms, and main constraints are the process of writing the tag described above and the mechanical device that applies it to the case. Variables that influence the process are related to bandwidth, power, functionality (anti-collision) and protocol, and they can be translated into [54]:

- time required to establish communication between the writer and the tag
- amount of data to be written
- tag design & technology used
- number of verifications that need to be performed
- design & technology of the mechanical device.

The mechanical design of labeling device will also need to be done under the time constraint, and the use of adequate technology is necessary to guarantee process throughput. For example, pneumatic devices although beneficial in terms of cost and maintainability, tend to have slower responses than electromechanical ones.

Another alternative is to decouple the tag application to the case from the other steps of the process. That could be done for example if cases were already delivered to the point of usage with the tag attached to it. That could be something done at the case's supplier or at the manufacturer's own premises. This decoupling would allow step 3 – Tag Application - to be isolated from this process. Encoding and association however would still need to be performed on-line and therefore this solution doesn't address the writing time constraint.

From the timing estimates for each of the individual processes, it is expected that the major time constraint will be on the tag writing process. To improve its time performance, it will be necessary to reduce the time required to establish the communication between writer and tag and also to reduce the risk of interferences. To address that issue, it is possible to increase field homogeneity by installing RF shielding material around the writer and the case at the point of writing [58]. That would also allow a configuration that requires less verifications and false writing attempts. It is also possible to design antennae (1 or more) position and power in a way that the case is inside the RF field for the most time [51]. The use of buffers in the form of parallel conveyors, each one operating as a writing station is another alternative proposed by the experts. Costs and space requirements are characteristics that should be evaluated for this alternative.

The figure below illustrates a situation where shielding material is used. An adjustable speed conveyor can also be used to allow adjustment to different case sizes, adjusting the time the case spends within the reading/writing zone.

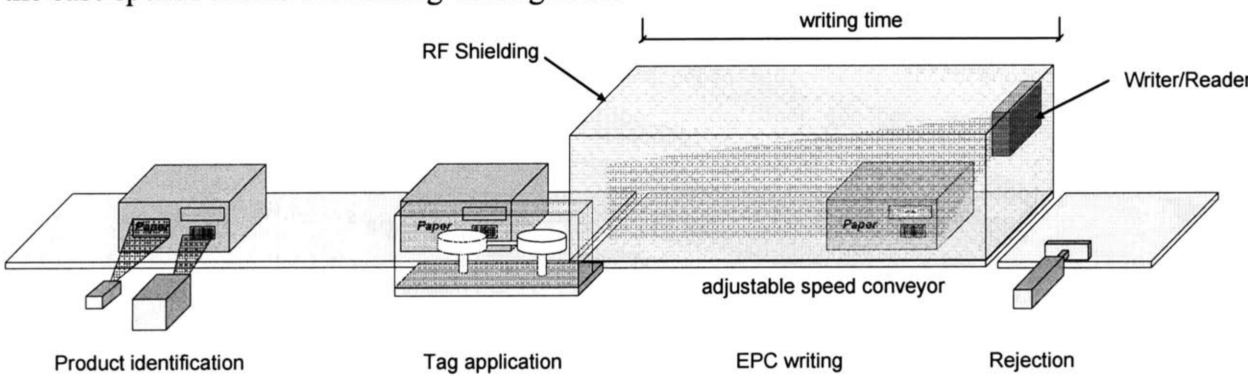

Figure 6 - Tag writing with shielding material

It is possible to evaluate and compare timing considerations with a simple analysis of Wal-Mart's initial requirements for the EPC reading operation. Their initial requirement is to be able to read 100% cases traveling at a conveyor speed at 600 feet per minute with 6 inch separation between cases [43], [49]. Under the same case lengths considered above (range from 8 to 72 inches), the average number of cases traveling on the conveyor can range approximately from 1.5 to 8.5 cases per second. If the reader's field allows multiple readings up to a distance of 5 feet for example, there will always be an average of 1 to 5 tags "visible", and there will be a new tag in the reader's field at a rate that ranges from 100 milliseconds to 650 milliseconds. Since our process will involve additional more intricate steps within a similar time frame, it is possible to evaluate tag encoding, application and association is cases as a more complex problem.

Under these considerations, the suggested methodology is to perform the steps according to the sequence illustrated in Figure 7. Step 1 starts allowing step 2 to start as well. After step 1 is completed, step 3 can start placing the tag on the case and step 2 can finish the encoding. After step 2 is completed, the tag is ready to be written in step 4. Step 3 is completed before the end of step 4 that is expected to be the longest part of the process. If any verification fails, step 5 is executed and if the writing step was successful, step 6 completes the process by registering the EPC to the database.

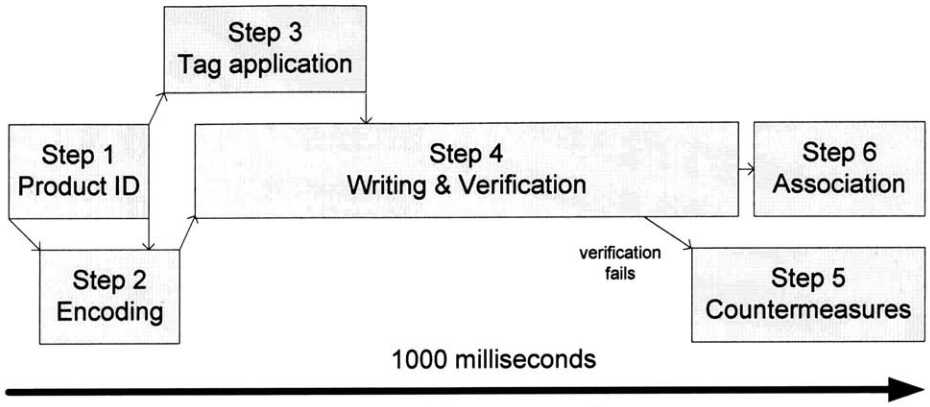

Figure 7 - Case level time process flow

In conclusion, the case level application, encoding and association time requirements are the most critical elements of the implementation on high speed manufacturing lines. Up to now, we found no report of system integrations under such conditions and it is expected that the most critical step is the tag writing process.

4.3. Material

Excluding the influence of product contents since we assume RF permeable products, the influence of the materials involved on the performance of case application process is primarily related to the case and the tag used. The considerations analyzed here are [6],[26]:

- Case physical characteristics
- Tag position in the case and pallet formation
- Tag quality
- Material reutilization

The case consists of the corrugated paper outer packaging used for transporting the goods. Case dimensions are relevant because they determine the area available and speed necessary for tag application. It also defines the pallet formation and consequently the number of cases per pallet and tags per pallet. Case dimensions are strongly tied to the product density, since it determines the volume and the case total weight. Product selling price also plays an important role in determining the packaging dimensions, since it determines SKU unit cost and the order lot sizes.

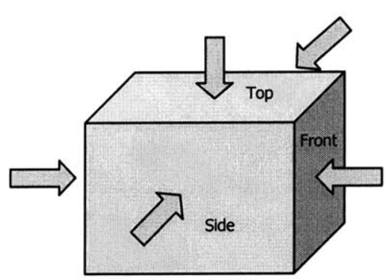

Figure 8 – Corrugated case

Arrows on the figure above indicate all the possible positions where the tag could be placed. Tag positioning criteria must include performance and tag durability concerns and it will have to be analyzed according to the packaging and product characteristics. From the experience obtained during the test pilots, it was observed that is was possible to achieve better reads if the tag was placed in a position were the most quantity of free air was present, so the RF field could have better penetration.

Since the EPC will also be required to be human-readable, it is necessary that it is placed in a position where it can be seen. It was also noticed that it is possible to prevent tag damaging by placing it on a position where it is less likely to be exposed to mechanical stresses. Under all these considerations and also that we have RF friendly product characteristics, the position were most of these issues are minimized is on the upper part of one of the case sides as shown in Figure 9. In this position, usually the least mass is present, the most free-air is available and where the mechanical stresses to the tags are reduced.

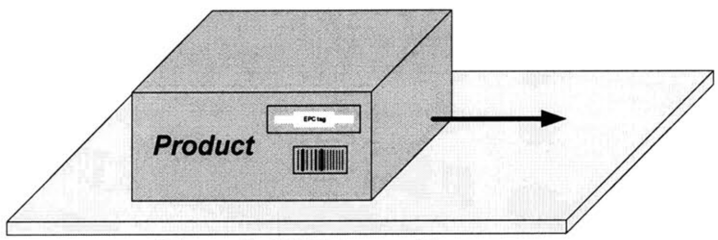

Figure 9 - EPC tag position

Since tag application into the case requires a certain area, artwork design will be required to adapt to the tag size. Most tags are made of a self adhesive paper or plastic substrate, and area required depends on the tag to be used, usually of square or rectangular shape.

Pallet formation is also important since it will determine how many tags per pallet will exist and how many layers of material will be between the tag and the reader. According to the principle that RF waves propagate differently across different materials, the general rule is that the less material between the tag and the reader, the less interference is observed and consequently the better the reading performance.

Tag quality considerations may affect the proposed sequence of steps defined for the application process as well. If the condition is that the number of defect tags is negligible, it is best to apply the tag to the case first and then perform the writing and verification like Figure 7 illustrates (step 3 before step 4). By doing so, it will be possible to verify whether the tag is properly working at the point closest to the end of the process, when no additional mechanical handling will occur.

If the condition is that the number of defect tags is higher than expected, by performing step 4 first and trying to write the tag before applying it to the case, it is possible to perform tag selection and attach to the cases only the tags that were written properly, reducing the need for handling cases with malfunctioning tags. Figure 10 illustrates this process.

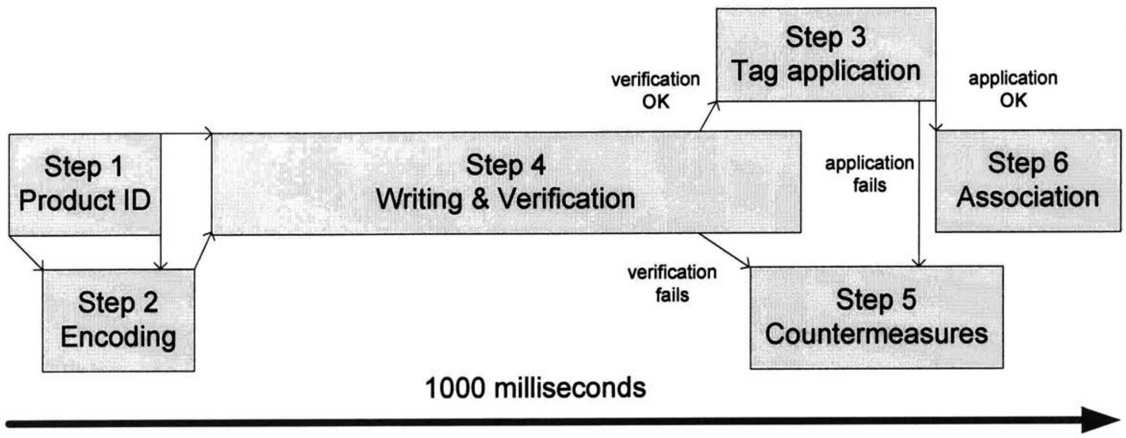

Figure 10 – Alternative case level time process flow

Substrate adhesive quality is also a factor that requires attention to prevent tags from falling out, a recurrent problem observed over the first field trials performed.

Packaging re-utilization is another factor that needs to be considered. Major concern when it comes to reusable packaging using Auto-ID is data consistency, and it is all related to the uniqueness of the association process. If the goal is to identify the case and its contents, if the packaging is reusable, anytime the original content of the container changes, a new association is necessary and the old association is no longer valid. If the goal is to identify the case in itself, than once it is tagged, the case will be always associated with that EPC and it will be valid throughout the case lifecycle. For the first option, when we need to identify the case and the content, since our goal is to use class 1 tags that can only be written once, the user will have to consider the tradeoff between the cost of managing the data from previous uses of the case and the cost of using a new tag. A new association will be necessary in both cases. Additional tradeoff to be considered is the adoption of a tag that allows writing multiple times, eliminating the need of a new tag and adding the memory erases operation to the process.

All these consideration have to be though not only for the location where the tags will be placed, but also across the supply chain at the different places where reading the tag is required. Therefore, coordination of design between the different players will be important and will help improve overall system performance.

4.4. Equipment Performance

In this topic, the goal is to address some considerations related to the performance of different devices involved on the process. It includes an evaluation of the current development state of the technology, comments about the available functionality and an overview of the expected trends in development [6], [26], [53]. The focus is on the devices used for case level and several of the findings are equivalent for the pallet level application analysis will follow.

4.4.1. Tags

Due to the relatively early stage of technology maturity, low cost passive tags are devices that are likely to experience several improvements over the next years. As usage increases and new manufactures enter the market, it is expected that costs will go down and that performance will increase. This is a particular important topic because it can potentially influence the evolution of all other systems.

According to the feedback from experts involved on the early implementations, tag performance has demonstrated to vary. The Hardware Focus Group at EPC Global is still working on a set of standards for controlling such parameters and it is also probable that a small percentage of tags are defective after their manufacturing process. Whether this percentage is acceptable or not will depend on the standards set by the different companies and, according to the previous analysis, it is possible to improve the results with careful design.

Today, within the available passive tags, it is possible to find a good variety of options, with different antennae and chip design, greatly influencing the overall system performance. According to experts and based on their experiences during the field trials, the process of selecting the most efficient type of tag involves the analysis of the process, the product and the packaging and it is still at a large extent an empirical process, that requires testing and experimentation.

4.4.2. Tag application technology

The currently available information suggests that automatic RFID tagging technology is also at an early stage of development at this point. Automatic RFID tag application is being developed both by traditional labeling equipment companies and by companies that deal with automation and material handling devices. Currently available devices operate under different conditions and follow different sequence of steps.

Although it was not possible to evaluate the performance of such devices under the 1 case per second time constraints, it is possible to highlight some of the key points that need to be addressed while evaluating such equipment.

In addition to the time and speed considerations examined, another important criterion to be considered is how flexible the device is to the different case sizes and conveyor speeds. The flexibility of the device will define how well the system will perform with the different products that currently run on the line and also future introductions. Depending on the number of different products that run on the same line, different types of tags will be required and the capacity to operate with several types of labels will be necessary.

Performance reliability is crucial and main factors to consider include maintainability, parts availability and after sales support. People on site will be required to not only to be able to operate but also to provide service since this equipment is likely to be considered mission critical and ranked among the devices that require high mean time between failures and low mean time to repair.

4.4.3. Printing technology

Assuming that there is going to be a transition between current processes and technologies and the RFID enabled ones, it is necessary to keep existing human readable and barcodes printed in the exterior of the packaging. Depending on the technology used, the adopter will have the option of keeping existing coding and adding the EPC tags or to migrate to EPC coding.

Typically, barcodes and human readable coding come pre-printed, but with the introduction of the serial number to the EPC, that will require on-line printing capabilities. Experts in the industry, when asked to compare thermal versus ink-jet printing, indicate that thermal printing is more robust and in many cases may result in better cost and quality.

4.4.4. Reading and writing equipment

Being able to read multiple tags efficiently and to write a tag quickly are the main aspects that need evaluation and that is something that can be optimized with design and configuration of the system. Some of these considerations include the communication protocol between reader and tag, relative position between tag and reader, the requirement of having only one tag within the field for writing the EPC and the parameters that are going to be set for programming the tag.

Working with both classes 0 and 1 tags require the reader to be able to communicate in two different air protocols and different anti-collision algorithms. The readers that are capable of doing so are known as agile readers and they allow for greater flexibility in selecting the type of tag to be used.

Optimal positioning and distance between the writer/reader antenna and the tag is usually indicated by the equipment manufacturer and it needs to be kept within the range that is specified. Depending on the coupling technology between the tag and the reader, it is possible to improve reading performance according to the position of the tag relative to the readers on the different reading locations. For inductive coupling, typically the best reading condition is when the tag's antenna is directly facing the reader, that is, when the tag's antennae is perpendicular to propagation of the waves. Tags positioned on the sides of the case will be better read by antennas with stronger propagation in the horizontal direction while tags positioned on the top to the case will be better read by an antennae positioned over the conveyor facing down as it can be seen in Figure 11.

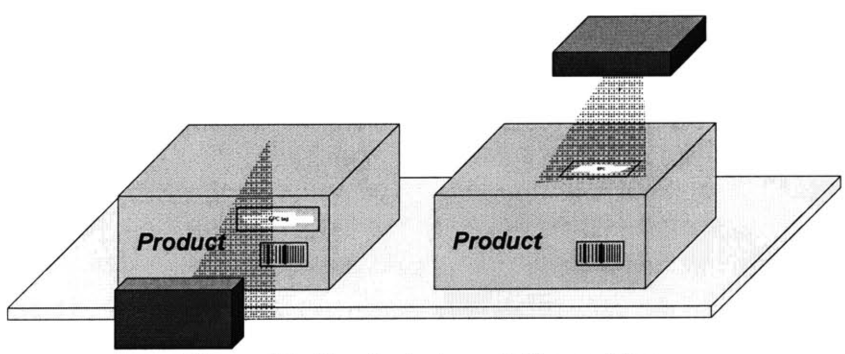

Figure 11 - Reader to tag relative position

Regarding the configuration of the writer/antennae's parameters, the main settings include the power and command settings. Power settings include the appropriate adjustment of the system gains and sensitivities. Command settings include the number of retries to be performed after each failed attempt to read or write and the use of verification schemes like checksum. The use of verification schemes and an increased number of retries increase the likelihood that the system will have better outputs, but it also increases the time required to perform the writing.

The design of the positioning of the readers also has to take into consideration the local safety requirements. In the US, it is required to comply with safety regulations that define that personal should not be positioned closer than 23 cm (9 in) to antennas for prolonged periods. (FCC OET Bulletin 56 "Hazards of radio frequency and electromagnetic fields" and Bulletin 65 "Human exposure to radio frequency electromagnetic fields").

In conclusion, high speed manufacturing and case level application equipment's performance requirements evolve around all individual components of the system. Current research indicates that solutions are still evolving and will require a rigorous commissioning, qualification and verification process. Performance based try-outs and acceptance tests can help adopters to evaluate the systems offered by different suppliers and the recommendation is to perform such tests as close as possible to the real environment where the system will be installed.

4.5. Procedures

The introduction of RFID technology into manufacturing lines will require the revision of a set of standard operating procedures and processes to include the inspection of the EPC and the information associated with that.

EPC tag will be another variable in the manufacturing process and the information associated with it can be used to perform other processes like inventory management for example. According to a quality control expert interviewed, it is recommended that the EPC tag application is considered a quality attribute and the information written on the tag is considered a quality process variable. This means to apply to the information generated the same quality controls other quality variables such as temperature or weight receive on a given company. Tag application problems will be considered a quality problem, passive of the same countermeasures adopted by the company to other quality issues.

Depending on the industry's nature and the different company's policies, different processes will be affected by the introduction of such technology. On the line operations, the typical processes that will be affected are:

- Material receiving and inspection - quality control of starting materials
- Line clearance - tagging system will be required to be operating to allow line startup
- Process control - period inspections of tag application and data read
- Product reprocessing - data associated with product that was damaged downstream on the process
- Validation and change control - impact on the RFID system will have to be addressed for any change on the line
- Training, maintenance and safety procedures - updated to include the new technology
- Product release - will require to include tag inspection as a quality control measurement

Additional processes that will be required for the line operation may include:

- Data management and maintenance
- System periodic inspections

Inside the data management and maintenance processes, the serial number generation is particularly import. In large organizations that have several facilities were tags can be placed, another process that will be introduced is related to the management of number quotas that from time to time will have to be revised in order to guarantee EPC uniqueness. Right now the UPC/EAN Manufacturer-ID is unique for the company and you cannot distinguish each of the subsidiaries. Usually companies have an internal code that identifies each site, and that number can be incorporated into the Manufacturer-ID. Depending on the coding system used, different numbers will remain for the serial number and that is something that has to be managed carefully, preferably by a central organization that is capable of overseeing the development of products across the different sites, taking into consideration the estimated volumes to be produced during the product life cycle.

The generation of the unique serial number may include the addition of some form of structure can be used on such algorithms and it is especially useful for organizations with multiple manufacturing locations. Examples of structured serial numbers are the ones that include a geographical and or product related information to the serial number, forming a code that is unique across the organization. For example a 15 digit serial number could be in the form a,bbb,ccc,pp,dd,rrrr where "a" is the last digit of the year of production, "bbb" is the Julian day of production, "ccc" is the site ID, "dd" is the manufacturing line, "pp" is the product family and "rrrr" is a daily generated serial number.

5. Pallet Level

Pallet level encoding, application and association of EPC tags is a process that can be divided into the 3 different steps described below. The time required to perform each task is no longer considered to be the main constraint of the process, therefore, the main focus of the analysis is shifted to the capacity of reading multiple tags simultaneously with high performance and to making sure the pallet EPC identifies correctly its contents. It includes the materials used during the operation, the equipment performance requirements and the procedures involved in the process. The document highlights the main challenges and provides suggestions for addressing then.

5.1. The Process

A full representation of the pallet level application, encoding and association process can be viewed below.

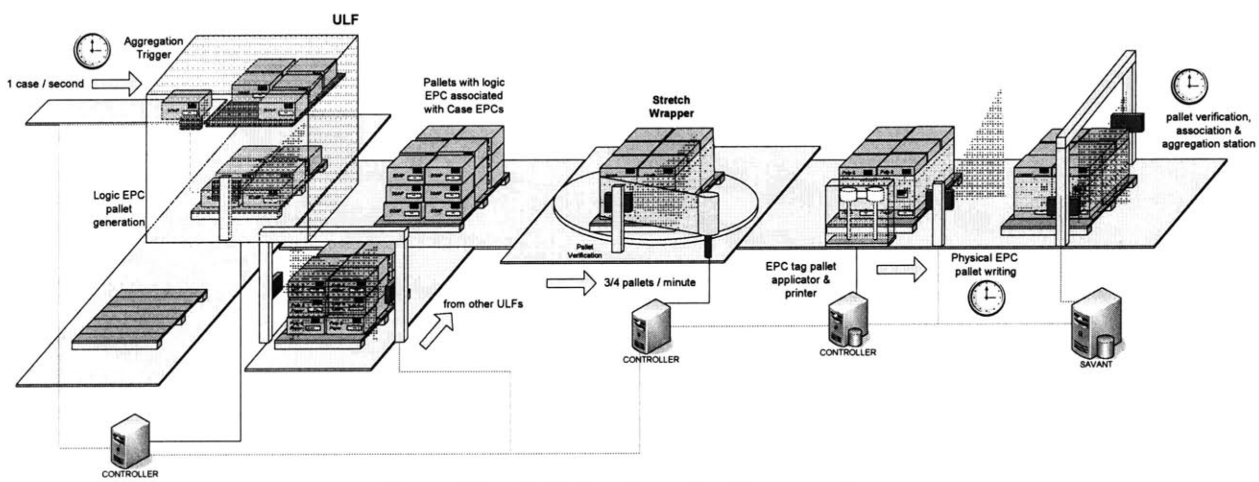

Figure 12 – Pallet level application overview

It can be divided in 3 main steps: 1) pallet building and encoding, 2) Pallet verification, EPC tag application and writing and 3) Pallet association, aggregation and final verification.

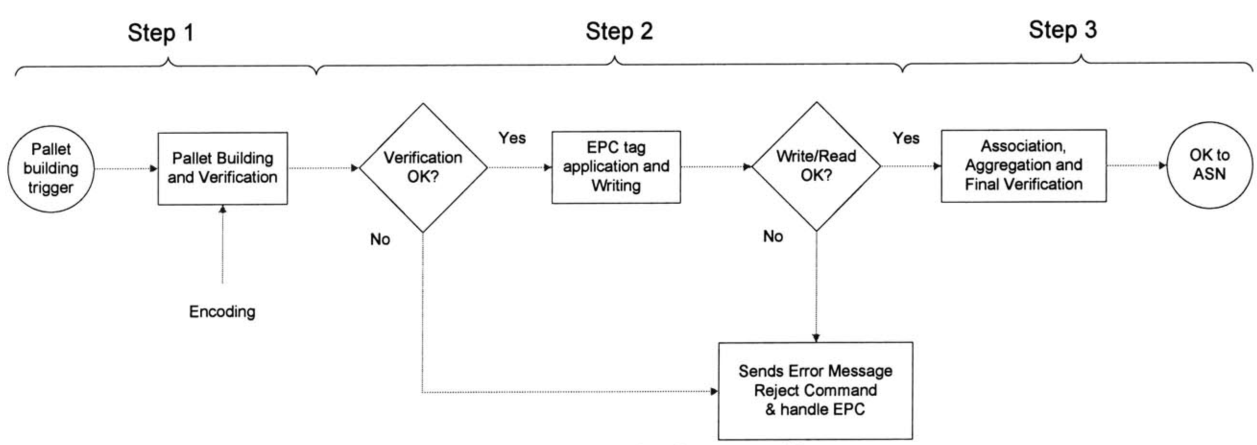

Figure 13 – Pallet level process flow

Step1, the pallet building is the process represented in Figure 14.

This process starts with a trigger that indicates that a new pallet is going to be built. The suggestion, based on the experiments from early adopters and experts in the field, is to use an EPC reading coming from a reader placed at the entrance of the palletizing process. Every case with an EPC tag that passes this point will be part of a pallet that will be formed. The palletizing process can be either manual or automatic, like it is displayed in Figure 14, and in both cases, an additional reader placed at the location where the pallet is being built will promote the association of cases that are being placed together.

To enable the verification of the pallet building step, it is necessary that the pallet formation process is something that can be previously determined and programmed into an EPC enabled control system. The formation program must also include information on whether the pallet will have a RFID tag or not, and if the cases used in the pallet are RFID enabled or not. By having a reference formation, the system allows monitoring of both manual and automatic pallet building; when the formation is always constant for a given product and when the formation changes from pallet to pallet.

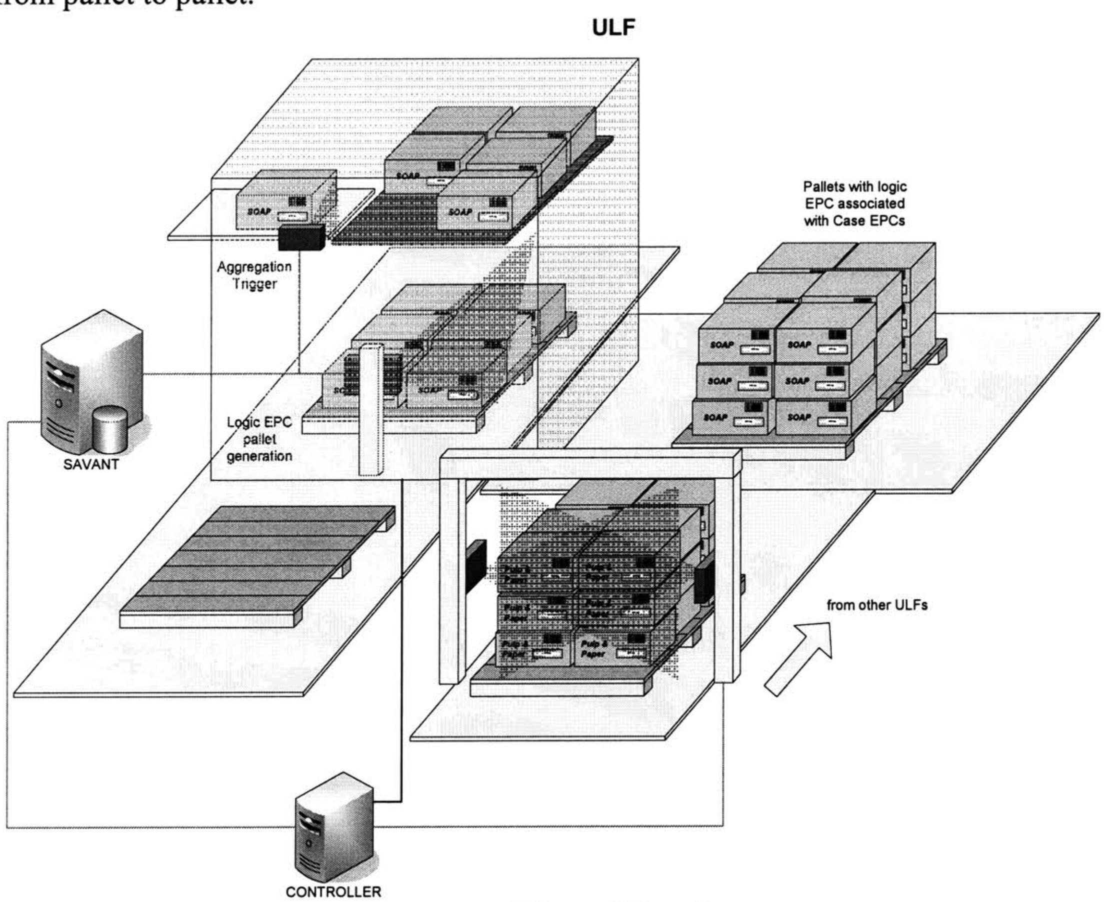

Figure 14 – Pallet building and Encoding

After the pallet is fully built, the bundling is complete and an individual ID can be associated with the pallet – the encoding process. This process will consist of generating the different fields of the EPC code, based on the information from the different cases that constitute the pallet and the manufacturer ID. This code can be generated at this point and will be written to an EPC tag further on the process.

As illustrated in figure 3, the endpoint of this process may be a confluence point for pallets coming from other pallet build equipments or processes. This could happen to take advantage of high capacity equipment located downstream on the process, for example a shrink wrapping machine.

Step2, EPC tag application is the process represented below:

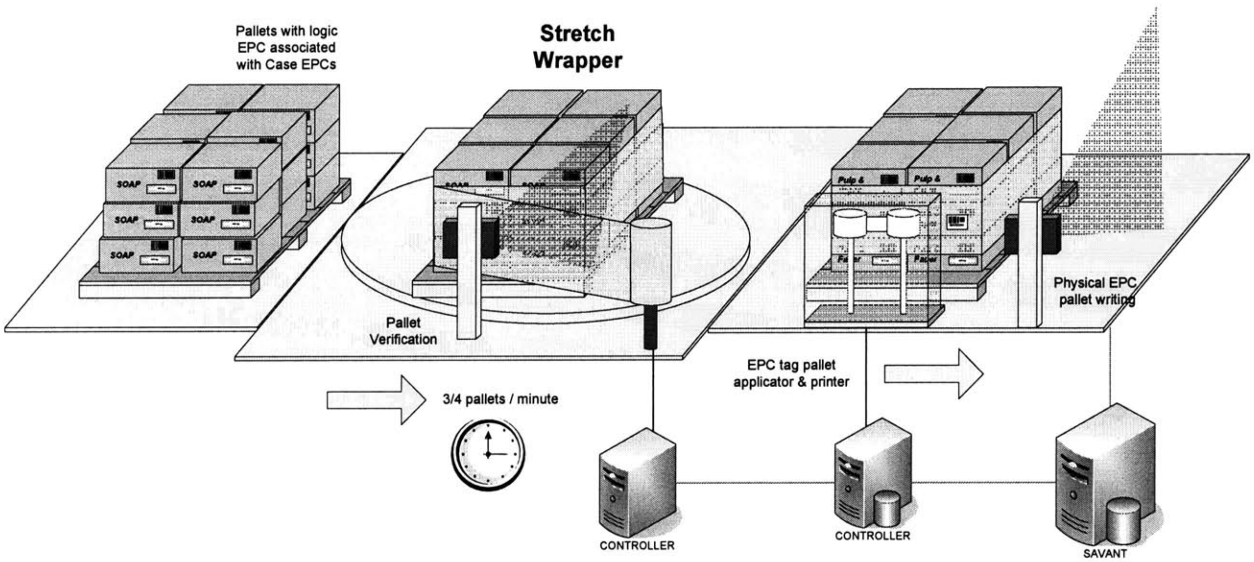

Figure 15 – Verification, tag application and writing

First part of this process is the pallet verification. It consists of performing a full read of the cases that form the pallet in order to determine, under pre-defined criteria, whether the full pallet is "readable" or not. These criteria can be a comparison between the expected number of tags and the number read, the expected identities to be found together and the actual result or both.

The suggestion is to make the verification at the stretch wrapper point of the process. This is the point where the pallet is going to be "sealed" and, if the verification criteria are not met, the pallet could be ejected before wrapping. Another potential benefit of making it at such device is to make use to the rotating functionality of the equipment that allows sweeping the different sides of the pallet.

Optionally, or if the process does not include a stretch wrapping device, the verification could be performed at the same spot were the encoding process took place, as the final part of the pallet building step.

If the result from the verification is good and criteria are met, the pallet continues to the next step in the process. It consists of doing the final association between the pallet's and case's EPCs previously generated to the tag.

At this point, the process of applying a tag to the pallet and of writing the EPC is different that of the case level. First because writing speed is not as critical and also because the writing process many times requires that only one tag is present in the writer's field. The reduced requirement in terms of application speed enables additional solutions that can be more flexible and reliable, simplifying the application. The proposed solution if the writer requires only one tag in his field is to perform the tag writing before the application and some sort of enclosure may be required. The after application verification can be performed in the following step.

Step3, pallet association, aggregation and verification process is represented below:

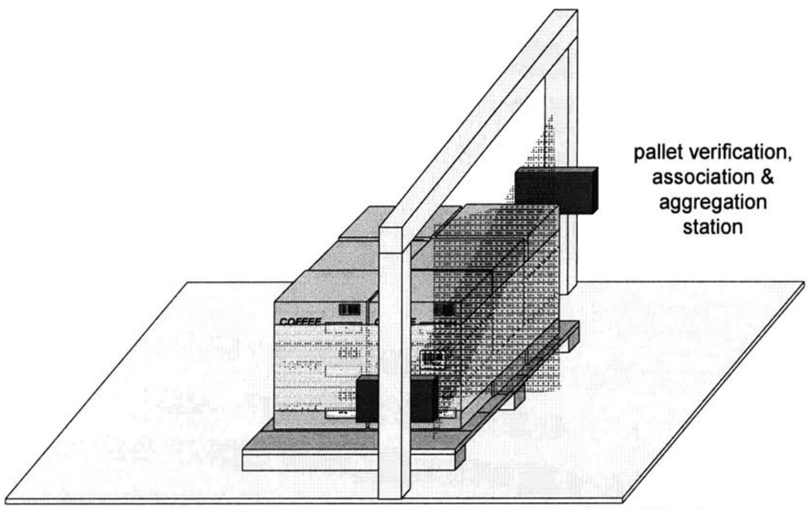

Figure 16 – Association, aggregation and final verification

Last step of the pallet encoding, application and association is to perform a "close to reality" final read on the whole group formed by pallet and cases.

Pallet aggregation is the process of being able to identify a loaded pallet, even if not all tags can be read. According to some of the companies interviewed, it was verified and reported on the first field tests performed that depending on factors like the pallet formation, the product and the physical environment were reads take place, it is not always possible to read all cases on all pallets passing through a portal like the one portrait in Figure 16. However, it is possible to increase system performance by assuming that it is possible to identify the entire group with only a partial read of the tags included in it.

Following the process illustrated here, one can see that such assumptions are not detrimental, especially if all the verifications are performed and the process includes stretch wrapping the pallet, which prevents cases from being separated from the original pallet, unless the wrapping is destroyed.

The end of this process is the inclusion of this bundle of pallet and cases that is now ready for shipment or storage. This is the point were pallet EPC information will be integrated into systems like the Warehouse Management Systems were inventory management and shipping transactions will take place.

5.2. Time Considerations

Time considerations are less critical in this process that it was on the case level. Although the number of cases per pallet can change considerably, the process will always be slower than or equal in speed to the case process. Additional equipment and process considerations that are relevant will be discussed below.

5.3. Material

The influence of materials on the performance of the pallet level application process is similar to the influence analyzed for the case level application and it is primarily related to:

- Pallet formation
- Tag position on the pallet
- Use of pre-tagged pallets

Pallets, differently than cases, are a more standardized unit for loading and handling materials. The International Standards Organization (ISO) lists six different standard sizes at the ISO/DIS 6780 - Flat pallets for material handling – Principal dimensions and tolerances norm. However, the most commonly adopted ones range from 32-40 X 40-48 inches, and the 800X1200mm EURO pallet is the one most widely used [60]. The area base, in addition to height and total weight limitations are the main variables that define the number of cases that can be placed on a pallet. That means that a pallet can contain from 1 single case up to a 100 cases, and that is order of magnitude for the number of tags that will be found on a loaded pallet. This defines the number of reads per pallet and the dimensions of any mechanical device that is going to be used on the system. In addition to the number of tags per pallet, the formation will also define how many layers of material there will be between the tags and the readers and, since radio frequency waves can be influenced by such layers of material, the performance of the system can be also be affected [2].

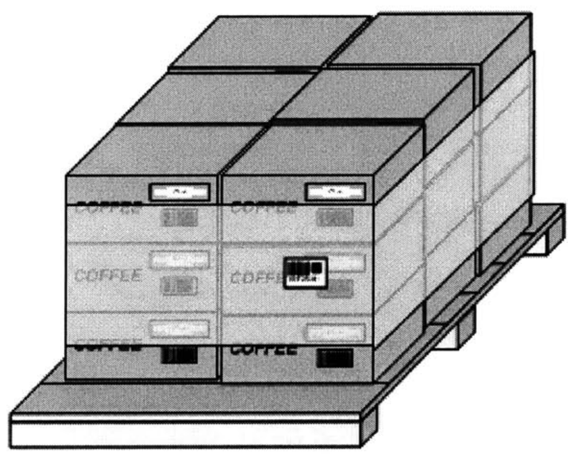

Figure 17 - Loaded pallet with EPC tag

On tag position on the pallet, the analysis showed that pallet level tags can be placed in three different locations: at different places on the pallet. One is at the top, on one of the cases that form the bundle; two is on one of the sides, on one of the cases or at an external wrapping and three is on the pallet itself. According to experts in the industry, the ideal position to place the pallet EPC tag is on one of the sides, preferably at an external wrapping, as it is displayed in Figure 17. This alternative makes the tag less vulnerable to damaging comparing to placing it on the pallet body. It also prevents the occurrence of an object having two different tags comparing to the placing it on one of the cases. Because of the wrapping, this option also helps to have a unique relation between the EPC and the bundle composed by pallet and cases. In order to remove any of the cases from the bundle it is necessary to damage the wrapping and this is the event that determines that the association is no longer valid, since the bundle's contents changed.

Material reutilization at the pallet level is primarily related to the use of pre-tagged pallets, pallets that permanently carry an EPC identification. It is common practice in certain industries to have all pallets supplied by a vendor and those pallets are shared by multiple customers, one practice sometimes called pallet pooling.

Some of these vendors are already starting to offer RFID enabled pallets [12] and although this in an interesting solution that eliminates the need for repeatedly applying new tags to the pallet bundle, it is necessary to carefully consider the issues involved in data consistency and uniqueness of the pallet to product association. Assuming the EPC on the pooled pallet is fixed, it will be necessary to add to the process the control over every new use of the pallet to allow the system to make the correct association. In the case the EPC on the pooled pallet is re-writable, the need for control shifts to the point were the tag can be re-written assuring protection against incorrect tag re-writing. According to experts in the field, these issues could be overcome with the use of a logic EPC, that would be associated with hard coded EPC. This logic EPC would be volatile and would be used only while the association was valid.

5.4. Equipment Performance

In addition to the considerations previously stated for the case level equipment performance, the main RFID related considerations for pallet level application are regarding the capacity of performing multiple reads simultaneously and the for preventing the interference from the various nearby readers and pallets

The number of tags on a pallet bundle can reach magnitudes in the order of hundreds. For this reason, the challenge of reading performance is different from the case level were it was necessary to make single reads very fast. At the pallet level, it is necessary to be able to read several different tags, on a larger window of time. That means the system will have time to perform several reading attempts, but the reader will be required to "see" all tags that will be trying to respond simultaneously. To address this requirement, the design of the reading stations will have to evaluate different antennae configurations, with different field properties. Reader settings' will have to be carefully adjusted to these conditions and field trials and experimentation will have to be performed to validate the design.

The design of the pallet reading stations or portals is also important to minimize interference. It is expected that pallet level application will involve larger distances between the tag and the reader's antennas. This requirement exposes the system to the possibility of having the fields from adjacent readers interfering with each other. It is also possible that pallets are close enough to each other so that readers are able to capture readings from two different pallets. To prevent such undesirable effect and improve equipment performance, it will also be necessary to carefully design the location of the reading stations in the line and perform adjustments to the reader's settings. Pallet flow on the conveyor will need to be controlled and the use of RF absorptive material may be required, similarly to the solution proposed in Figure 6 - Tag writing with shielding material.

5.5. Procedures

In addition to the considerations previously stated for the case level work processes, the main RFID related considerations for pallet building are the ones related to exceptions and countermeasures handling, or conditions where the assembly process don't follow the normal process or for any reason it is disrupted or it is required to be aborted.

As explained in the pallet building and encoding processes, it is at this point that the pallet EPC is generated in our model. Therefore, if a pallet enters the system after any of these steps, it would not pass the verifications performed and would have to be ejected from the line.

According to the group interviewed, the process of having to reprocess a pallet or cases of a pallet after it left the final reading station is something that needs to be contemplated in the EPC pallet tagging system. These processes however interfere with the information that was already stored at a pallet/product database, as it crossed the reading portal in the end of the production line.

Depending on how critical individual case identity information is, different set of rules can apply. To make sure the information is consistent and that the EPC association is correct, one extreme alternative is to consider that every time you change the contents of a pallet you lose the EPC attached to it. In this case, the recommendation is to generate a new EPC every time such an event occurs. In this event, the cases that need reprocessing would have to re-enter the process at the pallet building step and the old association would have to be canceled on the database. The suggestion in this case is to include these tasks as part of standard operating procedure for handling the incident that generated the need for reprocessing the pallet originally.

6. Information systems

The information systems infrastructure is treated on a separated chapter here due to the importance and influence it will have on the entire system. To access the design requirements of these systems, the methodology adopted here consisted of building one example elaborated for the case and pallet level applications. This exercise allows a rough estimate and evaluation of the network bandwidth and data volume and storage requirements for the implementation of an RFID – IT network on a manufacturing site with high speed lines and automatic material handling equipment.

Information systems encompasses the hardware and software infrastructure required to retrieve, process and store the data generated by the RFID network of tags, writers / readers and database servers. Information systems can be divided in three areas: 1) Base systems consisted of logic controllers and operation equipment; 2) Middleware consisted of data management and storage systems and 3) Applications, consisted of decision, planning and business transaction systems.

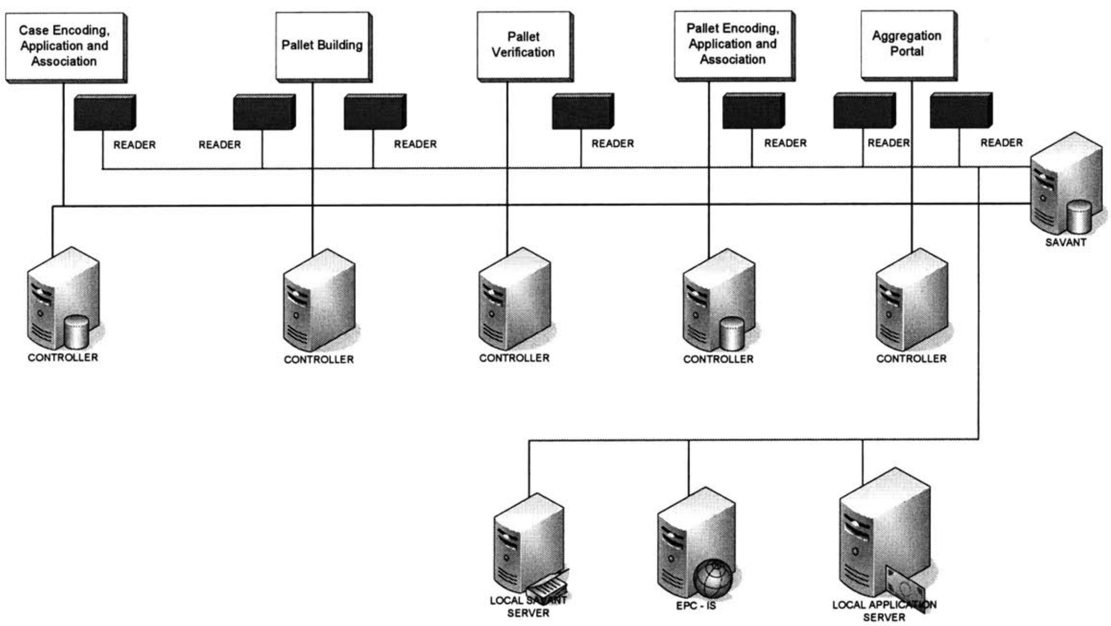

Figure 18 - Information system infrastructure

As it can be seen in the GTIN-96 example showed under Auto-ID standard components – a single tag read of 96 bits, after combined with timestamp information and formatted in PML, becomes a packet of 196 characters, or an .XML file of 209 bytes. This is the least amount of information that is going to be generated on each reading, and it is based on this minimum information size that will discuss the information system requirements.

It is also necessary to differentiate case and pallet level requirements. Case level application will consist of reading and writing single tags at the fastest rate - 1 per second. Pallet level application will consist of writing a single tag and reading multiple tags (up to a 100 + 1 at a time) at a slower rate of 4 pallets per minute.

This analysis will be based on an exercise proposed by Kocur [34] and building on his proposed framework; we will provide an estimate of requirements for network bandwidth and design, database speed and capacity. This estimate assumes that at all times, 100% of the tags can be read.

On our considerations will use the following notation:

Y_C	- yield of cases per line per second	[case/second]
Y_P	- yield of pallets per line per second	[pallet/second]
L_C	- number of lines at YC cases per second on the network	[case lines]
L_P	- number of lines at YP pallets per second on the network	[pallet lines]
S	- number of scans per second on the network	[scans/second]
D_S	- data size per scan	[bits/scan]
B_W	- minimum required bandwidth	[bits/sec - bps]
N_C	- number of readers scanning cases on the network	[case level readers]
N_P	- number of readers scanning full pallets	[pallet level readers]
P	- total number of pallets at any given second	[pallet]
C	- total number of cases per pallet Considered constant for all pallets coming from the same line	[case/pallet]

Each production module j will consist of a group of n L_C lines running at Y_C cases per second, converging into one pallet line (Building + Verification + Writing + Reading Portal), in a way that:

$$Y_{P_j} = \sum_{i=1}^{n} \frac{L_{C_i} \times Y_{C_i}}{C_i} \qquad (1)$$

And the total yield of pallets from the m production modules will be:

$$L_P \times \sum_{j=1}^{m} Y_{P_j} \qquad (2)$$

In our example, each line producing cases has 1 reader that will perform the encoding and the verification and therefore:

$$N_{C_i} = 1 \times Y_{C_i} \times L_{C_i} \qquad (3)$$

And each pallet line will have 6 readers (2 Building + 1Verification + 1 Writing + 2 Portal) and therefore:

$$N_{P_j} = 6 \times Y_{P_j} \times L_{P_j} \qquad (4)$$

This makes the total number of scans per second and the minimum required bandwidth for the total system to be:

$$S = \sum_{i=1}^{n} N_{C_i} + \sum_{j=1}^{m} N_{P_j} \times (C_i + 1) \tag{5}$$

$$B_W = S \times D_S \tag{6}$$

6.1. Network bandwidth

Using the equations above, lets analyze the example were there is only one production module (m=1). We have 4 production lines (n=4) and they all run at the same rate of 1 case per second ($Y_{C\,i}$ = 1 for all *i*). Each pallet holds 60 cases (C_i = 60 for all *i*) and data size per scan is 300 bytes - (D_S = 300 x 8). 300 bytes per read is the file size from PML example in item 2.1.5.

Variable	Value	Unit
m (production modules)	1	module
n (production lines)	4	line
$Y_{C\,i}$ (line yield for all lines)	1	case / sec
Y_P (yield of pallets)	1/15	pallet / sec
C_i (number of cases per pallet)	60	cases / pallet
D_S (data size per scan)	300	bytes

Table 4 - Data volume per second example

From (1) we have that the process output will be 1/15 pallets per second, or 4 pallets per minute. From (5) we have that the number of scans per second on the network will be 28.4. Coming from case readers we will have 4 scans per second and coming from the pallet readers we will have 24.4 = [6 x 1/15 x (60 +1)] scans per second.

From (6) we have that one production module will generate 68.2 kilo bits of data per second, or 68.2 kbps.

With readings generating this amount of information, it is possible to estimate that a 10 Mbps Ethernet network, the protocol commonly used for database servers and computer communication within a site, is enough to handle one facility like the one we described, even at its 60% theoretical throughput. Considering that this facility uses a T1 (1.5 Mbps) connection exclusively to share RFID information, the total number of lines that the bandwidth could hold @ 60% utilization is in the order of 20 lines.

6.2. Data volume and storage

With the generation of the amount of data per second described above, the amount of data after 24 hours of operation will be in the order of the units of Giga bytes of raw data and in the order of units of Tera bytes on a per annum basis. For compassion purposes, according to experts in supply chain and data warehouse information systems, this estimate represents a data volume that is 3 to 6 times the current amounts generated today. According to the current available specifications from integrators and developers [40], it is expected that after the raw data is filtered at the Savant/Middleware level, this volume will be reduced considerably. However, it is not all clear at this point what will be impact of further aggregation of information as it migrates to different points in the supply chain. Nevertheless, this analysis provides an assessment for one individual organization, and that is that it will be dealing with approximately 1 to 10 Tera bytes of data per year, assuming all information generated is retained.

The research performed indicates that to handle that volume of information there are 3 main equipment /hardware requirements that need to be considered. They are:

- Capacity to handle I/O operations
- Storage capacity for volume
- Data protection - mirroring

Going back to the exercise proposed by Kocur [34], it is possible to estimate the number of I/O operations your data storage systems will have to handle by first assuming that each RFID scan results in 1 disk read and 4 disk writes on the RFID database (indexes, logs, tables and statistics are updated; ID tags are checked for validity; etc.)

With a disk operating at *W* I/O operations per second and an *S* number of scans occurring every second, it is possible to estimate the minimum number of disks required to perform all these transactions and also the best disc configuration to be used.

$$\text{Minimun number of disks required (I/O operations)} = \left(\frac{5 \times S}{W \times 0.6} \right) \qquad (7)$$

Based on the previous example, suppose we have S = 28.4 scans per second and that W = 140 I/O operations per second. From (7) we have that we will need 2 disks per operation module only for data. In order to include data protection, a recommended strategy is to use mirroring. That requires you to add 2 disks in a RAID 1+0 configuration (striping and mirroring) and the total number of disks per operation module reaches the number of 4. By using standard hard-drives available today, it is possible to estimate that a group of 4 40 Giga bytes RAID 1-0 hard drives will be close to capacity after approximately one month of operation.

It is also recommended to have separate disks for the operating system, with the same type of protection. That adds another 2 disks to the system.

This exercise provides an estimate that if used as reference allows adopters to better evaluate the impact the new information format and content can have on current systems. It shows that the amount of information that is going to be generated is significant and that it required high performance and high capacity systems, especially at the middleware level of the infrastructure, where the information will be filtered. The increased volume of information however is still consistent with the increase in storage and computational capacity that has occurred for the last several years. As a reference, current estimates are that it will take from 3 to 5 years for the technology to reach full implementation stage with EPC data sharing across organizations, and that it will potentially increase data volume from 3 to 6 times. During this 5 years period, it is also expected storage and processing power doubles 2 or 3 times, adapting accordingly to the additional information generated.

7. Observations and conclusions

This research document was developed based on the analysis of current implementations of RFID systems, with the inputs from some of the leaders in the industry and taking into consideration a good portion of the published information on the topic available today. Under the definition of the time and performance constraints and motivated by the importance of making these processes a reliable source of information for the broad range of supply chain applications envisioned for the future, the boundaries of the problem were defined. The document was divided into system integration challenges, case and pallet level encoding, application and association and information technology requirements. The focus relied on the design of the processes and on making sure that most critical characteristics of the problem were captured under the different considerations.

Under such conditions, this analysis suggests that the integration of the different components of the system will include challenges related to performance maximization, investment analysis addressing the risk of obsolescence and system interoperability with internal and external systems. It will also have to address requirements for technology transfer and training, data management, product and process design. The analysis also suggests that early adopters will benefit the most of the technology by developing it internally and using the test pilot implementation approach, learning with the process and building capability to develop, operate and maintain this mission critical system.

For the case level application, the observation is that the tag writing step is the most critical one when it comes to time and that the reliability of the tag applicator and the tags themselves are the most critical considerations when it comes to performance. At the pallet level, it suggests that the most critical considerations are related to performance, and the potential major sources of impact are data consistency during pallet formation, the influence the operation procedures, as well as the need to prevent interferences from different readers and pallets on the physical layout of operation.

Related to the data generation and storage requirements, the analysis presented here suggests that the volume of data that the RFID system is going to generate is compatible to currently available data management systems and that the expected evolution of the capacity of information systems is also in synchronism with the expected growth in volume of data.

Limitations from this analysis rely on the several simplifications that were done. By selecting a narrow range of products and only one type of packaging, the case level application process was limited in scope and pallet level application assumed a sequence of events and a level of automation that is not always possible to have or to achieve at the different manufacturing sites. Also, the analysis for the Information System requirements only included one type of electronic product code and did not include the dynamic characteristics of the information sharing between the different systems, restricting the analysis to one link of the network, between the readers and the first database server.

From a broader perspective, the processes analyzed here illustrate the complexity and multidisciplinary characteristic of implementing this new technology and integrating all these different systems. With the potential to affect disciplines that range from product development and process engineering to information management and logistics, the project design and execution phases with have to adapt to existing and processes in order to guarantee the sustainability of the operation. This analysis also indicates that the design of the system will have to contemplate compatibility and the capacity to expand to new RFID-enabled processes that will evolve with the introduction of the technology.

7.1. Future work

Along with the current research under development at the different Auto-ID centers, the Packaging Special Interest Group from US center and the System Integration research from the UK center are the ones that have strongest interface with the issues discussed in this research document.

In line with the Packaging SIG focus, during the course of this research, a number of issues related material RFID compatibility and application guidelines were identified but excluded from the focus of this research. Although some general principles were highlighted on different publications, the interference each material has on the operation of passive tags is one of the areas that I have identified as crucial and deserving of more understanding. Tag application in different packaging alternatives, other than corrugated cases, is another possible expansion to the topic surfaced here.

Related to the work developed by the UK center, the use of the product identity for controlling the manufacturing operation is an topic that was covered by Brusey et all [11], Hodges et all [28] and MacFarlane et all [37], [38] on a robotic manufacturing cell. The suggestion is to expand this application to additional manufacturing processes, in other industries such as pharmaceutical's packaging, electronics and semi-conductors fabrication.

8. Bibliography

[1] AIM - Association for Automatic Identification and Mobility. (2004) Notes on Wal-Mart Requirements, **RFID Connections**, www.aimglobal.org

[2] Albano, S., Engels, D. (2001) Auto-ID Center Field Trial: Phase I summary, **Auto ID Center Technical Report**, MIT-AUTOID-TR-006, www.autoidlabs.org.

[3] Alien Technology, (2003) Nanoscanner RFID Primer, DOC # 8101014-000 Rev B, **Technical Manual**, Alien Technology Corporation.

[4] Alien Technology, (2003) Nanoscanner Reader, DOC # 8101024-000 REV A, **User Guide**, Alien Technology Corporation.

[5] Alien Technology, (2003) Nanoscanner Reader - Tag Programming Guide, DOC # 81010 50-000 Rev A, **User Guide**, Alien Technology Corporation.

[6] Benjamin, D. (2003) The New Revolution in Product ID: Electronic Product Code (EPC) Integration with RFID, **MARKEN Corporation** Company Presentation at the PackExpo 2003 Las Vegas - NV, www.markem.com

[7] Berral, J. (2003) RedPrairie's RFID Strategy Supports Immediate Compliance and Future Scan-Free Environments, **RedPrairie Company** Press Release, www.redprairie.com

[8] Blue, L., Powell, K. (2004) EPC and Radio Frequency Identification Standards. **Matrics White Paper**. www.matrics.com/resource/

[9] Brock, D. (2002) Survey of Languages, Specifications and Standards for Database and Network communication, **Auto ID Center White Paper**, MIT-AUTOID-WH-015, www.autoidlabs.org.

[10] Brock, D. (2001) Integrating the EPC and the GTIN, **Auto ID Center White Paper**, MIT-AUTOID-WH-004, www.autoidlabs.org.

[11] Brusey, J., Fletcher, M., Harrison, M., Thorne, A., Hodges, S., McFarlane, D. (2003), Auto-ID Based Control Demonstration Phase 2: Pick and Place Packing with Holonic Control, **Auto ID Centre White Paper**, CAM-AUTOID-WH011, www.autoidlabs.org.

[12] Carayannis-Pararas, J. (2002) **RFID-Enabled Supply Chain Replenishment**, Master's Thesis, Alfred P. Sloan School of Management, Massachusetts Institute of Technology.

[13] Chang, D., McFarlane, D., Koh, R., Floekmeier, C., Putta, L. (2002) Methodologies for Integrating Auto-ID Data with existing Manufacturing Business Information Systems, **Auto ID Centre White Paper**, CAM-AUTOID-WH-009, www.autoidlabs.org.

[14] Chappel, G., Grimburg, L., Schmidt, P., Smith, J., Tobolski, J. (2003) Auto-ID on the Line: The Values of Auto-ID Technology in Manufacturing. **Auto ID Center Business Case**, MIT-AUTOID-BC-005, www.autoidlabs.org.

[15] Dempsey, M., Ellis, S. (2003) Getting Started with AUTO-ID – Putting RFID/EPC to Work, **Global Supply Chain Conference**.

[16] Eberhardt, N. (2002) Towards RFID Performance Benchmark Tests, **Auto ID Center White Paper**, MIT-AUTOID-WH-013, www.autoidlabs.org.

[17] Engels, D., Sarma, S., Putta, L., Brock. (2001). The Networked Physical World System. **Auto-ID Technology Guide**. www.autoidlabs.org.

[18] EPC Global Inc (2004) **Version 1.0/1.1 Specifications** www.epcglobalinc.org/standards_technology/specifications.html

[19] Finkenzeller, K. (2003) **RFID Handbook**, 2nd ed., John Wiley & Sons, West Sussex, England.

[20] Goulbourne, J. (2001) Checking the Total Integrity on an LF System. Texas Instruments, **Technical Application Report**. www.ti.com

[21] Goyal, A. (2003) Savant Guide, **Auto ID Center Technical Report**, MIT-AUTOID-TR-015, www.autoidlabs.org.

[22] Greenwood, N. (1988) **Implementing Flexible Manufacturing Systems**, MacMillan Education LTD, London, England.

[23] Gross, S., Lo, J. (2003) Change Readiness Guide: Project Management Edition, **Auto ID Center White Paper**, STG-AUTOID-WH-002, www.autoidlabs.org.

[24] Harrison, M., McFarlane, D. (2003) Development of a Prototype PML Server for an Auto-ID Enabled Manufacturing Environment, **Auto ID Centre White Paper**, CAM-AUTOID-WH-010, www.autoidlabs.org.

[25] Harrison, M., Moran, H., Brusey, J., McFarlane, D. (2003) PML Server Developments, **Auto ID Centre White Paper**, CAM-AUTOID-WH-015, www.autoidlabs.org.

[26] Harty, D. (2003) RFID Integration – Lessons from the Frontline. **ACSIS, INC. White Paper**, www.acsis.com.

[27] Hines, M. (2004) Roadblocks could slow RFID, **CNET News.com**, http://znet.com.com

[28] Hodges, S., Thorne, A., Garcia, A., Chirn, J., Harrison, M., McFarlane, D. (2002) Auto-ID Based Control Demonstration Phase 1: Pick and Place Packing with Conventional Control, **Auto ID Centre White Paper**, CAM-AUTOID-WH06, www.autoidlabs.org.

[29] Joshi, Y. (2000) **Information Visibility And Its Effects On Supply Chain Dynamics**, Master's Thesis, Department of Mechanical Engineering, Massachusetts Institute of Technology.

[30] Kambil, A., Brooks, J. (2002) Auto-ID Across the Value Chain: From Dramatic Potential to Greater Efficiency and Profit. **Auto ID Center Business Case**, MIT-AUTOID-BC-001, www.autoidlabs.org.

[31] Kellam, L., (2003) **P&G Rethinks Supply Chain**. Optimize at Information Week.

[32] Keyence (2003). High Speed Digital Machine Vision – CV2100 Series. **Technical Manual**. www.keyence.com/dwn

[33] Kinsella, B. (2004), RFID – it's more than tags and standards – **UsingRFID article**, www.UsingRFID.com.

[34] Kocur, G. (2003) – ESD.264 Database, Internet & System Integration Technologies lecture notes. Massachusetts Institute of Technology.

[35] Koh, R. (2001) **The Use of Item Identification Data In the Supply Chain**. Master's Thesis, Engineering Systems Division, Massachusetts Institute of Technology.

[36] Lo, J., The Auto-ID (2003) The Auto-ID Transformation: Succeeding in a large-scale change effort, **Auto ID Center White Paper**, MIT-AUTOID-WH-023, www.autoidlabs.org.

[37] McFarlane, D. (2003) The Impact of Product Identity on Industrial Control Part1: "See More, Do More...", **Auto ID Centre White Paper**, CAM-AUTOID-WH-012, www.autoidlabs.org.

[38] McFarlane, D. (2002) Auto-ID Based Control – An Overview, **Auto ID Centre White Paper**, CAM-AUTOID-WH-004, www.autoidlabs.org.

[39] Moran, J., McFarlane, D., Milne, T. (2003) Use Case approach for determining the impact of Auto-ID implementations on Business Information Systems, **Auto ID Centre White Paper**, CAM-AUTOID-WH-016, www.autoidlabs.org.

[40] Oat Systems & MIT Auto-ID Center, (2002) The Savant Version 0.1 (Alpha), **Auto ID Center Technical Manual**, MIT-AUTOID-TM003, www.autoidlabs.org.

[41] Oat Systems & MIT Auto-ID Center, (2002) The Object Name Service Version 0.5 (Beta), **Auto ID Center Technical Manual**, MIT-AUTOID-TM004, www.autoidlabs.org.

[42] Pappu, R. (2003) Privacy and Security in the EPC Network. **RFID Privacy Workshop**, MIT.

[43] Powell, K. (2004) Passive RFID – A Primer for New RF Regulations. **Matrics White Paper**. www.matrics.com/resource/

[44] RedPrairie, (2003) RFID Just the Facts, Company Publication. www.redprairie.com

[45] RFID Journal. (2004). 10 Questions to Ask RFID Vendors. **News Article**. www.rfidjournal.com/articleprint/821/-1/800

[46] Richards H., Notes on Manufacturing Strategy and Performance Measurement Processes', **Institute for Manufacturing, University of Cambridge**. http://www-mmd.eng.cam.ac.uk/people/ahr/dstools/dstools.htm

[47] Rindle, K. (2003) RFID in Business Process. IBM Paper on SmartTags. IBM.com.

[48] Rockwell / Allen-Bradley (2002) PLC-5 Controller System Overview, **Selecting PLC-5 Processors**, http://www.ab.com/catalogs/b113/plc5/processor.html#standard.

[49] Rommel, J. (2004) Understanding the Wal-Mart Initiative - Making Sense of EPC Standards and Wal-Mart RFID Requirements, **Matrics White Paper**, www.matrics.com

[50] Sarma, S. (2002) "A Proposal for a Standard Process for the Auto-ID Center", **Auto-ID Labs White Paper**, MIT-AUTOID-WH-009, www.autoidlabs.org

[51] Sarma, S., Subirana, B., Ashton, K., Pappu, R. (2004) ESD.290 – Business Impact of RFID lecture notes, Massachusetts Institute of Technology.

[52] Sawyer, L. (2003) The Acquisition and Implementation of an Automated Data Collection System in an SAP/R3 Environment. **ACSIS, INC. White Paper**, www.acsis.com.

[53] Scharfeld, T. (2001) **An Analysis of the Fundamental Constraints on Low Cost Passive Radio Frequency Identification System Design**, Master's Thesis, Department of Mechanical Engineering, Massachusetts Institute of Technology.

[54] Scharfeld, T. (2003) Compliance and Certification: Ensuring RFID Interoperability, **Auto ID Center Technical Report**, MIT-AUTOID-TR-017, www.autoidlabs.org.

[55] Siemens Dematic (2004) Dynamic RFID Label Applicator. Form 9067 2/04. **Equipment pamphlet**, Siemens Dematic Corporation.

[56] Sun Microsystems (2003) Sun and Auto-ID Supply, Enabling Smart Objects: Breakthrough RFID-enabled Supply Chain Execution Infrastructure – **Company White Paper**, www.sun.com

[57] Sun Microsystems (2003) Sun's Auto-ID Architecture – **Company White Paper**, www.sun.com

[58] Texas Instruments (2001) HF Reader Shielding. Texas Instruments, **Technical Application Report** 11-08-26-002. www.ti-rfid.com

[59] Verisign (2004) The EPC Network – Enhancing the Supply Chain, **White Paper**. www.verisign.com

[60] White, M. (2002) Pallets Move the World – The need for International Pallet Standards. **ISO Bulletin August 2000**.

[61] Wong, C. (2001) Integration of Auto-ID Tagging System with Holonic Manufacturing Systems, **Auto ID Centre White Paper**, CAM-AUTOID-WH-001, www.autoidlabs.org.

[62] Zebra Technologies (2003) RFID-The Next Generation of AIDC, **Application White Paper**, pp. 2-3.www.zebra.com

[63] Zebra Technologies (2003) Zebra's RFID Readiness Guide: Complying with RFID Tagging Mandates, **Application White Paper**. www.zebra.com