8-2011

An Experimental Approach for Developing RFID Ready Receiving and Shipping

Amoldeep Singh Jaggi
asingh9@utk.edu

To the Graduate Council:

I am submitting herewith a thesis written by Amoldeep Singh Jaggi entitled "An Experimental Approach for Developing RFID Ready Receiving and Shipping." I have examined the final electronic copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Industrial Engineering.

Rupinder Singh Sawhney, Major Professor

We have read this thesis and recommend its acceptance:

Xueping Li, Joseph Wilck

Accepted for the Council:
Carolyn R. Hodges

Vice Provost and Dean of the Graduate School

(Original signatures are on file with official student records.)

An Experimental Approach for Developing RFID Ready Receiving and Shipping

A Thesis

Presented for

The Master of Science

Degree

The University of Tennessee, Knoxville

Amoldeep Singh Jaggi

August 2011

Acknowledgments

First and foremost I am thankful to almighty to bless me with the opportunity to come to United States to pursue my higher studies. I want to thank Dr. Rupinder Singh Sawhney for his guidance and support throughout the course of my stay at University of Tennessee. Undoubtedly, I have seen him as a great source of inspiration and a role model for both professional and personal life. I am really thankful to him for providing me the platform where I have learnt exceptional skills at technical, communicational and behavioral levels under his leadership. His confidence and encouragement in this research topic has motivated me to maintain a constant focus despite of many obstacles and hardships during the course of this thesis. I would like to offer my sincere gratitude to Dr. Pedro Balestrassi for helping me to conduct physical experiments in the RFID laboratory. He has contributed significantly in this thesis by helping to plan Design of Experiments for all the scenarios and analyzing the results of experiments. I would also like to thank my thesis committee members: Dr. Xueping Li and Dr. Joseph Wilck for helping me complete this thesis through all my hurdles.

I am grateful to all my colleagues in the Department of Industrial Engineering who have assisted me in the course of this work and have been particularly helpful and generous with their time and expertise. I would like to extend my special thanks to Aman and Sachin for being very supportive and pushing me forward to achieve my end goal whenever I used to get distracted.

Above all I want to thank my parents and sister who are always my first priority in life. I want to thank them for backing me up through all these years and whose constant love and encouragement has helped me to face the toughest challenges in life. I am thankful to almighty for blessing me with such a wonderful family.

Abstract:

Radio Frequency Identification (RFID) and related technologies have been touted to allow exponential improvements in supply chain logistics and management. However, many industrial users have indicated that these technologies have not provided the anticipated benefits. The two complimentary strategies required to address the RFID reliability are: to improve the reliability of RFID technology and to design the supply chain infrastructure that enables RFID. The focus of this paper is on designing the supply chain infrastructure to enable RFID by developing guidelines for "RFID Ready Facilities". These guidelines were developed based on a set of experiments conducted in the RFID supply chain laboratory. These guidelines were developed by using Design of Experiments (DOE) to determine the operational and facility factors that impact RFID reliability. The three different packaging strategies were tested on packages, boxes and their various combinations. The main factors considered in the experiments were the following among many others: Package Orientation (PO), Tag Placement (TP), Package Placement (PP), Reader Location (RL), Box Orientation (BO), Tag Placement on Box (TPB) and Tag Placement on Package (TPP). Based on the DOE results, general guidelines were developed for RFID packaging.

Table of Contents

List of Figures

List of Tables

Chapter 1

Introduction

Chapter 1 provides an overview of RFID technology and its applications in the area of packaging. This chapter states the relevance of the problem which outlines the objective of this research. An outline of the general approach to develop RFID functional guidelines is illustrated in this chapter. The chapter also gives an overview of the organization of this thesis.

1.1 Background

1.1.1 Wal-Mart RFID Mandate

Wal-Mart issued a RFID mandate in January 2005 to its top 100 suppliers with the requirement to apply RFID labels to all shipments. Three years later in January 2008, Sam's Club, another Wal-Mart division issued letters to its suppliers with the requirement of RFID tags on the pallets shipped to its distribution center in DeSoto, Texas. The suppliers were held responsible for this mandate and failing to comply would be charged with a service fee. [1,2] The reason for this mandate was that Wal-Mart can improve store operations and enhance profits by improving the product availability on store shelves, and by increasing the visibility in their supply chain.

The major problem for the suppliers associated with this mandate was that their facilities did not have a RFID infrastructure as this was a new and emerging technology. Therefore, it became difficult for these suppliers to comply with the mandate. The second biggest concern was the costs associated with RFID implementation. Since, being an emerging technology, the costs associated with the implementation were higher than the profits from the sales. Therefore, the profit margin of the suppliers was also reduced.

1.1.2 Department of Defense (DOD) RFID Mandate

The DOD issued similar a RFID requirements for its suppliers followed by Wal-Mart amending the Defense Federal Acquisition Regulation Supplement (DFARS), recognizing the technologies' ability to track dangerous and expensive supplies. These requirements were pertaining to packaging with passive RFID tags both on the cases and pallets when shipping to the Defense Distribution Depot. Additionally, DOD considered RFID as a truly transformational technology for knowledge – enabled logistic support to war fighters through automated visibility and asset management [3].

Again, the problem faced by the suppliers of DOD was that there is no specific method for using RFID technology, nor is there one specific solution to be applied across industries. There are many different ways of implementing RFID technology and therefore, the procedure of implementation and refined information is not standardized.

1.1.3 Effect of Corporate Takeovers on Packaging

Globalization has made mergers and acquisitions an important aspect of corporate strategy. The management deals with the buying, selling and combining of different companies to form a bigger company without having to create another business entity. Most of the time, the acquirer company has no choice to select the target company if it is the right opportunity and the acquisition is beneficial for the company and its stakeholders. Consequently, the acquirer company inherits brands, work culture, production processes, labor policies, plant locations, financial debts, domestic issues, leadership, partnerships, company relations with suppliers and customers. The emphasis of the new management is to improve the production processes and packaging is mostly neglected. The packaging in the target company might not be necessarily using state of the art technology. While a company can generate more profits if its products have more visibility with superior packaging. Therefore, packaging is an important branch of an organization that can create new paradigms to generate revenues and help to develop strong bonds in the supply chain. This is critical because the modern and innovative packaging strategies lead way for impressive product marketing and better quality finished products.

1.1.4 RFID in Packaging

Packaging is a critical component of receiving and shipping functions that determine the overall quality, cost and time line parameters of an efficient and effective supply chain. In essence, receiving and shipping are the linkage points within a supply chain. The key is the manner that one receives and manages the inventory and how one allows packaging to determine the shipping logistics. The packaging function is the leverage point in this network that has the possibility of truly impacting the performance of a supply chain. Enhancing the reliability of this function is critical because a reliable packaging enables the company to:

- forecast the supply and demand of products within the supply chain
- monitor the movement of products in the supply chain and improves inventory transparency
- modify and allocate product costs
- determine the shipping logistics
- read multiple items simultaneously with remote scanning
- reduces variation in receiving and shipping
- supports dynamic information flow, where information on the tags can be changed with the change in inventory status
- flexibility to reschedule

A current market study reveals that barcode is the primary technology utilized to facilitate the packaging process, which is outdated technology, because bar-coding is not fully automated and requires considerable large scale operations [4-6]. RFID technology can be a successful replacement for barcode technology as it is an advanced version of the conventional bar-coding technology. The following are the added benefits of RFID over bar-coding in shipping and receiving function [4]: -

- RFID has greater capabilities to read through obstacles
- RFID can work in hostile conditions
- RFID is a real time-all time data capturing technology

The above mentioned features work successfully when RFID is customized to the specific receiving, warehousing and shipping infrastructure. However, it cannot deliver very reliable outputs if used in a universal manner. This means that results of RFID depends not only on the specifications of the RFID equipment, but on packaging alternatives, warehousing alternatives, layout alternatives and operating alternatives. Therefore, prior testing is necessary to find out which method of RFID implementation is most reliable.

1.1.5 Functions of RFID in Packaging

RFID performs the following critical functions to enable reliable packaging: -

- Increased package information – The package information is one of the core requirements of packaging. This is a critical function as package information provides us the basic knowledge such as: -
    - what is inside the package
    - when was it manufactured
    - what are the ingredients
    - how it should be stored
    - what is the expiration date

RFID greatly enhances the communication flow between the product and the consumer by storing a huge amount of information about the product and its logistics in an easy user-interface. The following are the key impacts of having increased package information to the consumer: -

  - The shipment delays are reduced significantly due to instant availability of information about the package all the time. This means that the package information can be read anytime.
  - The lost shipments can be tracked quickly. The information can be posted on each package to locate lost shipments.
  - RFID makes the packaging process faster by reducing the order filling time as it is connected with the central database or SAP. This feature enables the automatic order filling and thereby reduces the labor costs.
  - Other communications such as: telephone calls or internet queries to track down lost shipments, order status of shipments, billing and invoices are decreased drastically with the automatic update feature of this technology.

- Increased package protection – Package protection constitutes both product and information protection associated with the package. Product protection includes safe handling, storage and transportation of the products while information protection includes providing right information about the right product and at right place. In some cases, the embedded information is for manufacturers and retailers only and not for the customers. In such cases, the information protection feature should keep the classified information confined for the specified user as well as keep the information safe and secure. Following are the key impacts of having increased package protection in supply chain by RFID: -
  - It radically reduces product theft and decreases the product damage. This is because RFID scans the inventory in a continuous and frequent mode. Therefore, if a product is not at its designated place and the authorities are not aware of its movement then it

alarms the system. Similarly, if the packaging is tampered or the product is damaged then it notifies the system.

- RFID can reduce the package weight by innovative packaging design. The package information is embedded on RFID tags and these tags are exclusively light weight, therefore, a large amount of information can be encrypted on RFID tags. This eliminates the requirement of paper based information on the packages like stickers, cardboard tags and metal plates, thereby, reducing the package weight considerably.

- Increased standardization – The standard operating procedures are followed in RFID packaging to enable uniform packaging which over the period of time reduces labor costs and packaging lead time. One of the key benefits of integrating RFID with packaging is that it enhances the packaging standards. This is because RFID has specific requirements such as: -
  - clean and tidy environment
  - no radio frequency interference
  - fixed tag locations on packages
  - standard packaging material
  - standard RFID equipments
  - RFID skilled labor
  - standard reader locations
  - fixed reading distance

The following are the key impacts of having increased standardization on packaging by RFID: -

- It considerably decreases the product and equipment handling costs. The products on RFID packaging assembly move through RFID readers which are fixed at their specified locations, thereby, considerably decreasing equipment handling. Likewise, the products have a standard path of movement on conveyors or fork-lifts which leads to better product handling and control.

- It enhances the communication flow between the shipper and the receiver. The same RFID tags can be used by the receiver with product information predominantly embedded by the shipper. This leads the way for faster communication and deliberately reduces inventory stocks at both ends.
- The standardized shipping procedure creates the foundation for better quality and customer trust. This is because RFID automatically filters the products that do not meet quality standards of shipping. Therefore, the customers receive superior quality products and therefore spend less time and labor to check the product quality. This eventually builds good business relations in the supply chain. [4]

1.2 Problem Statement

The RFID tags embedded on products do not guarantee that all the products will be detected. There are many factors that impact RFID packaging other than “slap and ship” of products or using superior RFID equipments. Additionally, the success of RFID depends on the method of packaging and RFID equipment specifications. For example, an RFID reader can fail to detect products with inappropriate package orientation and package placement. Therefore, a balance is necessary between selecting the packaging factors and RFID technology factors.

Like any other technology, RFID has some limitations due to which RFID receiving and shipping functions fail. The failure to detect the products thus results into loss of revenue in the supply chain. For example, if the products are not detected on the pallet load, the customer would not know the product was received and most likely would not pay to retailer. On the other hand, if the product is detected more than once, then the customer will pay for the extra units of products which were actually not received.

Therefore, error in detecting the products causes financial loss to retailers and customers. Therefore, this thesis proposes general guidelines for an 'RFID Ready Facility' to improve the reliability of RFID in a packaging environment.

Figure 1 below depicts the goals, failures and their symptoms of integrating RFID technology with packaging. The end goal is to have a reliable and sustainable RFID packaging by integrating this technology with packaging. As seen in Figure 1, the three different types of failures observed by integrating RFID technology with packaging are: strategy failures, technology failures and infrastructural failures. The strategy failures are caused due to failure or lack of adequate RFID implementation strategy whereas technology failures are directly related with RFID operational capabilities. The literature review shows that a lot of efforts are being carried to understand and solve strategy and technology failures in implementing RFID solutions. The research efforts conducted in this thesis focus mainly on understanding and solving infrastructural failures which are caused due to the absence of guidelines for an 'RFID Ready Facility'. The factors selection is an important component that determines RFID planning and implementation. The RFID implementation strategy is formed on the basis of these factors and subsequently it determines the guidelines for a reliable and sustainable RFID packaging.

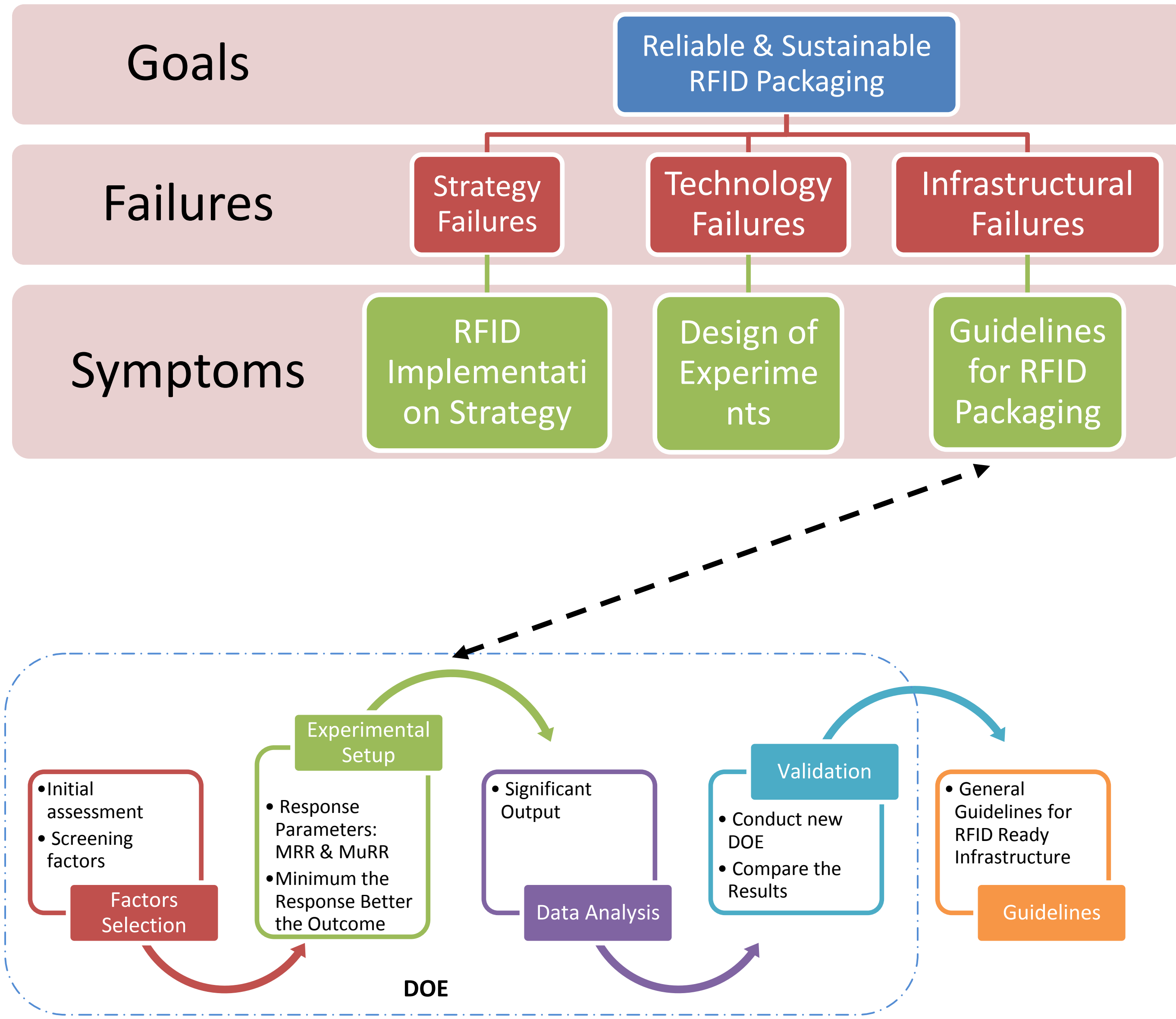


Figure 1: Problem Statement

The general approach followed in this thesis to develop the guidelines for 'RFID Ready Facility' consists of five phases shown in Figure 1. In the first step of factor selection phase, an initial assessment is conducted to select all the factors that could possibly impact the RFID packaging. The second step further screens the factors which are significant to conduct DOE. The DOE is conducted in the second phase to calculate the response parameters: Missed Read Rate (MRR) and Multiple Read Rate (MuRR). The response parameters obtained in DOE indicate how reliable is RFID in detecting the packages passing through the reader. Therefore, the best outcome is based on the minimum value of response parameters. In the third phase of data analysis, the significant outcome is achieved by comparing the visual results with statistical results. The visual results represent the packaging settings observed visually in which all the packages are detected and none are missed by the RFID reader while the statistical results represent the best packaging settings given by the statistical output in MINITAB. Further, the significant output achieved is validated in the validation phase by conducting a new DOE. The results of the new DOE should show that all the packages are detected successfully to validate the outcome obtained in the data analysis phase. Finally, the guidelines for 'RFID Ready Facility' are developed in the last phase based on the best results of DOE.

To design an efficient RFID packaging the following objectives are proposed in this thesis:

- Conduct experiments by using DOE as core methodology
- Compare the physical and analytical results of DOE
- Develop the general guidelines for an 'RFID Ready Facility

Chapter 2

Literature Review

Chapter 2 provides a brief introduction to RFID technology in the area of packaging. It provides a comprehensive review of the current factors and policies used in the RFID implementation models. The objective of this chapter is to identify the gap between the non-RFID and RFID integrated facility.

2.1 Introduction to RFID Technology

RFID technology and its applications have shown immense potential in the field of supply chain management. In the era of globalization and advanced technology adaption, the companies are emphasizing on the use of intelligent tracking technologies to receive, manage and ship the products in market. RFID is one of the intelligent tracking technologies that have gained attention among the companies worldwide, especially involved in receiving and shipping.

RFID is a data collection technology with an ability to transfer the information from the tagged product into the computer system [7]. This information can be then used to track the product, manage inventory and make advanced decisions related to supply and demand. There are four components of an RFID system to function properly:

- RFID Reader (also known as interrogator)
- RFID Antenna
- RFID Middleware Software with computer
- RFID Tag (also known as transponder)

The RFID reader sends the radio signals which are reflected back by RFID tags at the same frequency. The information captured by RFID reader is then fed into the middleware software to extract meaningful value from the captured information.

Prior to the RFID technology innovation, barcodes were primarily used as a fundamental source of tracking the entities in business and retailing. The application of barcodes was commercialized in the late 1960's when representatives from a number of associations dealing with the food and retail industry decided that there was a need for an "inter industry product code". The result of this was "Universal Product Code (UPC)" which commercialized the bar-coding technology. RFID technology is gaining importance over barcodes these days because of its remote tracking and the ability to read multiple units of products at the same time. Similar to the UPC standards of bar-coding, the "Electronic Product Code (EPC)" was designed as a universal identifier that provides a unique identity for every physical object around the world tracked by RFID technology [8].

There were many technology barriers and obstacles with bar-coding which RFID was able to overcome. For instance, creating the barcodes small enough to fit on certain packages and synchronizing barcodes across the company was a major challenge which was solved by using RFID technology [9]. RFID chips of the size of rice grain have been developed these days which can be easily integrated with any complex product to track its visibility.

2.2 Packaging in Supply Chain Management

The traditional supply chain incorporates three main components: the supplier network, the manufacturing unit and the customer network [10]. The different types of companies may have different types of supply chains depending upon the production and distribution system. For example, a company that is actively involved in manufacturing as well as distribution might not fall under the traditional category of supply chain. The components such as distribution, warehousing, transportation and packaging may require further consideration. These components play a crucial role in the effectiveness of a supply chain as illustrated in Figure 3 below.

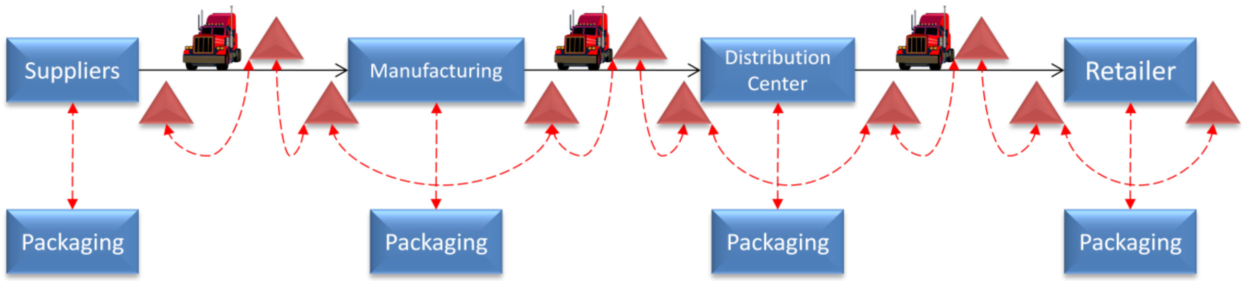


Figure 2: Packaging in Traditional Supply Chain

Packaging plays a very crucial role in the supply chain of a company because it has a very strong effect in enhancing the market of the products. The extent to which it affects the supply chain is determined by the overall cost as well as its ability to successfully accomplish the four main functions of package: containment, protection, utility and communication [11]. Packaging also plays the role of effective communication in the supply chain. For example, packaging modification may seem trivial, but if changes are not effectively communicated, substantial difficulties can result for all the components of supply chain [11].

Another significant factor that impacts packaging in supply chain is the packaging logistics [12]. Packaging logistics is an important factor to determine the time required for completing packaging operations which eventually affects the product lead time and delivery to the customer [13]. Table 1 below shows the relationship between packaging and logistical activities. The concept of packaging logistics can enhance the supply chain efficiency and effectiveness, through the improvement of both packaging and logistics related activities. The present period is the beginning of an evolution that can deliver new tools to improve efficiency and effectiveness of packaging and the related logistical system. There is the requirement of well defined measures or factors that can improve the existing packaging performance model and eventually the overall impact of packaging in the supply chain [14].

Table1: Relationship between Packaging and Logistics Activities [15]

Logistics activity	Trade-offs
Transportation	
Increased package information	Decreases shipment delays; increased package information decreases tracking of lost shipments
Increased package protection	Decreases damage and theft in transit, but increases package weight and transport costs.
Increased standardisation	Decreases handling costs, vehicle waiting time for loading and unloading; increased standardisation; increases modal choices for shipper and decreases need for specialised transport equipment
Inventory	
Increased product protection	Decreased theft, damage, insurance; increases product availability (sales); increases product value and carrying costs.
Warehousing	
Increased package information	Decreases order filling time, labour cost.
Increased product protection	Increases cube utilisation (stacking), but decreases cube utilisation by increasing the size of the product dimensions.
Increased standardisation	Decreases material handling equipment costs.
Communications	
Increased package information	Decreases other communications about the product such as telephone calls to track down lost shipments.

2.3 RFID in Packaging

The literature review shows that that there is a need for new tools and methods to allow reliable packaging in the supply chain management. Existing methods are limited by the boundaries of a single company and therefore can only be used for certain stages in supply chain. The current market demands multifunctional and systematic methods in order to emphasize the understanding of the role of packaging along the supply chain. This initiative would also encourage enhanced communication and information sharing in supply chain [16].

RFID tops the chart of innovative technologies that can help the companies to meet the above objectives in the area of packaging. It can provide valuable information regarding inventory data and shipment locations if used optimally. Figure 4 below depicts the information flow pattern using RFID in traditional supply chain. The integration of RFID in packaging will automate the receiving and shipping processes, thereby, eliminating requisite time and labor costs as well as increasing the throughput process. This will provide the confidence to allow raw material suppliers, manufacturers and retailers to reduce the overall inventory levels and safety stocks [17].

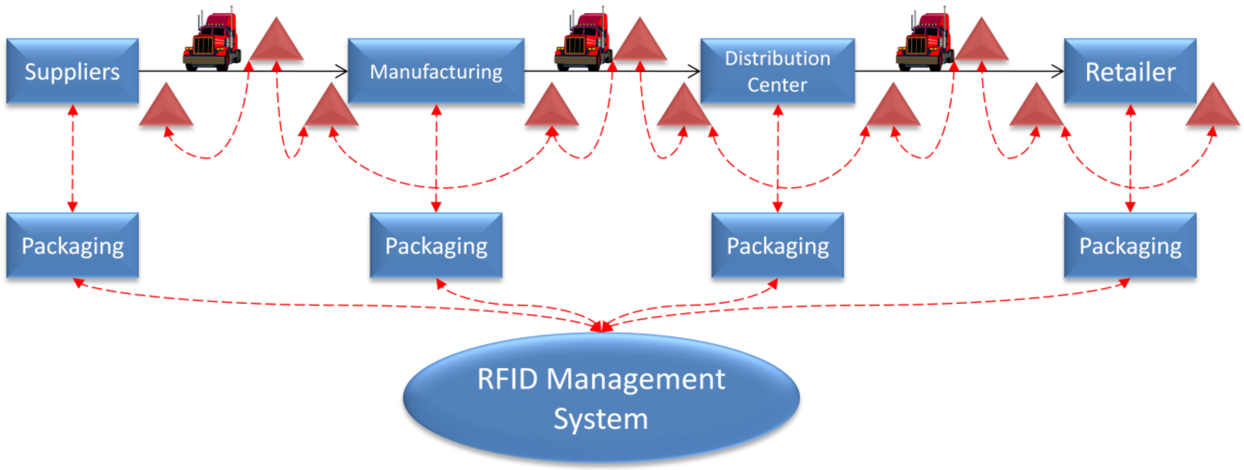


Figure 3: Packaging Using RFID Technology in Traditional Supply Chain

An intense review of literature shows substantial work done in identifying and understanding the factors that impact RFID technology [18]. Also some research signifies the impact of RFID factors that can affect the physical infrastructure [11]. But there is the lack of evidence that shows the relationship between the factors affecting RFID technology and the factors that impact the physical infrastructure where RFID technology has to be implemented.

One such study shows the evidence of research to determine the impact of conveyor speed, packaging materials and product on the readability of RFID transponders. The variables for this testing were conveyor speed (300 fpm, 600fpm), package type (case of chips in plastic tubes, case of chips in metalized spiral wound fiberboard containers, package shape (case of metal cans, case of metal bottles and case of metal tins), product type (case of bottled ketchup, case of bottled motor oil and tag generation (Alien Gen 1, Alien Gen 2) [7]. The research found that conveyor speed, package type, package shape and product type all had the significant effect on the average amount of trial reads per trial. Moreover, tag type was found to have a significant effect when testing the product effect and package shape effect but did not have a significant effect when testing the package type effect [7]. This research neglected many other potential factors that could possibly impact the RFID readability. For example, package and product separation distance, RFID reader – tag distance, orientations of the entities, etc are the important factors that determine RFID reliability. Secondly, the runs were not planned statistically and rather scheduled randomly. The planning of the runs using statistical methods like Design of Experiments can help to understand the affect of variation in detail.

The other such study showed evidence of the effect of different products and tag orientations on the readability of RFID transponders in pallet loads. This study was conducted by using Matrics 915MHZ Class 0 RFID tags with several different orientations like: tags facing inward, outward, forward, upward and downward and products such as foam, rice, empty bottles and water filled bottles[18]. This research found that orientation and product type have a significant effect on tag readability. Granular and water based products have a negative effect on tag readability, etc. Both these studies and other research initiatives do not deliver the fundamental RFID operational guidelines that can be used by the facilities to evaluate and integrate this technology within their packaging system. The research presented in this thesis provides an example of RFID integration into the packaging system of a company by using the factors that impact both RFID technology and physical infrastructure of the facility.

2.4 RFID Applications

2.4.1 Application in Mining

RFID can provide improved response to downtime, identification of personnel involved in mining operations, monitoring the personnel traffic into hazardous areas, warning and alarming signals, identification of vehicles involved in mining operations, tracking of supplies and materials, reducing the fatal accidents due to collisions, monitoring of underground gases and maintenance scheduling [19]. RFID technology was identified as the best technology to pursue for underground applications. This technology is being extensively used by the mining industry in South Africa for rescue, gas detection and first aid equipments. iPico Holdings (http://www.ipico.co.za/), a privately held RFID technology firm is into the active business of developing dual-frequency RFIF tags to automate the processes to generate reliable and real – time information for about 6000 employees a shift. Another organization, MSHA has been working on accident prevention through the use of RFID technology. MSHA believes that proximity detection and protection systems can prevent a large number of fatal accidents in mining industry [19]. Following are the general functions of RFID technology in mining industry:

- Message Communication
- Online monitoring of labor and vehicular movement
- Alarming signals and warnings
- Reducing fatal collision accidents and improving productivity

2.4.2 Application in Construction and Facilities Management

There is a vivid evidence presently of RFID adoption in the area of construction section. It has a great potential to provide real time information on parameters such as location, condition and timing. RFID tags can be used to control the access of the facilities by attaching it to the employer's ID badges [20]. This method is already in use in hospitality sector and commercially sensitive sites to control staff access to specific sites. RFID management system is combined with tracking cameras enabling, for example, the identification of workers in the hazardous region of construction site. Control of inventory is one of the widest application areas of RFID in the field of construction. The stocks of millions of dollars of construction materials is stored by most of the construction companies so that the supply of raw materials and other building materials is not interrupted in any consequences. The reputation and profit margins in construction sector largely depend upon the inventory stocking strategies of the companies. RFID provides visibility in supply can delivery of raw materials and also helps to automate the inventory replenishment polices of the construction companies.

Future materials tracking management systems may be able to provide site owners with the ability to determine construction progress and materials delivered by simply walking around the site where all materials are identified and tagged using an RFID system. RFID technology can also be used to track documents essential in the construction phase to identify the latest version of files and drawings and also in facilities management phase to locate original build specifications and layouts.

2.4.3 Application in Smart Parking

The RFID technology has been used for the management, controlling, transaction reporting and operation tasks for the parking lots located on various parts of the city. Check – ins and check – outs of the parking lots are controlled with RFID readers, labels and barriers. RFID technology is an automated vehicle identification system that requires no personnel to identify vehicles in the parking lots and can collect parking fees automatically via the system [21] The timing of the gates and additional sensors enables one by one parking lot circulations thus preventing multi check – ins or check – outs at a time [22]. The centralized database system is used to remotely access and administer the system. Over the internet, administrators will be able to view identification and dept information of any vehicle and monitor the efficiency and functionality of RFID-enabled parking-lots [23].

2.4.4 Application in Manufacturing

The smart part based manufacturing system are addressing the concerns of personalized products and tailor – made solutions which are taking over large shares of the marketplace from mass produced goods and standardized solutions respectively. RFID offers features that are well suited to be adapted for such flexible smart – parts manufacturing [24].

In the past, Ford Motor Company has successfully implemented RFID to improve products quality on the automated assembly production lines in its facility at Mexico. This facility produces cars and trucks based on Just in Time manufacturing model. The RFID tags are used to identify the vehicles and their parts as they pass on the production line using standard 22 to 23 digit serial numbers as reference for locating the parts. RFID allowed automatic updates on the tags which otherwise were accomplished by manually updating the production sheet at every turn in production line [25].

The concept of smart parts manufacturing involves the following aspects [24]:

1. Self identification of unique parts – Each part is treated as a unique entity in the mass production system. The identity of each unit is restored by using a tag with unique serial number which remains intact to the specific part till the end of production process. The information is embedded on the tag which serves to distinguish the part from other similar parts in the same production line [23].

2. Communication between parts and equipment for flexible manufacturing – The radio communication between the tag and the reader transfers information to the quality station of the department about the processes carried out on the part. This information can be used by the quality assurance personnel to run quality inspection checks and track the operations on each part on the production line [24].

3. Automation in manufacturing, quality control, packaging, storage and delivery – the RFID tags are embedded on the parts in the production cycle which are carried by the part in the future processes like packaging, storage and delivery. These tags can be identified for subsequent field service records in order to retain the part performance history and to update the manufacturer's management information system for the purpose of warranty enforcement [24].

4. Enabling concurrent manufacturing – The response times to customer inputs can be dramatically reduced by integrating RFID technology with the concurrent manufacturing model. At any moment of time, the specifications written onto the tag could be modified and production could proceed normally. This would shorten response times because design and manufacturing periods would have overlaps.

The RFID technology provides the ability to control the process changes using wireless signals to directly update the information on RFID tags, thereby reducing the paperwork and human interference. This also provides the ability to the customers to obtain the automatic status updates to track the process of their orders in real time. Figure 5 below represents the smart parts manufacturing concept using RFID technology. This model has the ability to integrate between customers, vendors, design & process planning, marketing and warehousing with real time information [24]. RFID technology thus enables the business to provide customer satisfaction through tailor made solutions supplied reliably and efficiently with competitive response times. It also improves the after – sales services and warranty obligations by tracking and recording previous histories of the products.

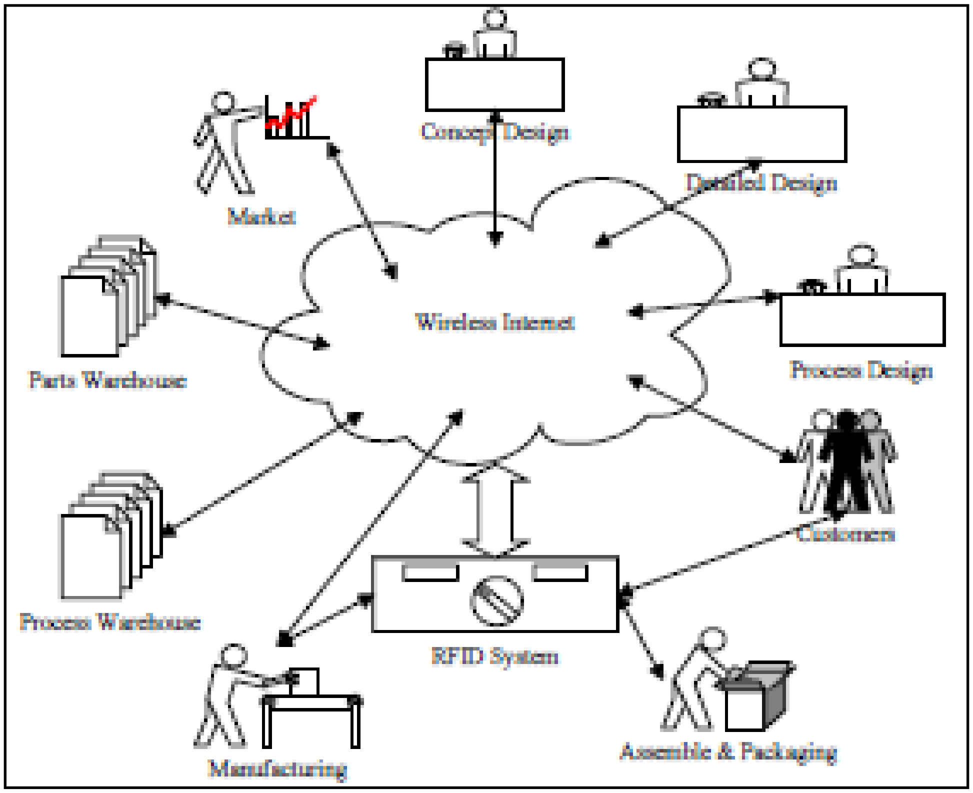


Figure 4: Smart Parts Concept Using RFID Technology [24]

2.5 RFID Challenges and limitations

The RFID applications have created swirling hype and promises of opportunities in almost all the sectors of industry. There is a considerable potential in implementing RFID technology but there are also some challenges and limitations that require careful attention to deliver its inherent benefits. The major issues can be broken down into the following categories: -

- Technical Challenges – The RFID technology changes its behavior when integrated with metals and liquids. This is because radio waves are reflected or refracted differently by the different materials to which a tag is attached. The large portion of UHF radio waves is refracted when propagated towards liquid. On the other hand, if UHF radio waves pass through a metal, a large portion of the radio energy is reflected [37]. In both cases, there will be signal strength degradation and interference in the reception quality of the tag antenna.

RFID readability is affected by the relative position and orientation of the tag antenna and reader antenna because the power pattern affects the orientation properties of antenna. Therefore, if a tag antenna is perpendicular to reader antenna, the former cannot receive the latter's radio signal [27]. In real world goods-tracking applications, RFID tags attached on variety products will have random antenna orientations, while some tag antennas may happen to be perpendicular to a reader antenna by chance. This will cause such tags to be unreadable as they travel through the portal with just one unidirectional reader antenna [28].

When the RFID signals are sent simultaneously to a large number of antennas, it causes the collision interference to the reader. The main issue with this technical challenge is that when a large number of tags are being read simultaneously, it becomes difficult to identify which tags have not been detected. Therefore, standard anti-collision procedures are required to achieve multiple tag reading without any failures.

- Standard Challenges – RFID operational standards are determined by the two major organizations: EPC Global and International Standards Organization (ISO). But these standards are not unified across the globe. The problem arises when the products need to be shipped overseas; there are no common standards that are followed globally [26]. Similarly, the regulations on Radio spectrum allocation are not unified among nations. A large portion of the UHF spectrum has already been auctioned to cellular phone service providers for high license fees by a few countries. It would be difficult, if not impossible, to buy that portion of spectrum back for RFID use. This adds complexity to the adoption of RFID for global supply chain management applications where tagged goods must often travel across borders. RFID tags which respond only to a specific UHF frequency range cannot be read in countries where different spectrum bands are allocated for RFID use [29.30]. Cost Challenges – There are many cost challenges associated with RFID technology. The primary cost challenge associated with RFID is the manufacturing costs for RFID hardware. The RFID chip manufacturing costs is relatively high as compared to other RFID manufacturing costs. This is because RFID chips are very small in size (0.4 – 1.0 mm^2). The chip cost can be decreased by increasing the chip order volume [26]. The second major cost challenge associated with RFID is the customization costs. An RFID system requires to be customized to the specific working and application environment. These requirements include standard radio spectrum band, regulatory licenses of the country, tag – antenna design, type of materials, client's mission and performance expectations of the RFID applications. Therefore, the successful operation of an RFID system will have to incur considerable system design, customization and configuration costs.

- Physical Infrastructure Challenges – In order to have a reliable RFID implementation, the entire infrastructure must be established. This will allow for the collection of real-time tag information from anywhere in the supply chain, including the manufacturer's factory, local logistic/warehouse, air cargo, foreign logistic/warehouse and the retailer or department stores [31]. This requires the establishment of a standard RFID information management system that can transfer the RFID information effectively and enable a transparent flow system across t he supply chain. The adoption of UHF RFID system along an entire supply chain will benefit multiple companies but at the same time establishing an RFID infrastructure to track every tagged item from the beginning to the end of the supply chain is really a challenge.

2.6 Summary of Literature Review

This chapter provides a review of the RFID technology in the area of packaging as well as other areas of industry and the models that are commonly used to implement RFID technology at the enterprise level. These models testify various factors that can impact the RFID technology; however, these models lack the ability to provide RFID operational guidelines to enable RFID implementation in a traditional facility. The following chapter discusses the methodology involved in assessing and selecting the significant factors that impact RFID physical infrastructure and conduct Design of Experiments to select the best strategy for RFID implementation.

Chapter 3

Methodology

Chapter 3 illustrates the methodology for developing the guidelines for 'RFID Ready Facility' with the prime focus in the area of packaging. The chapter gives a detailed description of the RFID equipments used, packages and boxes for testing used and various phases involved in the methodology. The phases of methodology include identifying critical factors, conducting DOE, data analysis, validation and guidelines for RFID packaging.

3.1 RFID Laboratory Setup

The testing of this thesis took place at UT RFID Laboratory in Industrial and Systems Engineering Department at University of Tennessee, Knoxville. The RFID system and other equipments used in this testing were assorted from different suppliers, the details are mentioned below. This system utilizes radio frequency waves in the 915 MHz region of the electromagnetic spectrum. The following are the equipments and software used in the laboratory: -

1. ALIEN RFID Readers

ALIEN ALR – 9650 single antenna RFID reader was used in the experiments. The reader electronics and a high-quality, circularly polarized antenna resides in a single package, eliminating external antenna cables, resulting in the simplest and least expensive installation. A second antenna port enables 2-antenna applications.

Figure 5: ALIEN ALR – 9650 RFID Reader

A single unit of RFID reader was used and the reader configuration was kept constant throughout the experimentation.

2. ALIEN RFID Tags

EPC Global Class 1 Gen 2 compliant Alien ALN-9640 - "Squiggle®" Inlay tags were used in all the experiments. These tags work between 860-960MHZ with antenna dimensions: 95mm * 8.2 mm.

Figure 6: ALIEN ALN – 9640 RFID Tag

These tags have a 512- bit user memory bank and the data on these tags can be secured with a password. These tags support all mandatory and optional Gen 2 commands which also include item level tagging. Each unit of package, box and pallet used in the experiments was tagged with these tags. The identity of the tags used in the experiments was determined by allotting serial numbers to the tags which were programmed by using ALIEN tag programmer [40].

3. ALIEN RFID Gateway Software

This is free version of the software provided by ALIEN Technologies along with the purchase of ALIEN RFID readers. The purpose of using this software is to show the connected RFID readers to the ports of computer, visible on the local network. The user can select the reader by clicking on the list of visible readers on the control panel of the software and then select the applications from the menu button. This software is an important part of the system as it displays the RFID tags on the screen when detected by RFID reader.

4. NETGEAR ProSafe 8 Port Switch with 4 Port POE

NETGEAR Power over Ethernet (POE) switch is used to supply power to the RFID reader. It integrates 100 Mbps fast Ethernet and 10 Mbps Ethernet capabilities in a sturdy, compact package to provide standard networking for the data transfer. The switch provides 15.4 W of power on each POE port to connect multiple readers at the same time.

Figure 7: NETGEAR ProSafe 4 Port POE

5. Conveyor

The experiments were conducted on a 12 ft by 6 ft XK FLEXLINK conveyor loop with 143.30 lbs (65kg) weight capacity, running in counter-clockwise direction. The conveyor has 10 pallet frames which can move freely over the chain guide in clockwise and counter-clockwise directions. The conveyor has a complete range of standard divert/merge devices and easily assembled standard component kits for easy and fast configuration of experimental layouts. These component kits can be attached to an existing conveyor without the need for cutting or welding of the beam.

Figure 8: XK FLEXLINK Conveyor

6. BOWH RFID Middleware Software

BOWH RFID software was used to track the RFID tags on the items. The unique feature of this software is that the user can create the blueprint of the scenario. This helps to clearly illustrate the receiving and shipping functions in a scenario. As seen in Figure 7 below, on the right hand side is the Events Toolbar. This toolbar explicitly shows the tag number when it is visible to the RFID reader. The zone tracking feature keeps the track of the RFID tags when they enter and exit the system. The data captured by the software is stored in the SQL database where the queries can be made to retrieve the stored data.

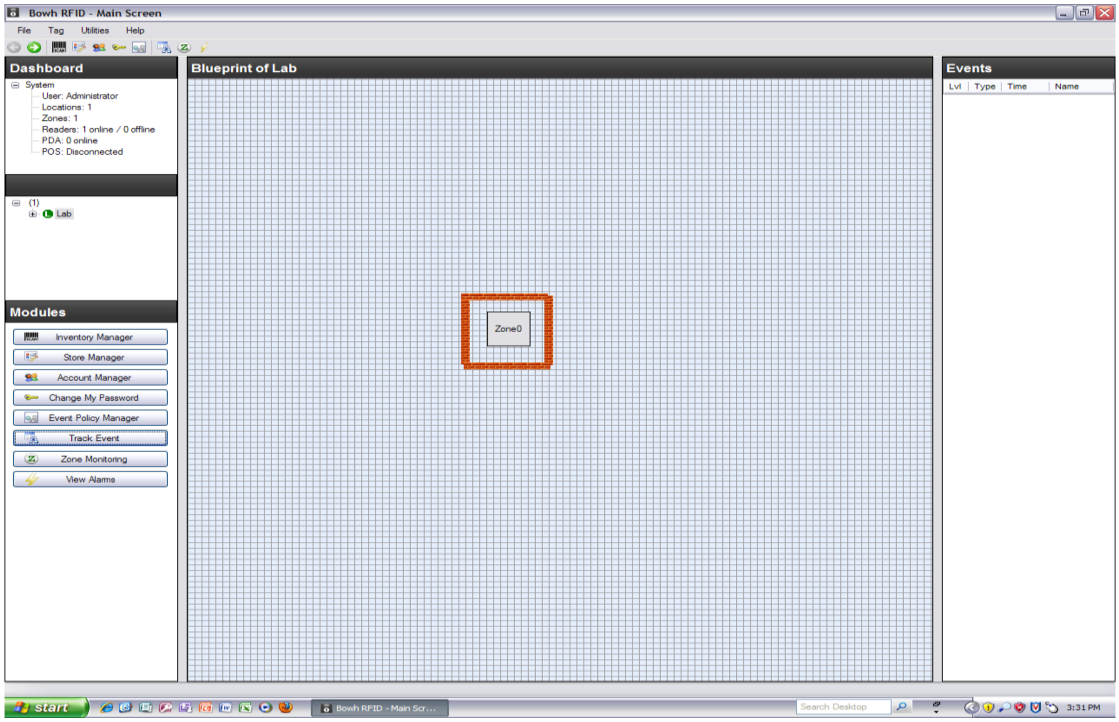


Figure 9: BOWH RFID Software Screenshot

3.2 Methodology

This section illustrates the methodology for developing the guidelines for RFID packaging. The significant factors identified in Phase 1 are used to run DOE in Phase 2. The MRR and MuRR calculated in Phase 2 are used in Phase 3 for data analysis and determine the significant packaging strategy. In phase 4, a comparative analysis is performed on all the significant strategies and the best selected strategy is validated. RFID packaging guidelines are developed in Phase 5.

3.2.1 Factor Selection

In this phase, the factors that are critical for RFID packaging are identified by following a two step procedure. In the first step, an initial assessment is conducted in which all the factors are enlisted that impact RFID packaging followed by factors screening in the second step. A detailed description of the processes involved in selecting the factors is given below. Table 2 below illustrates the format for factors selection.

Table 2: Factors Selection

	Factors	Sensitivity	Levels		
			1	2	3
A					
B					
C					
D					

3.2.1.1 Initial Assessment

In this step, an initial assessment is conducted based on a literature review and a subsequent brainstorming session of University of Tennessee (UT) RFID team which consists of RFID lab technicians, industrial, mechanical and electrical engineers. Additionally, it includes a survey of the UT RFID laboratory to investigate the factors that impact RFID packaging. In this assessment, all the factors are thoroughly analyzed to understand their impacts and determine the levels of interest for each factor.

3.2.2.2 Factors Screening

In this step, the potential factors enlisted in step 1 are ranked based on their criticality to determine the sensitivity of each factor. These potential factors are assigned a sensitivity number ranging from 0 to 2, and factors having the sensitivity number 2 are considered as critical factors. Table 3 provides the guidelines for ranking the factors based on their criticality.

Table 3: Sensitivity Ranking Guidelines

RANK	CRITICALITY	DESCRIPTION
0	Uncontrollable Factors	All levels of interest

		uncontrollable
1	Partial-controllable Factors	Some of levels of interest controllable
2	Controllable Factors	All levels of interest controllable

The objective of factors screening is to filter the factors based on the following criteria: -

- The fixed factors which should be kept constant throughout the procedure
- The selected factors based on sensitivity ranking

As a result, all the factors with sensitivity number 2 are selected as significant factors and concluded for DOE factors selection.

3.2.2 DOE

DOE is chosen as the core methodology to conduct experiments. The results of DOE provide the RFID packaging strategy in which all the items are detected successfully. Based on this packaging strategy and other experimental conclusions, the operational guidelines are developed for RFID packaging.

The DOE methodology used in this thesis is applied to three different scenarios. In the first scenario, the experiments are performed for USPS priority mail small flat rate boxes (8-5/8" x 5-3/8" x 1-5/8"). Twenty packages are tested in this scenario; the details of procedure are discussed in the following sections. In the second scenario, the small packages are packed inside USPS medium flat rate (11" x 8-1/2" x 5-1/2") boxes. Ten boxes are tested in this scenario with five packages inside each box. The third scenario tests the pallet tagging using USPS large flat rate boxes (10” x 12” x 15”). Ten pallets are tested in this scenario with six boxes in each pallet.

Following are the common experimental factors for the three scenarios (package, box and pallet testing) which were fixed and kept constant throughout the experimentation to minimize their impacts on outputs:-

- RFID Readers - The Alien 9500 RFID readers were used to read the RFID chips on packages, boxes and pallets. A single reader unit was used in experiments and the same unit used at both reader locations (front, corner).
- Reader Power – The power of the reader was set to 9db with reading frequency at 2.5 seconds. The power of the reader means the reading intensity of RFID reader and reading frequency depicts how frequent the reader reads the next/same tag.
- Conveyor Operation – The experiments were conducted on a 12 feet by 6 feet conveyor loop and 143.30 lbs (65kg) weight capacity, running in counter-clockwise direction. Two levels of speed were fixed for conveyor operation: low level at 50 ms; high level at 100 m/s.
- Middleware Software - BOWH RFID middleware software was used to capture the RFID information in conjunction with Alien RFID software. This middleware was used to capture and store RFID information, which was later used for statistical analysis.
- RFID Tags – EPC Global Class 1Gen 2 compliant Alien ALN-9640 - "Squiggle®" Inlay tags were used in all the experiments. These tags work between 860-960MHZ with antenna dimensions: 95mm * 8.2 mm. These tags are powered by the industry leading Higgs – 3 IC boasting a total of 800 bits of memory and are top ranking general purpose Squiggle inlay with exceptional performance in multiple applications, including package tagging and pallet tagging, etc [6]
- Package Boxes – The boxes used in experiments are United States Postal Service priority mail small flat rate boxes (8-5/8" x 5-3/8" x 1-5/8"), medium flat rate (11" x 8-1/2" x 5-1/2") boxes and large flat rate boxes (10” x 12” x 15”).

A. Scenario 1 - DOE for Package Testing

This section explicitly explains the DOE procedure for package testing. The packages used in this testing are standard USPS priority mail small flat rate boxes (8-5/8" x 5-3/8" x 1-5/8"). The objective of package testing is to develop the RFID packaging strategy in which all the packages are detected by the RFID reader in the first round of the conveyor loop. The conveyor should not run the second round of the loop to detect the missed packages or the same package should not be detected multiple times. The RFID embedded packages are run on the conveyor loop at different speeds and pass upfront a fixed RFID reader. The different types of packaging strategies are tested in this scenario based on DOE. The results of DOE are then used for statistical analysis. Consequently, the RFID packaging strategy in which all the packages are detected successfully is chosen for implementation. The RFID embedded packages are later packed in medium size boxes for further testing in Scenario 2. The following are the real world examples related to Scenario 1: -

- Tropicana Pure Premium Juice Bottles (32 Ounces)
- Egg Cartons
- Marlboro King Size Cigarette Packets
- Corona Extra Beer Bottles

The DOE for package testing is followed in a two step procedure. In the first step, the significant factors are identified by factors selection, as explained in section 3.2.1 above. In the second step, the DOE layout is developed and the experiments are conducted using Taguchi design.

B. Scenario 2- DOE for Box Testing

This section explicitly explains the DOE for box testing. The boxes used in this testing are standard USPS priority mail medium flat rate boxes (11" x 8-1/2" x 5-1/2"). In this scenario, 6 tagged packages used in

Scenario 1 are packed in a medium box embedded with RFID tag. The tag on the box consists of information about the box as well as the inside packages. For instance, when the box is scanned, the RFID tag on the box delivers information like type of packages, number of units, manufacturing date, expiration date and serial numbers of packages. The objective of this testing is to develop a packaging strategy for medium boxes in which only the RFID tag on the box is detected and the packages inside the box are not detected. This scenario mimics the packaging in which multiple units of items are packed together and shipped as a consolidated unit. Therefore, in such cases, it is more convenient to detect a consolidated package rather than reading multiple items together which makes the system more complex and time consuming. Moreover, reading the inside packages creates a huge bank of redundant data and reduces the RFID reliability as the same information can be delivered by reading a single tag on the box. A sample size of 10 boxes is selected for box testing. Later, 2 boxes, each consisting of 6 packages are packed in a large box for further testing in Scenario 3. The following are the real world examples related to Scenario 2: -

- 12 bottles of Tropicana Pure Premium juice in 1 box
- 200 cartons of egg in 1 box
- 24 packets of Marlboro King Size cigarettes in 1 carton
- 12 pack Corona Extra beer

The critical point to be observed in the above examples is that homogenous products are packed in the respective boxes. This may not be necessary in the actual scenario; for example, a grocery store can ship a box containing 6 bottles of juice and a 6 pack beer or another box containing 6 dozen eggs and 4 cigarette packets. One assumption in Scenario 2 is that all the goods in the box are homogeneous i.e. same type of items are packed together. The reason for this assumption is that it simplifies a highly complex and variable system of packaging. The second assumption in Scenario 2 is that the same quantities of the items are packed together. The reason for this assumption is that it simplifies the receiving and shipping process.

The DOE for box testing is followed in a two step procedure. The first step is the selection of significant factors as explained in section 3.2.1 above. In the second step, the DOE layout is developed and the experiments are run using half-fractional factorial design.

C. Scenario 3 - DOE for Pallet Testing

This section explicitly explains DOE for pallet testing. The pallets used in this testing are standard USPS priority large flat rate boxes (10” x 12” x 15”). In this scenario, 6 tagged boxes with each box consisting 6 tagged packages are packed in a large box embedded with RFID tag. The tag on the pallet consists of information about the pallet as well as the inside boxes and packages. The objective of this testing is to develop a packaging strategy for large boxes in which only the RFID tag on the pallet is detected and the boxes along with the packages inside the pallet are not detected. This scenario mimics the mass packaging in which a large number of packages are packed in the boxes and these boxes are further combined on pallets to ship as a consolidated unit. The outside tag reading on the pallet prevents the accumulation of unnecessary (redundant) data and enables even faster tracking. A sample size of 10 pallets is selected for pallet testing. Each pallet makes 20 rotations over the conveyor loop in order to achieve the most stable packaging setting. The following are the real world examples related to Scenario 3: -

- 30 boxes of Tropicana Pure Premium juice in 1 pallet (each box consists 12 bottles)
- 50 boxes of egg cartons in 1 pallet (each box consists 200 egg cartons)
- 500 cartons of Marlboro King Size cigarettes in 1 pallet (each carton consists 24 packets)
- 25 boxes of Corona Extra beer in 1 pallet (each box consists 12 bottles)

The DOE procedure for pallet testing has an additional step of factor testing. In this step, the potential factors identified are tested by running screening experiments. This step is necessary because the pallet testing scenario has large number of potential factors due to the influence of package and box factors. Therefore, the screening experiments are conducted in order to reduce the number of factors and have simple experimental design.

3.2.3 Data Analysis

The data analysis phase is subdivided into two parts; visual analysis and statistical analysis. In the visual analysis, those packaging strategies are identified which have “zero” MRR and MuRR by visually skimming the results of DOE. MRR is defined as the number of units missed by RFID reader during one cycle of conveyor loop. MuRR is defined as the number of units read more than one time by RFID reader during one cycle of conveyor loop. In the statistical analysis, MRR and MuRR are used to identify the reliable packaging strategies in Minitab. Consequently, the strategies which are common in visual and statistical analysis are selected as the best strategies for implementation. In case the analysis fails to identify common strategies, the first preference is given to statistical strategy. This is because statistical outputs are can be proved mathematically and are more stable than visual outputs.

3.2.4 Validation

In this phase, the best RFID packaging strategy provided by data analysis is validated by running a new DOE. It was observed in the statistical analysis that some factors of the best strategy do not contribute directly to the output. This means that these factors impact the output only when used in the combination with other factors. Such factors are considered as noise factors but are necessary in the strategy. Therefore, in the validation experiments, the noise factors are varied by keeping the significant factors constant. While on the other hand, in some cases, all the factors might be significant i.e. there are no noise factors. In such cases, there is no requirement to run a new DOE and the selected strategy is run for several trials to validate the statistical results.

3.2.5 RFID Operational Guidelines

This phase presents the operational and procedural guidelines for RFID ready receiving and shipping based on the results of data analysis and other experimental conclusions. These guidelines are user specific meaning that these guidelines are based on the specifications of operational environment. The guidelines are developed in order to facilitate, support and ensure a long term and reliable RFID receiving and shipping. The purpose of these guidelines is to encourage RFID packaging in different sectors of industry by providing the following: -

- The need for RFID packaging in the company
- The hardware and software requirements to implement RFID packaging
- The standard operating procedure for RFID packaging
- The guidelines to sustain RFID packaging

The guidelines for "RFID Ready Facilities" are presented in Chapter 5. These guidelines explain the procedure of RFID packaging for packages, boxes and pallets, as well as their combinations.

3.2.6 Steps Involved in the Methodology

Step 1: Identifying factors

In this step, the potential factors that impact RFID packaging are determined. This step is common and repeated again to identify factors for package, box and pallet.

Step 2: Selecting the factors for DOE

In this step, the significant factors are selected from the list of potential factors identified in Step 1. This is a common step for package, box and pallet testing.

Step 3: Determining DOE design

In this step, the DOE methodology is determined based on the selection of number of factors and their levels in Step 2.

Step 4: Calculating MRR and MuRR

In this step, MRR and MuRR are calculated by running the experiments to determine the best packaging strategy visually and statistically.

Step 5: Determining the best packaging strategy

In this step, the best packaging strategy is determined based on the data analysis.

Step 6: Validating the selected strategy

In this step, the best packaging strategy is validated by running DOE again. The results of validation experiments are compared with the results of previous experiments to testify the selected packaging strategy.

Step 7: Developing RFID packaging Guidelines

In this step, the RFID packaging guidelines are developed based on the results and other experimental conclusions.

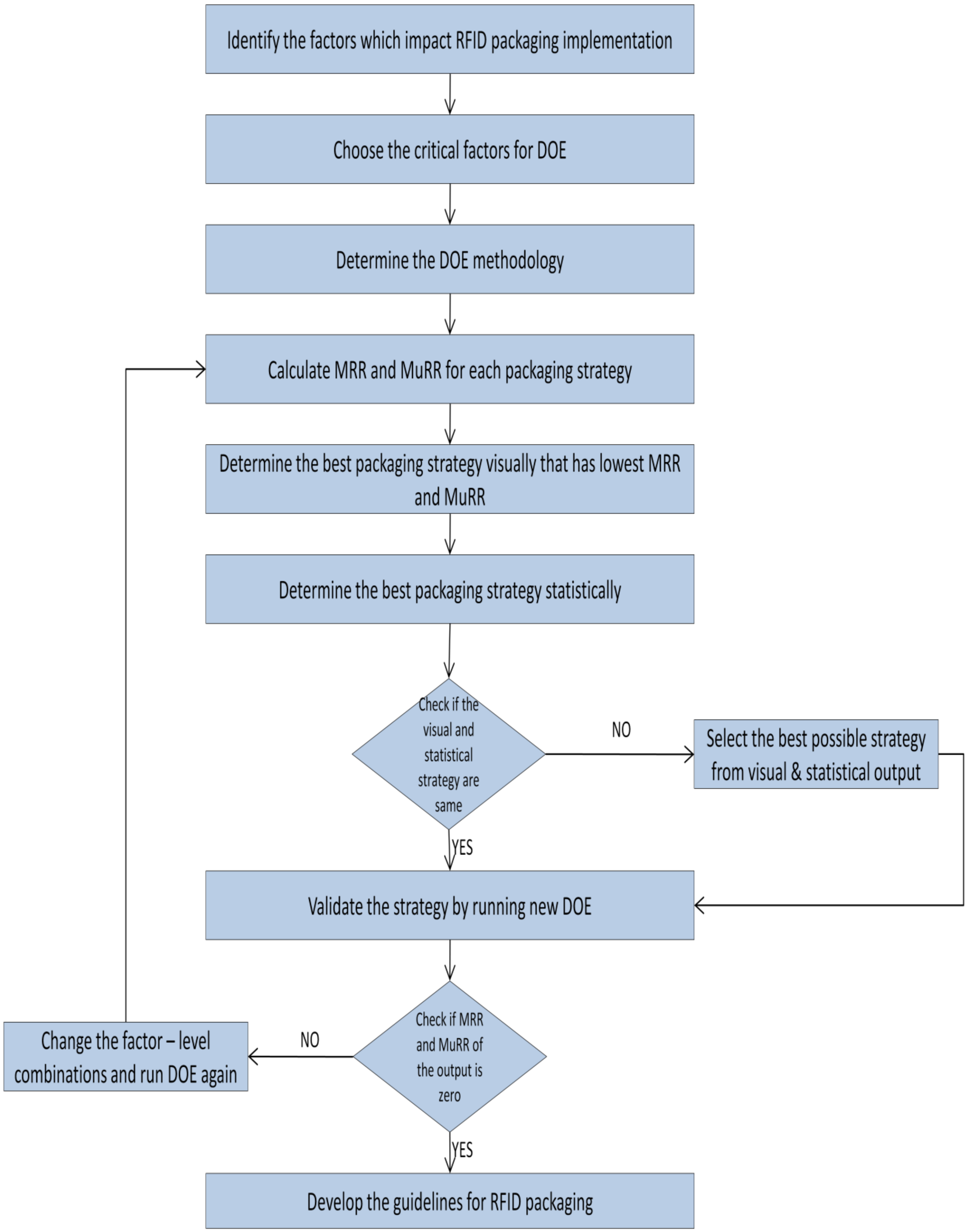


Figure 10: RFID Packaging Guidelines Methodology

Chapter 4

Data Analysis and Results

Chapter 4 illustrates the DOE methodology for package testing, box testing and pallet testing in detail along with the discussion of data analysis and results.

A. Scenario 1 - DOE for Package Testing

The following two phases illustrate the DOE procedure for package testing. In Phase 1, the significant factors are identified for package testing followed by DOE using Taguchi Methods (TM) in Phase 2.

Phase 1 – Factors Selection: In this phase, the significant factors are identified that impact RFID package testing. The test runs are conducted on the packages primarily to identify potential factors and to determine the sample size for package testing. The test results indicated that the sample size of 20 units is appropriate to measure the outputs of MRR and MuRR on packages. The following is the two step procedure for factors selection: -

Step 1: Initial Assessment – In this step, 11 potential factors are identified with their levels of interest as shown in Table 4. The vertical columns of the table represent the factors impacting RFID package testing and each horizontal row represents a combination of factor levels. In the real world experiments such as RFID package testing, it is very difficult and impractical to control more than, say, 10 factors. Some researchers have published results with 5 or fewer factors. The factors in the range of 5 to 7 are easy to control and economical. In our case, we have identified potential factors associated mainly with the configuration of package, RFID reader, conveyor operation and orientation of the tag. Next, these potential factors undergo factors screening as explained in Section 3.2.1 above, to reduce the number of factors for experimentation.

Table 4: Potential Factors for Package Testing

	Factors	Sensitivity	Levels		
			1	2	3
A	Package Orientation	2	vertical	Horizontal	side
B	Package Material	1	Metallic	Non-Metallic	x
C	Distance between boxes	1	Joined	Separated	x
D	Reader Location	2	Front	Corner	x
E	Vibration Level	0	1	2	3
F	Conveyor Speed	2	Low	High	x
G	Package Condition	1	Good	Bad	x
H	Package Placement	2	Straight	angle facing reader	angle not facing reader
I	Conveyor Operation	0	Intermitted	Continuous	x
J	Temperature Condition	0	Cold	Room Temp	Hot
K	Tag placement	2	on vertical side	on horizontal side	x

Step 2: Factors Screening - From Table 4, it can be observed that some of the potential factors are not controllable for package testing and therefore, these factors are fixed at certain levels for experimentation. The fixing of the uncontrollable factors helps to reduce the impact of the factor on the output of experiment. Table 5 below represents 3 factors with fixed levels of interest.

Table 5: Uncontrollable Factors for Package Testing

Factors	Sensitivity	Fixed at Level
Vibration Level	0	1
Conveyor Operation	0	Continuous
Temperature Condition	0	Room Temp

Similarly, from Table 4, it can be observed that some of the potential factors are partially controllable for package testing i.e. their levels of interest cannot be controlled completely. Therefore, these factors are also fixed at certain levels to reduce their impact on the output. Table 6 represents partial controllable factors with the fixed level of interest.

Table 6: Partial-Controllable Factors for Package Testing

Factors	Sensitivity	Fixed at Level
Package Material	**1**	Non-Metallic
Distance Between Boxes	**1**	Separated
Package Condition	**1**	Good

When using the DOE approach, it is better initially to focus on a large number of factors. In this way, the experimenter can look broadly across the factors with open mindedness and then select the significant factors based on their controllability. Using the similar approach, 5 significant factors are selected to conduct DOE for package testing from the list of 11 potential factors, shown in Table 7.

Table 7: Packaging Factors Selected for DOE

Factors	Levels		
	1	**2**	**3**
Package Orientation	vertical	horizontal	side
Reader Location	Front	Corner	x
Conveyor Speed	Low	High	x
Package Placement	straight	angle facing reader	angle not facing reader
Tag placement	on vertical side	on horizontal side	x

Phase II – Taguchi Method: Taguchi Method (TM) has been extensively used in diverse areas like biotechnology, marketing, advertising industries, corporations and universities. These methods are deliberate cost effective methods to improve the performance of a product by reducing its variability in customer's usage conditions [32, 33]. The 5 factor mixed factorial design for package testing is shown in Table 7 with 2 factors at 3 levels and 3 factors at 2 levels. TM is very effective for mixed factorial designs and therefore, is a natural candidate for package testing. Additionally, TM was used over classical methods in the methodology because:

- These methods have less hypothesis testing and are more robust with visual results.

- Orthogonal arrays are used to assure the reproduction of effects of parameters [34].
- These methods are more oriented toward engineering applications rather than advanced statistical techniques [35].

There are many statistical software packages available like Minitab, Statistica, SPSS, JMP, Matlab, among many others, which offer a library of designs for DOE. We have chosen Minitab to generate Taguchi design because it is widely used in the industry and also offers an easy user interface for Taguchi designs. There are two responses at the output of each experiment as shown in Table 8. These responses are directly affected by the factors listed in Table 7.

Table 8: Expected Responses for Package Testing

Y	**Name**	**Type of Response**
Y_1	Missed Read Rate (MRR)	The lower the better
Y_2	Multiple Read Rate (MuRR)	The lower the better

Mixed level TM (5 factors) with orthogonal array L_{36} (2**3 3**2) is used in the methodology for package testing. This means that resolution IV design with generator I = ABCDE and at least 36 runs will be able to estimate the effect of each factor. In this case, the interactions between the main factors could be considered and the design is randomized. The DOE data was collected based on the layout described in Table 4. There are 4 setups (replicated twice) that showed maximum RFID reliability and these setups are highlighted in Table 9.

Table 9: Taguchi DOE and Reliable Data for Package Testing

	Factors					**Output**	
Randomized Serial Number	**Reader Location (RL)**	**Conveyor Speed (CS)**	**Tag Placement (TP)**	**Package Orientation (PO)**	**Package Placement (PP)**	**Missed Read Rate**	**Multiple Read Rate**

7	Front	Low	Horizontal	Vertical	Straight	0	1
27	Corner	Low	Vertical	Side	Facing	0	0
36	Corner	High	Vertical	Side	Facing	0	0
29	Corner	High	Horizontal	Horizontal	Straight	0	0
30	Corner	High	Horizontal	Side	Facing	0	0
1	Front	Low	Vertical	Vertical	Straight	0	3
23	Corner	Low	Horizontal	Horizontal	NotFacing	5	0
19	Corner	Low	Horizontal	Vertical	Facing	0	0
18	Front	High	Horizontal	Side	Straight	0	1
6	Front	Low	Vertical	Side	NotFacing	0	10
34	Corner	High	Vertical	Vertical	NotFacing	0	0
16	Front	High	Horizontal	Vertical	Facing	1	0
14	Front	High	Horizontal	Horizontal	NotFacing	4	0
35	Corner	High	Vertical	Horizontal	Straight	5	0
4	Front	Low	Vertical	Vertical	Straight	0	0
13	Front	High	Horizontal	Vertical	Facing	0	1
2	Front	Low	Vertical	Horizontal	Facing	9	0
3	Front	Low	Vertical	Side	NotFacing	0	11
20	Corner	Low	Horizontal	Horizontal	NotFacing	7	0
17	Front	High	Horizontal	Horizontal	NotFacing	6	0
28	Corner	High	Horizontal	Vertical	NotFacing	0	0
12	Front	High	Vertical	Side	NotFacing	0	18
31	Corner	High	Vertical	Vertical	NotFacing	0	0
21	Corner	Low	Horizontal	Side	Straight	0	0
15	Front	High	Horizontal	Side	Straight	0	1
8	Front	Low	Horizontal	Horizontal	Facing	6	0
10	Front	High	Vertical	Vertical	Straight	0	0
22	Corner	Low	Horizontal	Vertical	Facing	0	0
25	Corner	Low	Vertical	Vertical	NotFacing	0	0
33	Corner	High	Vertical	Side	Facing	0	0
9	Front	Low	Horizontal	Side	NotFacing	0	0
26	Corner	Low	Vertical	Horizontal	Straight	4	0
24	Corner	Low	Horizontal	Side	Straight	0	0
11	Front	High	Vertical	Horizontal	Facing	10	0
32	Corner	High	Vertical	Horizontal	Straight	5	0
5	Front	Low	Vertical	Horizontal	Facing	10	0

The DOE data was analyzed using the MINITAB software. Taguchi proposes a summary statistic with an attempt to combine the information about the mean and variance, called the Signal-to-Noise ratio (S/N ratio). These S/N ratios are purportedly defined so that a maximum value of the ratio minimizes the variability transmitted from noise variables [36]. The outcome is based on various types of S/N ratios, to measure the variability around target performance. Therefore higher S/N ratios indicate better target performance. Subsequently, the means plot signifies how close the mean is to the target value. Therefore, lower means plot indicates better target performance [37-39].

Figure 12 below represents main effect plots of MuRR for package testing. In this figure, the main effect plots of S/N ratio are combined with the mean plots for the ease of comparing the levels of factors. The factor – level combination with high S/N ratio and low mean is selected as the best RFID packaging strategy based on MuRR dataset. The following conclusions are given by the main effect plots of MuRR for package testing: -

- Package Orientation has the most significant effect on package testing. The vertical level is selected as the best factor-level combination for this factor.
- Package Placement is the next significant factor for package testing. The straight level is selected as the best factor – level combination for this factor.
- Tag Placement is the next significant factor for package testing. The horizontal level is selected as the best factor – level combination for this factor.
- Conveyor Speed is the next significant factor for package testing. The high level is selected as the best factor – level combination for this factor.
- Reader Location is the least significant but necessary factor for package testing. The MuRR does not change with the change in the level of this factor.

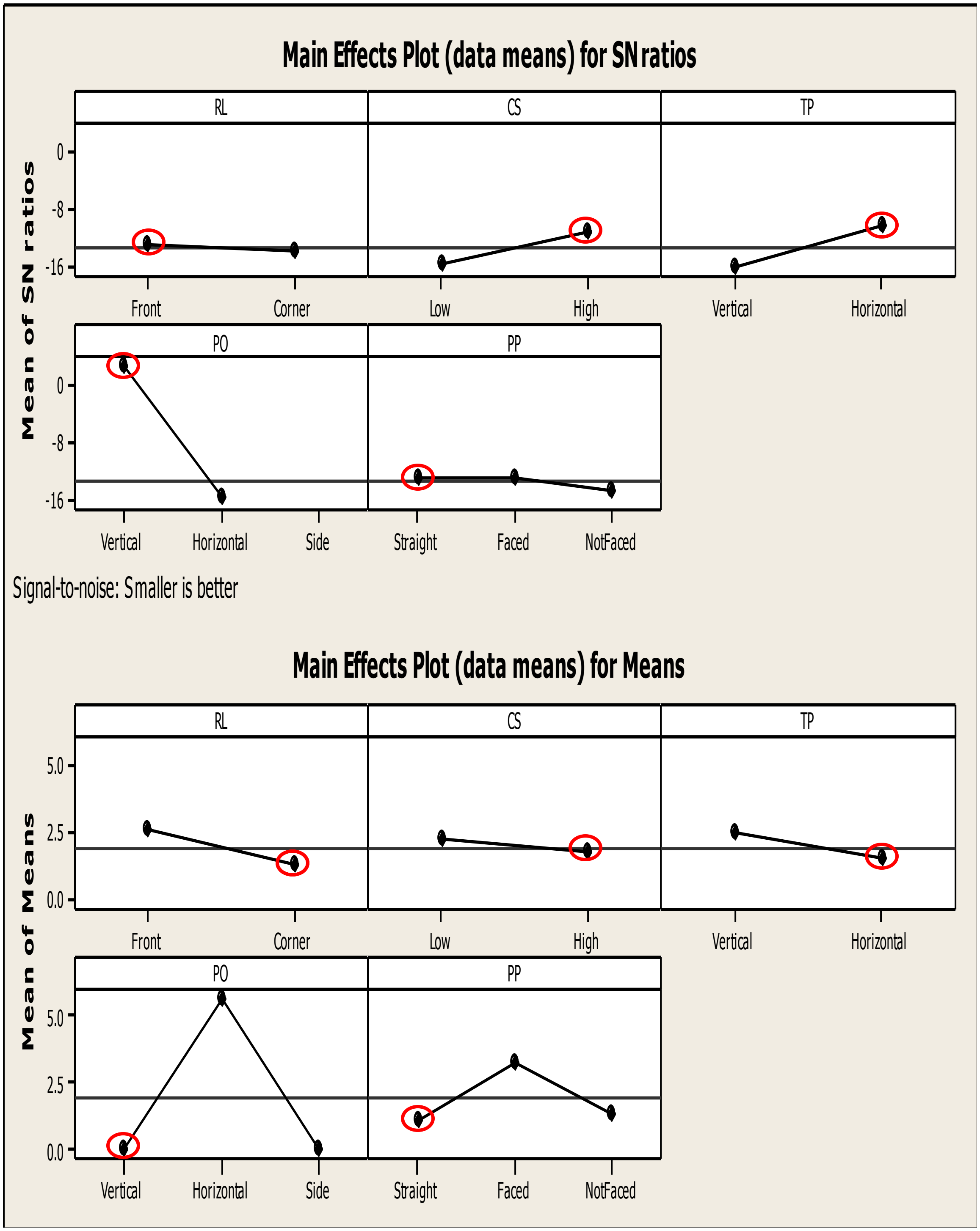


Figure 11: Main Effect Plots of MuRR for Package Testing

Figure 13 below represents the main effect plots of MRR for package testing. Similar to Figure 12, this figure also shows combined plots for S/N ratio and means for the ease of comparing the levels of factors. The factor – level combination with high S/N ratio and low mean is selected as the best RFID packaging strategy based on MRR dataset [41]. The following conclusions are given by the main effect plots of MRR for package testing: -

- Package Orientation has the most significant effect on package testing. The vertical level is selected as the best factor-level combination for this factor.
- Package Placement is the next significant factor for package testing. The straight level is selected as the best factor – level combination for this factor.
- Tag Placement is the next significant factor for package testing. The horizontal level is selected as the best factor – level combination for this factor.
- Reader Location is the least significant but necessary factor for package testing. The MRR does not change with the change in the level of this factor.
- Conveyor Speed is the next least significant factor for package testing. The high level is selected as the best factor – level combination for this factor.

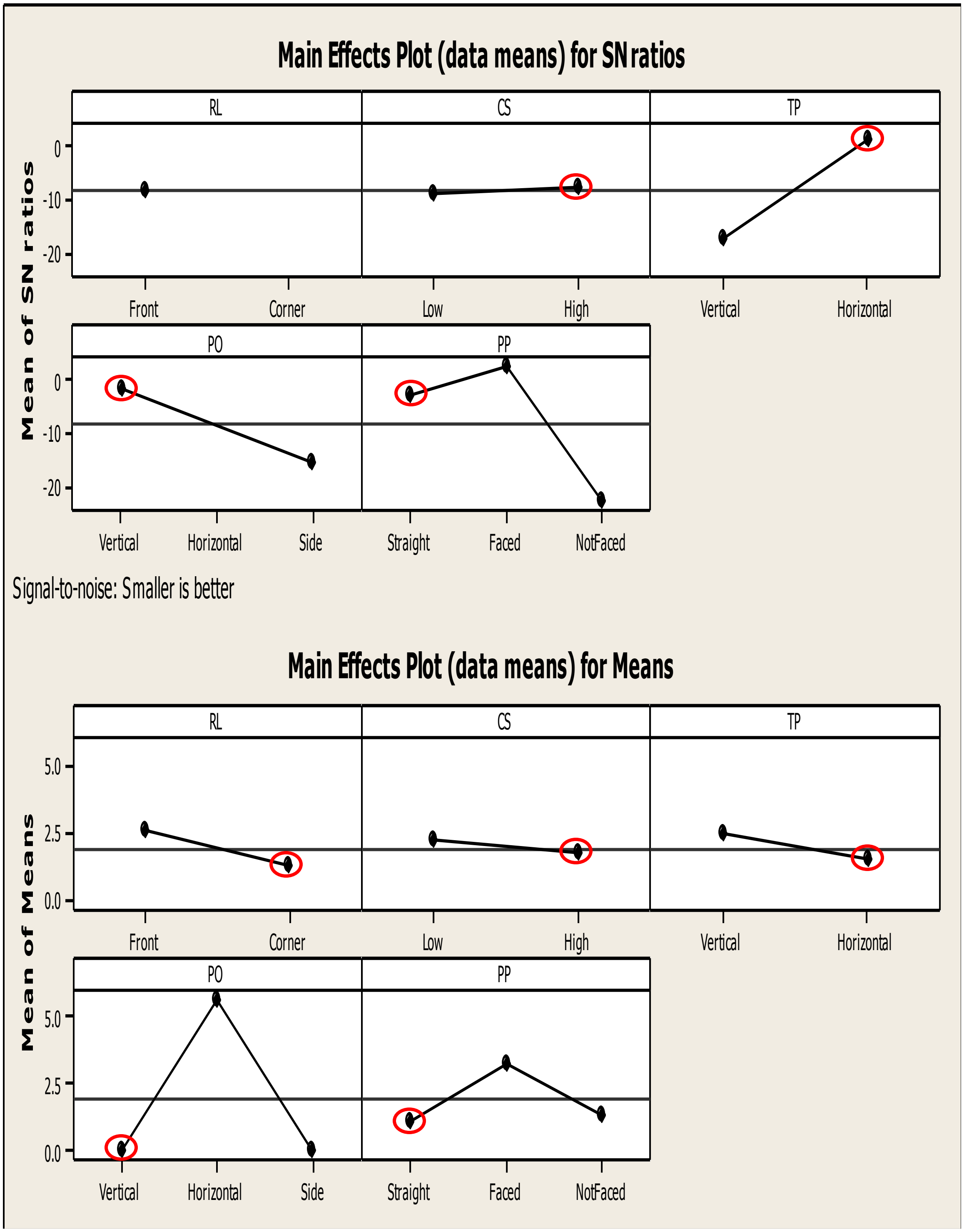


Figure 12: Main Effect Plots of MRR for Package Testing

The summary of the analysis is presented in Table 10 below. In this summary, each factor is allocated a rank ranging from 1 to 5, where, 1 is most significant factor and 5 is least significant factor. The levels selected as the results of comparison of S/N ratios and means plots are listed between factor rankings. The responses with minimum Y_1 (MRR) and Y_2 (MURR) yield the best results and provide with the most suitable factor – level combinations for packaging settings. It can be observed from Table 10, the two factor – level combinations: PO (vertical) and PP (straight) have the most significant effect in determining RFID packaging. However, in order to choose the optimum configuration of RFID packaging, it is necessary to consider the significant levels of noise factors. Therefore, the significant levels of noise factors are RL (corner), CS (high) and TP (horizontal), as shown in the table below.

Table 10: Significant Output for Package Testing

	Noise Factors			**Significant Factors**	
	Reader Location (RL)	**Conveyor Speed (CS)**	**Tag Placement (TP)**	**Package Orientation (PO)**	**Package Placement (PP)**
MRR (Y_1) S/N Ratio	5	3	2	1	4
	Corner	High	Horizontal	Vertical	Straight
MRR(Y_1) Mean	3	5	4	1	2
MuRR (Y_2) S/N Ratio	5	4	2	3	1
	Corner	High	Horizontal	Vertical	Straight
MuRR (Y_2) Mean	3	5	4	1	2

The Table 11 below shows the best factor – level combinations for package testing based on Taguchi analysis. The configuration shown in this table illustrates the settings of the experimental factors for package testing and how these factors should be handled to get the maximum RFID reliability.

Table 11: Best Factor Level Combination for Package Testing

Factors	**Levels**
Reader Location	Corner of lab room
Conveyor Speed	High (100m/s)

Tag Placement	Horizontal Side of package
Package Orientation	Placed vertically on the conveyor
Package Placement	Placed straight facing the reader

A new DOE was designed to validate the results of packaging experiments. The new DOE, shown in Table 12 is planned by keeping the significant factor levels constant and varying the noise factor levels.

This is because the significant factor levels were proved to be stable for package testing with both physical observations and statistically in the above sections. So, in order to check the stability of the noise factors, it is necessary to validate the noise factors by running a few more design of experiments.

Table 12: Validation of Packaging Results with New Design of Experiments

	Varied Factors			Constant Factors	
S.No	**RL**	**CS**	**TP**	**PO**	**PP**
1	Front	Low	Horizontal	Vertical	Straight
2	Corner	Low	Vertical	Vertical	Straight
3	Front	High	Vertical	Vertical	Straight
4	Corner	High	Horizontal	Vertical	Straight

The half-fractional factorial design with resolution III was selected to perform the new set of validation experiments. The results of new DOE indicate no failures in package tracking. This means that all the packages were tracked accurately in the new setup configurations. Hence, it proves the stability of the noise factors as well.

B. Scenario 2- DOE for Box Testing

A two phase methodology was followed for the DOE procedure for box testing. In the first phase, the significant factors are identified by following the same procedure as explained in package testing. In the second phase, the fractional factorial design is used to determine the best packing strategy for boxes.

Phase 1 – Factors Selection: In this phase, the significant factors are identified that impact RFID box packaging. The following is the two step procedure for factors selection: -

Step 1: Initial Assessment – In this step, 13 potential factors were identified with their levels of interest that have direct or indirect influences on RFID box packaging, as shown in Table 13. In addition to the box factors, the package factors were also considered in this scenario. This is because the packages inside the box were also embedded with RFID tags which might have direct or indirect impact on the RFID box packaging. In the next step, the potential factors identified in Step 1 undergo factors screening to reduce the number of factors for experimentation.

Table 13: Potential Factors for Box Testing

	Factors	Sensitivity	Levels		
			1	2	3
A	Package Orientation	2	vertical	horizontal	x
B	Condition of Box	1	Good	Bad	x
C	Box Orientation	2	straight	angle	x
D	Distance b/w Boxes	1	Joined	Separated	x
E	Package Material	1	Metallic	Non-metallic	x
F	Vibration Level	0	1	2	3
G	Conveyor Operation	0	Intermitted	Continuous	x
H	Temp Condition	0	Cold	Room Temp	Hot
I	Tag Placement on Box	2	Front	Side	x
J	Condition of Package	1	Good	Bad	x
K	Distance b/w Packages	1	Joined	Separated	x
L	Tag Placement on Package	2	Vertical Side	Horizontal Side	x
M	Box Material	1	Metallic	Non-metallic	x

Step 2: Factors Screening – In this step, the significant factors are filtered from the potential factors identified in Table 13. Table 14 below shows the list of uncontrollable factors. These factors are fixed at a specific level of interest to control their impact on the output.

Table 14: Uncontrollable Factors for Box Testing

Factors	Sensitivity	Fixed at Level
Vibration Level	**0**	1
Conveyor Operation	**0**	Continuous
Temperature Condition	**0**	Room Temp

Table 15 below enlists partially-controllable factors at fixed level of interest. These factors have indirect impact on the output and their levels of interest are not completely controllable based on the lab room infrastructure.

Table 15: Partial-Controllable Factors for Box Testing

Factors	Sensitivity	Fixed at Level
Package Material	**1**	Non-Metallic
Distance Between Boxes	**1**	Separated
Condition of Package	**1**	Good
Condition of Box	**1**	Good
Distance Between Packages	**1**	Joined
Box Material	**1**	Non-Metallic

Table 16 below represents 4 significant factors with their levels of interest that have a direct impact on RFID box packaging. These factors are used in the Phase II of box packaging to conduct DOE and are highlighted in Table 13 above as significant factors. The test runs in Scenario 2 indicated not much difference in the read rate with the change in the reader location from front to corner or vice-a-versa. Therefore, to simplify the experiments, the reader location was fixed at front. The reader power was fixed at 6db and kept constant throughout the box testing. Similarly, the conveyor speed was fixed at 100m/sec and kept constant throughout the box testing.

Table 16: Box Factors Selected for DOE

	Factors	Levels	
		1	2
A	Package Orientation	vertical	horizontal
B	Box Orientation	Straight	Angle
C	Tag Placement on Box	Front	Side
D	Tag Placement on Package	Vertical Side	Horizontal Side

Phase II – Fractional Factorial Design: As the number of factors in a two level factorial design increases, the number of runs for even a single replicate of the 2^k design becomes very large. For example, a single replicate of an eight factor two level experiment would require 256 runs. Therefore, fractional factorial designs are used in this case to draw out valuable conclusions from fewer runs. These designs obtain information about main effects and lower order interactions with fewer experiment runs by confounding these effects with unimportant higher order interactions. The 2_{IV}^{4-1} factorial design is used in the methodology for box testing. This means that resolution IV design with generator I = ABCD and at least 8 runs will be able to estimate the effect of each factor. Since the design is randomized and replicated 2 times, a minimum of 16 runs will be able to estimate the effect of each factor in this case. In resolution IV designs, no main effects are aliased with any other main effects or two factor interactions. However, some main effects are aliased with three factor interactions and the two factor interactions are aliased with each other. The response parameters for box testing are the same as that of package testing. This is because similar to package testing; MRR and MuRR are used to measure the output parameters. Minitab was used to generate ½ fractional factorial design to collect DOE data as described in Table 17. There are 2 setups that showed maximum RFID reliability and these setups are highlighted in Table 17.

Table 17: Two Level Fractional Factorial DOE and Reliable Data for Box Testing

	Factors				Output	
Randomized S.No	**Package Orientation (PO)**	**Box Orientation (BO)**	**Tag Placement on Box (TPB)**	**Tag Placement on Package (TPP)**	**Missed Read Rate**	**Multiple Read Rate**
14	Horizontal	angle	front	HS	0	5
12	Horizontal	straight	side	HS	2	3
4	Vertical	straight	side	HS	1	5
15	Horizontal	angle	side	VS	0	3
11	Horizontal	straight	side	VS	1	3
8	Vertical	angle	side	HS	0	7
13	Horizontal	angle	front	VS	0	3
9	Horizontal	straight	front	VS	0	2
2	Vertical	straight	front	HS	0	4
5	Vertical	angle	front	VS	0	1
6	Vertical	angle	front	HS	0	8
7	Vertical	angle	side	VS	0	0
10	Horizontal	straight	front	HS	0	4
1	Vertical	straight	front	VS	0	0
16	Horizontal	angle	side	HS	0	6
3	Vertical	straight	side	VS	2	0

Figure 14 below shows the Pareto Chart for fractional factorial design for box testing. The purpose of using Pareto Chart in this analysis is to highlight the most important factors among a set of factors that influence box packaging. All the effects that extend past the reference line drawn on the chart are significantly important. Therefore, the effects A, AD, C and AC are significantly important because they extend past the reference line. This means that the factors: Tag Placement on Package, Tag Placement on Package – Package Orientation, Box Orientation and Tag Placement on Package – Box Orientation are the most critical factors and impact the reliability of box packaging. The effects AB and B have the least impact on box packaging because they do not show any influence on the Pareto Chart. This means that the factors: Tag Placement on Package – Tag Placement on Box and Tag Placement on Box do not impact box packaging.

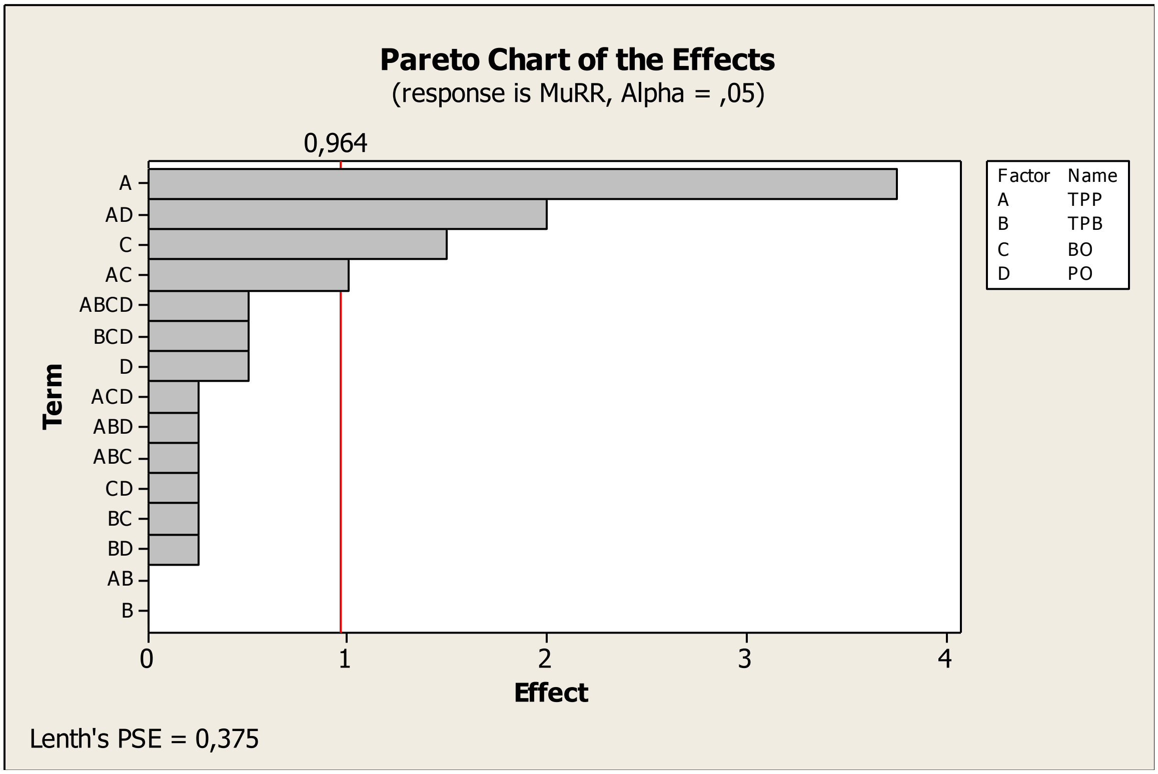


Figure 13: Pareto Chart for Fractional Factorial Design for Box Testing

The effects ACD, ABD, ABC, CD, BC and BD do not significantly affect RFID box tagging but are necessary for consideration. This means that the factors: Tag Placement on Package – Box Orientation – Package Orientation, Tag Placement on Package – Tag Placement on Box – Package Orientation, Tag Placement on Package – Tag Placement on Box – Box Orientation, Box Orientation – Package Orientation, Tag Placement on Box – Box Orientation, Tag Placement on Box – Package Orientation have the same and constant impact on the reliability of box packaging. The remaining factors and factor-factor interactions may or may not impact the box packaging depending upon the layout of the scenarios.

Figure 15 below shows the matrix of interactions plot for fractional factorial design for box testing. The interactions plot is used in this scenario because it helps to rank the factors and at the same time identify the best setting for each factor-level combination.

Figure 14: Interactions Plot for Fractional Factorial Design for Box Testing

The following conclusions are given by the matrix of interaction plots for fractional factorial design for box testing: -

- Tag Placement on Box – Box Orientation is the most significant interaction. The MuRR changes drastically when the Box Orientation is changed from straight to angle depending upon the level of Tag Placement on Box.

- Tag Placement on Box – Package Orientation is the next important interaction. The MuRR changes drastically when the Package Orientation is changed from vertical to horizontal depending upon the level of Tag Placement on Box.
- Tag Placement on Package – Package Orientation is the next important interaction. The MuRR changes drastically when the Package Orientation is changed from vertical to horizontal depending upon the level of Tag Placement on Package.
- Tag Placement on Package – Box Orientation is the next important interaction. The MuRR changes drastically when the Box Orientation is changed from straight to angle depending upon the level of Tag Placement on Package.
- Tag Placement on Package – Tag Placement on Box is the least significant interaction. The MuRR does not change with the change in the levels of either factor.
- Box Orientation – Package Orientation is the next least significant interaction. The MuRR does not change with the change in the levels of either factor.

Figure 16 below shows the main effects plots for fractional factorial design for box testing. The objective of using the main effects plot for this testing is to plot the means at various levels of each factor and compare the levels with the levels of the factors and interactions identified by using Pareto Chart and Interaction Plots above.

The following are the conclusions of main effects plot in conjunction to the analysis of Pareto Chart and Interactions Plot: -

- Tag Placement on Package (Estimated Level: vertical side)
- Tag Placement on Package – Package Orientation (Estimated Level: vertical side – vertical)
- Box Orientation (Estimated Level: straight)
- Tag Placement on Package – Box Orientation (Estimated Level: vertical side – straight)

- Tag Placement on Package – Tag Placement on Box – Box Orientation – Package Orientation (Estimated Level: vertical side – front/side - straight)
- Tag Placement on Box – Box Orientation – Package Orientation (Estimated Level: front/side – straight - vertical)
- Package Orientation (Estimated Level: vertical)
- Tag Placement on Package – Box Orientation – Package Orientation (Estimated Level: vertical side – straight - vertical)

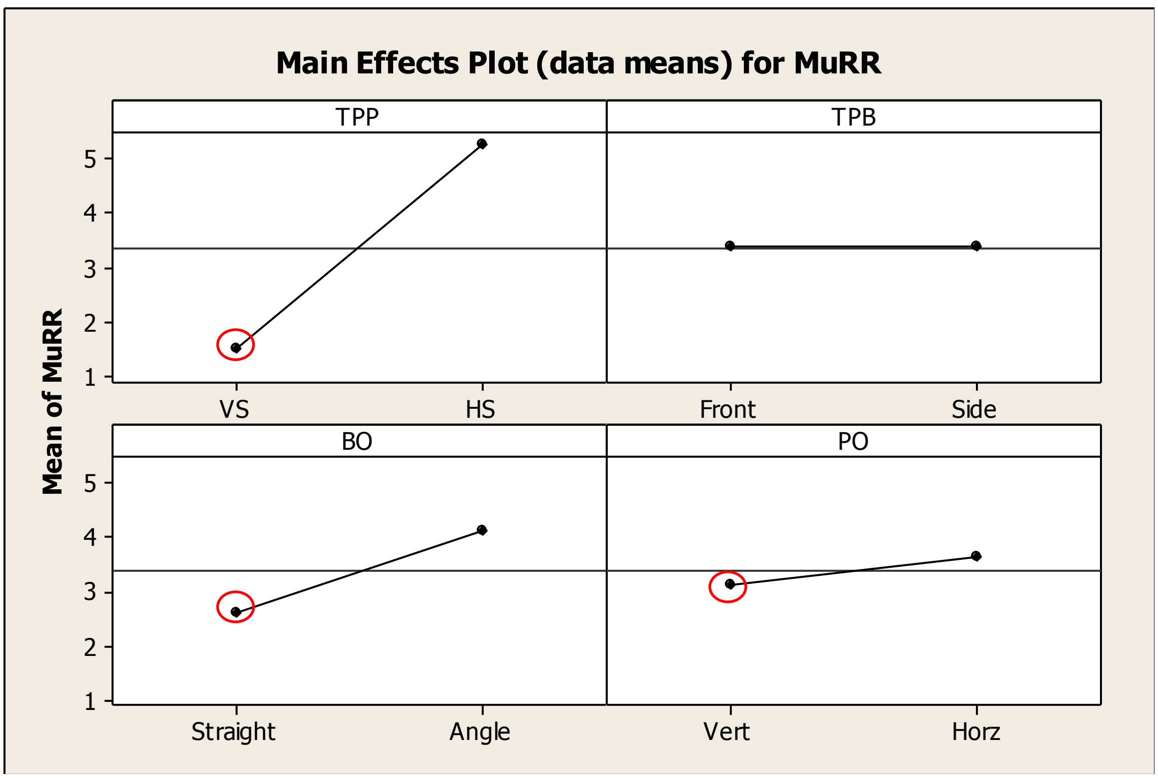


Figure 15: Main Effects Plot for Fractional Factorial Design

- Tag Placement on Package – Tag Placement on Box – Package Orientation (Estimated Level: vertical side – front/side - vertical)
- Tag Placement on Package – Tag Placement on Box – Box Orientation (Estimated Level: vertical side – front/side)

- Box Orientation – Package Orientation (Estimated Level: straight - vertical)
- Tag Placement on Box – Box Orientation (Estimated Level: front/side - straight)
- Tag Placement on Box – Package Orientation (Estimated Level: front/side - vertical)

Figure 17 below shows the estimated effects and coefficients table for full fractional factorial design for box testing. This table is a follow up step in which a mathematical model is developed to validate the output of main effects plot for box testing. Since, MuRR was used to estimate the effect of each factor therefore the regression equation that describes the relationship between avg. MuRR and factors for box testing is given by:

MuRR = 3,38 + 1,87 TPP - 0,000 TPB + 0,750 BO + 0,250 PO - 1,00 ad + 0,500 ac, where ad and ac are interactions between factors. It can be seen from the model that the factors impacting pallet testing are significant with p-Value lesser than 0.05. Also, the plot points fit the fitted line adequately; therefore, it can be assumed that the model is appropriate.

Factorial Fit: MuRR versus TPP; TPB; BO; PO

Estimated Effects and Coefficients for MuRR (coded units)

Term	Effect	Coef
Constant		3,375
TPP	3,750	1,875
TPB	-0,000	-0,000
BO	1,500	0,750
PO	0,500	0,250
TPP*TPB	-0,000	-0,000
TPP*BO	1,000	0,500
TPP*PO	-2,000	-1,000
TPB*BO	-0,250	-0,125
TPB*PO	0,250	0,125
BO*PO	-0,250	-0,125
TPP*TPB*BO	0,250	0,125
TPP*TPB*PO	-0,250	-0,125
TPP*BO*PO	-0,250	-0,125
TPB*BO*PO	0,500	0,250
TPP*TPB*BO*PO	0,500	0,250

Predictor	Coef	SE Coef	T	P
Constant	3,3750	0,1559	21,65	0,000
TPP	1,8750	0,1559	12,03	0,000
TPB	-0,0000	0,1559	-0,00	1,000

BO	0,7500	0,1559	4,81	0,001
PO	0,2500	0,1559	1,60	0,143
ad	-1,0000	0,1559	-6,41	0,000
ac	0,5000	0,1559	3,21	0,011

Figure 16: Estimated Effects and Coefficients for Fractional Factorial Design

The R^2 – Value indicates that the predictors explain 96.1% of the variance in MuRR for box testing. The adjusted R^2 is 93.5% which indicates that the model fits the data well. A three step procedure is followed to develop the mathematical model for significant levels of box testing. In the first step, a general mathematical equation is developed. In the second step, the significant levels of the factors are determined in terms of -1 (low) and +1 (high). The third step represents the final equation with significant levels.

Step 1 – General Mathematical Model:

Avg. MuRR = 3.375 + 1.875 (Tag Placement on Package) – 1.00 (Tag Placement on Package * Package Orientation) + 0.75 (Box Orientation) + 0.50 (Tag Placement on Package * Box Orientation) + 0.25 (Tag Placement on Package * Tag Placement on Box * Box Orientation * Package Orientation) + 0.25 (Tag Placement on Box * Box Orientation * Package Orientation) + 0.25 (Package Orientation) – 0.125 (Tag Placement on Package * Box Orientation * Package Orientation) – 0.125 (Tag Placement on Package * Tag Placement on Box * Package Orientation) + 0.125 (Tag Placement on Package * Tag Placement on Box * Box Orientation) – 0.125 (Box Orientation * Package Orientation) – 0.125 (Tag Placement on Box * Box Orientation) + 0.125 (tag Placement on Box * Package Orientation)

Step 2 – Mathematical Equation in terms of -1 (low) and +1 (high):

Avg. MuRR = 3.375 + 1.875 (-1) -1.00 (-1) *(-1) *(-1) + 0.75 (-1) + 0.50 (-1) * (-1) +0.25 (-1) * (+1) * (-1) * (-1) +0.25 (+1) * (-1) *(-1) + 0.25 (-1) – 0.125 (-1) * (-1) * (-1) – 0.125 (-1) * (+1) * (-1) + 0.125 (-1) * (+1) * (-1) + 0.125 (-1) * (+1) * (-1) – 0.125 (-1) * (-1) – 0.125 (+1) * (-1) + 0.125 (+1) * (-1)

Step 3 – Final Mathematical Equation:

Avg. MuRR = 3.375 – 1.875 -1 – 0.75 - 0.50 – 0.25 + 0.25 – 0.25 + 0.125 – 0.125 - 0.125 + 0.125 – 0.125 - 0.125 – 0.125

Avg. MuRR = - 1.375 (which is minimum)

C. Scenario 3- DOE for Pallet Testing

A two phase methodology was followed for the DOE procedure for pallet testing. In the first phase, the significant factors were identified based on sensitivity followed by factors screening using Placket-Burman design. In the second phase, the fractional factorial design was used to determine the best packaging strategy for pallets.

Phase I – Factors Selection: In this phase, the significant factors were identified that impact RFID pallet packaging. Unlikely, in the previous two scenarios, Phase I involves three steps for factors selection. The following is the three step procedure for factors selection: -

Step 1: Initial Assessment – In this step, 23 potential factors were identified with their levels of interest that have direct or indirect influences on RFID pallet packaging as shown in Table 18. In addition to pallet factors, the package factors and box factors were also considered in this scenario. This is because the packages and boxes inside the pallet were also embedded with RFID tags which might have direct or indirect influences on RFID pallet packaging.

Table 18: Potential Factors for Pallet Testing

	Factors	Sensitivity	Levels		
			1	2	3
A	**Package Orientation**	**2**	vertical	horizontal	x
B	**Tag Facing on Box**	**2**	facing	not facing	x
C	**Condition of Box**	**1**	Good	Bad	x

D	**Tag Placement on Pallet**	**2**	front	side	x
E	**Distance b/w Pallets**	**1**	Joined	Separated	X
F	**Box Orientation**	**1**	straight	angle	x
G	**Condition of Pallet**	**1**	Good	Bad	x
H	**Distance b/w Boxes**	**1**	Joined	Separated	x
I	**Pallet Orientation**	**2**	straight	angle	x
J	**Package Material**	**1**	Metallic	Non-metallic	x
K	**Box Placement in Pallet**	**2**	vertical side	horizontal side	x
L	**Vibration Level**	**0**	1	2	3
M	**Pallet Material**	**1**	Metallic	Non-metallic	x
N	**Conveyor Operation**	**0**	Intermitted	Continuous	x
O	**Reader Location**	**2**	front	corner	x
P	**Temp Condition**	**0**	Cold	Room Temp	Hot
Q	**Conveyor Speed**	**2**	low	high	x
R	**Tag Placement on Box**	**2**	Front	Side	x
S	**Condition of Package**	**1**	Good	Bad	x
T	**Distance b/w Packages**	**1**	Joined	Separated	x
U	**Humidity**	**0**	low	medium	high
V	**Tag Placement on Package**	**2**	Vertical Side	Horizontal Side	x
W	**Box Material**	**1**	Metallic	Non-metallic	x

Step 2: Factors Selection – In this step, the significant factors were selected from the list of potential factors in Table 18. The factors were classified based on their sensitivity into three categories; uncontrollable factors, partial-controllable factors and controllable factors which were used to conduct Plackett Burman Screening experiments. Table 19 below shows the list of uncontrollable factors for pallet testing. These factors were fixed at specific level of interest to minimize their impacts on the experimental output.

Table 19: Uncontrollable Factors for Pallet Testing

Factors	Sensitivity	Fixed at Level
Vibration Level	**0**	1
Conveyor Operation	**0**	Continuous

Temperature Condition	**0**	Room Temp
Humidity	**0**	Medium

Similarly, Table 20 below shows the list of factors which are partially controllable within the given experimental conditions. These factors are also fixed at certain level of interest to minimize their impacts on the experimental output.

Table 20: Partial Controllable Factors for Pallet Testing

Factors	Sensitivity	Fixed at Level
Package Material	**1**	Non-Metallic
Distance Between Boxes	**1**	Separated
Condition of Package	**1**	Good
Condition of Box	**1**	Good
Distance Between Packages	**1**	Joined
Box Material	**1**	Non-Metallic
Distance Between Pallets	**1**	Separated
Box Orientation	**1**	Straight
Condition of Pallet	**1**	Good
Pallet Material	**1**	Non-Metallic

Table 21 below represents 9 significant factors which are controllable in the given experimental conditions and used to conduct DOE for pallet testing. These factors are also highlighted in Table 18 as the significant factors for DOE. The significant factors in Table 21 have 2 levels of interest and are therefore perfectly suitable for Plackett-Burman design for screening experiments.

Table 21: Pallet Factors Selected for Screening Experiments Based on Plackett-Burman Design

	Factors	**Levels**	
		1	**2**
A	Box Tag Facing	Facing	not facing

B	Tag Placement on Pallet	Front	side
C	Tag Placement on Box	Front	Side
D	Box Placement in Pallet	Vertical	horizontal
E	Pallet Orientation	Straight	angle
F	Package orientation	Vertical	horizontal
G	Tag Placement on Package	vertical side	horizontal side
H	Reader Location	Front	corner
I	Conveyor Speed	Low	high

Step 3: Factors Screening – In this step, the Plackett-Burman DOE was conducted to screen the factors identified in Table 21. Plackett-Burman designs allow the estimation of K main effects using K + 1 runs. In these designs, the runs are a multiple of 4. The valid runs for Plackett-Burman designs are 4, 8, 12, 16, 20 and so on. A minimum of 12 runs will be able to estimate the effect of each factor in this case. When the runs are a power of 2, these designs correspond to the resolution III two factor fractional factorial designs. The objective of test runs using Plackett-Burman design was to reasonably reduce the number of significant factors in order to have simple experimental design and to clearly understand the impact of these factors on pallet packaging. As shown in Table 22, the design is randomized and the data is collected for two response parameters; MRR and MuRR. The MRR was observed to be zero for all run orders except for the run order # 11 indicating an overall reliable data for MRR. On the other hand, in case of MURR, only run order # 4 showed maximum RFID reliability, highlighted in Table 22. Since run order # 4 has zero MRR and MuRR, it is considered as the most reliable RFID packaging strategy for Plackett-Burman design. Each run order is repeated two times to understand the impact of variation in detail. Since MRR is zero for almost all the run orders, it is not considered in the statistical analysis. The average of MuRR 1 and MuRR 2 as Av. MuRR is used to verify the statistical significance of the run orders in Table 22 below.

Table 22: Plackett-Burman DOE

Std Order	Run Order	Box Tag Facing	Tag Plmt on Pallet	Tag Plmt on Box	Box Plmt in Pallet	Pack Orient	Pallet Orient	Tag Plmt on Pack	Reader Loc	Conv Speed	MRR 1	MuRR 1	MRR 2	MuRR 2	Av. MuRR
9	1	facing	front	front	horiz	horz	angle	vert side	corner	high	0	4	0	3	3.5
1	2	N facing	front	side	vert	vert	straight	horz side	corner	high	0	6	0	6	6.0
4	3	N facing	front	side	horiz	vert	angle	vert side	front	low	0	14	0	14	14.0
3	4	facing	side	side	vert	horz	straight	vert side	front	high	0	0	0	0	0.0
11	5	facing	side	front	vert	vert	angle	horz side	corner	low	0	13	0	13	13.0
8	6	facing	front	side	horiz	horz	straight	horz side	corner	low	0	11	0	13	12.0
6	7	N facing	side	side	vert	horz	angle	vert side	corner	low	0	8	0	9	8.5
10	8	N facing	front	front	vert	horz	angle	horz side	front	high	0	8	0	7	7.5
2	9	N facing	side	front	horiz	vert	straight	vert side	corner	high	0	11	0	11	11.0
7	10	facing	side	side	horiz	vert	angle	horz side	front	high	0	6	0	6	6.0
5	11	N facing	side	front	horiz	horz	straight	horz side	front	low	1	10	0	11	10.5
12	12	facing	front	front	vert	vert	straight	vert side	front	low	0	4	0	4	4.0

The variation within the run order of Plackett-Burman design is identified by using the R Chart as shown in Figure 18 below. The R Chart is used to track the process variation and to detect which run orders are out of control limit. The R Chart produces the output with a visual user interface and bases the estimate of process variation by default. In order to ensure the packaging quality, two measurements were taken for each run order. The process variation in R Chart was estimated on the basis of Av.MuRR because the data for MRR was constant and equal to zero. It can be observed in Figure 18 that the points are randomly distributed between the control limits, implying a stable process. It can be interpreted that run orders # 2,3,4,5,9,10 & 12 indicate no variation within the packaging process because these are exactly on the

LCL of the output. Run orders # 1, 7, 8, & 11are just close to the mean of the control limits. Run order # 6 lies on the border of UCL which is still inside the control limits, therefore is acceptable.

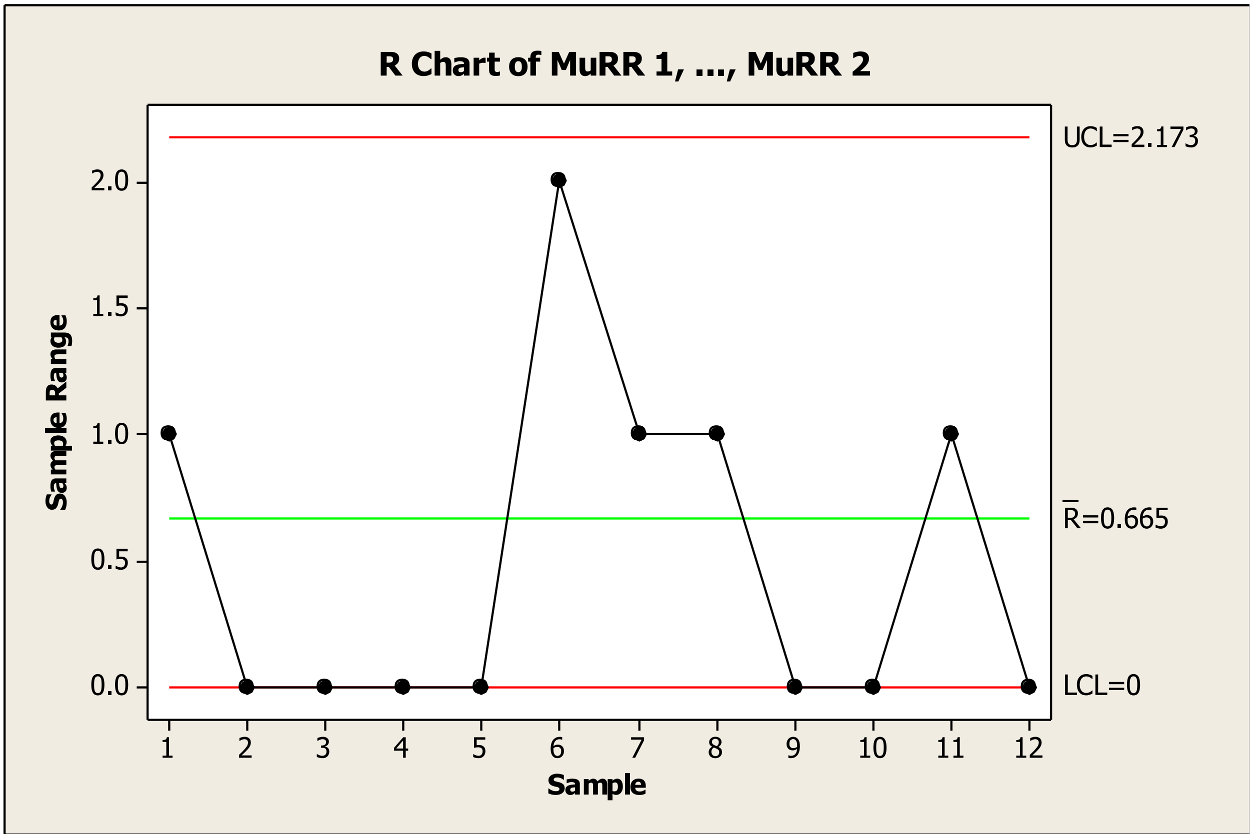


Figure 17: R Chart for Av. MuRR (Plackett-Burman DOE)

Figure 19 below shows the Pareto Chart for Plackett-Burman design. The Pareto Chart allows to identify visually both the magnitude and the importance of an effect. This chart displays the absolute value of the effects and draws a reference line on the chart.

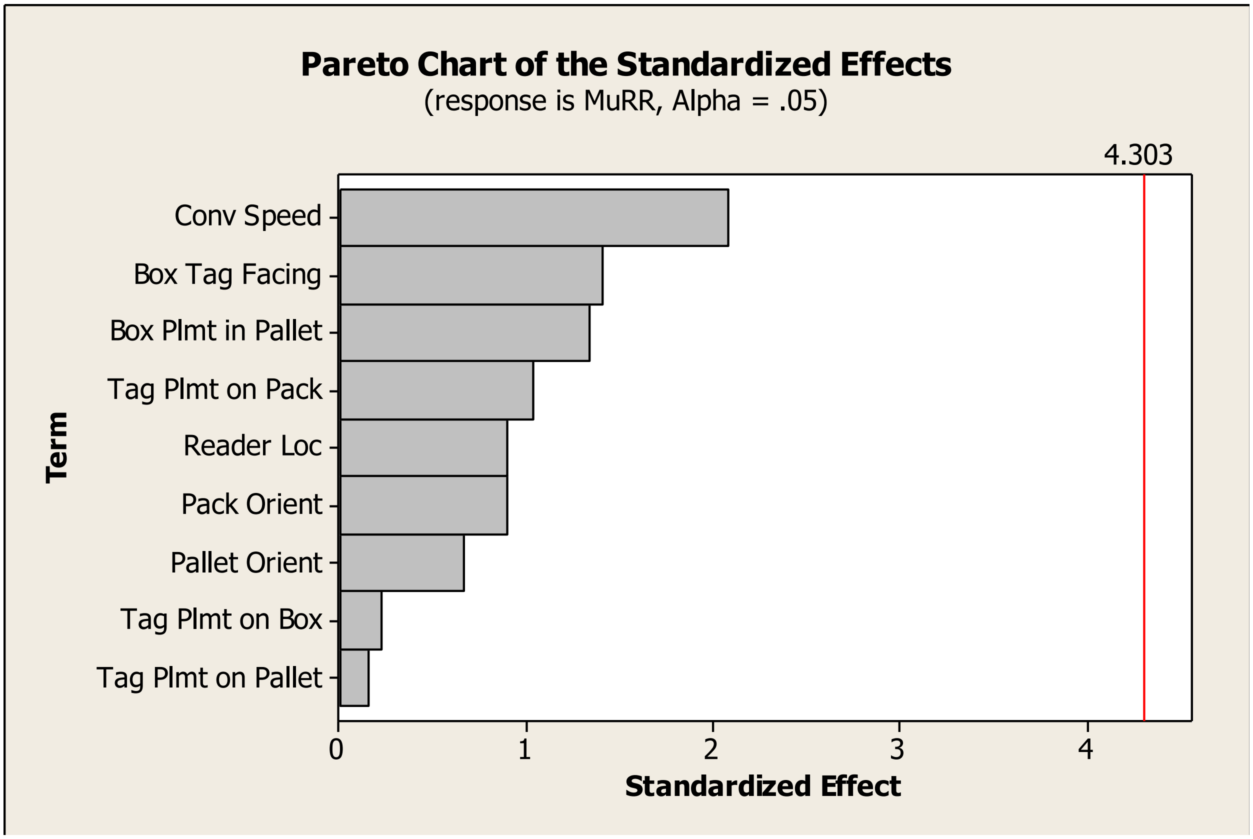


Figure 18: Pareto Chart for Plackett–Burman Design

It can be observed that Conveyor Speed is the most significant factor with the p-value equal to 0.176. Box Tag Facing is the next significant factor with p-value equal to 0.295 followed by Box Placement in Pallet with p-value equal to 0.314. Tag Placement on Pallet is the least significant factor with p-value equal to 0.896. The remaining factors may or may not impact the pallet packaging depending upon the layout of scenarios. Since, Conveyor Speed, Box Tag Facing and Box Placement in Pallet have the most stable effects on pallet packaging; these are fixed at the significant levels for further experimentation.

Figure 20 below shows the main effects plot for Plackett-Burman design. A main effect occurs when the mean response changes across the levels of a factor. Therefore, the main effect plots are used to compare the relative strength of the effects across factors and to indicate the levels of these effects. It signifies how close the mean is to the target value. Therefore, lower means plot indicates better target performance.

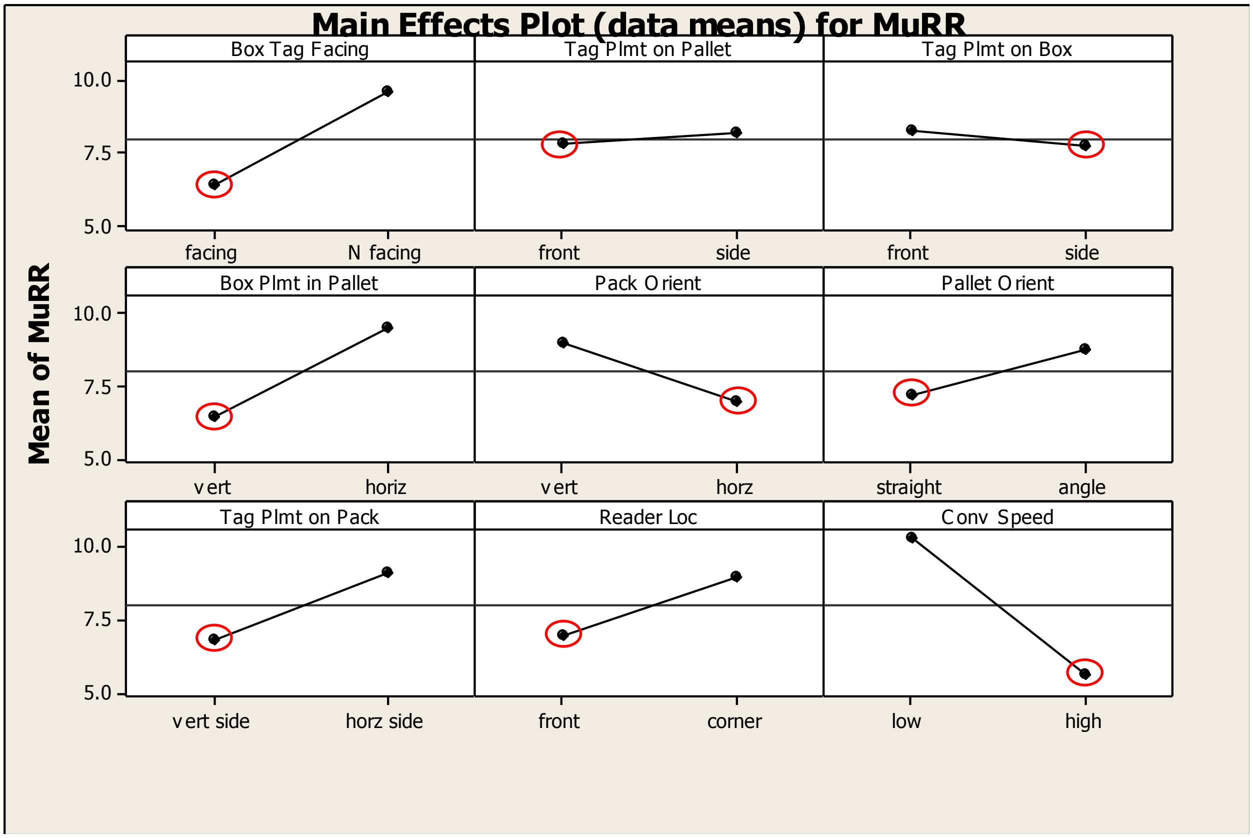


Figure 19: Main Effects Plot for Plackett-Burman Design

The following are the conclusions of main effects plot in conjunction to the analysis of Pareto Chart: -

- Conveyor Speed (Estimated Level: high)
- Box Tag Facing (Estimated Level: facing)
- Box Placement in Pallet (Estimated Level: vertical)
- Tag Placement on Package (Estimated Level: vertical side)
- Reader Location (Estimated Level: front)
- Package Orientation (Estimated Level: horizontal)
- Pallet Orientation (Estimated Level: straight)
- Tag Placement on Box (Estimated Level: side)
- Tag Placement on Pallet (Estimated Level: front)

Phase II – Fractional Factorial Design: The results concluded in the screening experiments in Phase I are used to conduct DOE in this phase. Table 23 below shows the list of factors which were fixed at certain levels to reduce the actual number of factors involved in the experimentation. These factors were selected from the list of 9 factors used to conduct Plackett-Burman experiments in the previous phase. The remaining 6 factors are varied at different levels and are considered potential factors for fractional factorial DOE.

Table 23: Fixed Factors for Fractional Factorial Design

	Factors	**Fixed at Level**
A	Box Tag Facing	facing
B	Box Placement in Pallet	vertical
C	Conveyor Speed	high

Table 24 represents the significant factors with their levels of interest that have direct impact on RFID pallet packaging. These factors were selected based on the results of experiments in Phase I. The DOE is conducted in this phase using these factors to conclude the best packaging strategy for pallets. Since, all the factors have 2 levels of interest; the 2^{6-1}_{IV} fractional factorial design is selected as the most suitable design to test the significance of these factors. This means that resolution IV design with generator I = ABCDEF and at least 16 runs will be able to estimate the effect of each factor in this case.

Table 24: Pallet Factors Selected for DOE Using Fractional Factorial Design

	Factors	**Levels**	
		1	**2**
A	Tag Placement on Pallet	Front	side
B	Tag Placement on Box	Front	Side
C	Pallet Orientation	straight	angle
D	Package orientation	vertical	horizontal
E	Tag Placement on Package	vertical side	horizontal side
F	Reader Location	Front	corner

The response parameters for pallet testing are the same as that of box testing and pallet testing. This is because similar to previous scenarios; MRR and MuRR are used to measure the output responses. Table 25 below represents the fractional factorial DOE and the reliable data for pallet testing. The MRR was observed to be zero for all the run orders, indicating an overall reliability for MRR. On the other hand, in case of MuRR, only run order # 8 showed maximum RFID reliability, highlighted in Table 25. Therefore, run order # 8 was selected as the most reliable RFID pallet packaging strategy in fractional factorial design. In fractional factorial design, each run order was repeated two times to understand the impact of variation in detail. The statistical significance of the run orders was estimated using Av. MuRR for all the runs. Since, MRR was observed to be zero for all the run orders, it was not considered to test the statistical significance of the runs.

Table 25: Fractional Factorial DOE and Reliable Data for Pallet Testing

Std Order	Run Order	Tag Plmt on Pack	Reader Loc	Pack Orient	Pallet Orient	Tag Plmt on Box	Tag Plmt on Pallet	MRR 1	MuRR 1	MRR 2	MuRR 2	Av. Murr
15	1	vert side	side	horz	angle	front	side	0	4	0	5	4.5
7	2	vert side	side	horz	straight	front	front	0	9	0	10	9.5
16	3	horz side	side	horz	angle	side	side	0	4	0	4	4.0
12	4	horz side	side	vert	angle	front	front	0	9	0	9	9.0
6	5	horz side	front	horz	straight	front	side	0	5	0	5	5.0
2	6	horz side	front	vert	straight	side	front	0	2	0	2	2.0
13	7	vert side	front	horz	angle	side	front	0	2	0	1	1.5
5	8	vert side	front	horz	straight	side	side	0	0	0	0	0.0
9	9	vert side	front	vert	angle	front	side	0	8	0	8	8.0
11	10	vert side	side	vert	angle	side	front	0	5	0	6	5.5
1	11	vert side	front	vert	straight	front	front	0	4	0	4	4.0
4	12	horz side	side	vert	straight	front	side	0	11	0	10	10.5
3	13	vert side	side	vert	straight	side	side	0	11	0	11	11.0
8	14	horz side	side	horz	straight	side	front	0	11	0	12	11.5
10	15	horz side	front	vert	angle	side	side	0	6	0	7	6.5
14	16	horz side	front	horz	angle	front	front	0	8	0	8	8.0

In a reliable packaging strategy, the assumption is that quality of the packaging is not compromised and the same results are produced each time with the same packaging strategy. In order to ensure quality, it is very critical to identify the variation within the run orders [42]. If there is no variation within the run order of the selected packaging strategy, it proves the reliability of the packaging. The R Chart is used to identify the variation within the run order of fractional factorial design, as shown in Figure 21 below. The estimation of the process variation in R Chart is done on the basis of Av. MuRR. As seen in Figure 21 below, the points are randomly distributed within the control limits of the chart with the run orders # 3, 4, 5, 6, 8, 9, 11, 13 & 16 indicating no variation within the packaging process. These points lie exactly on the LCL of the output. Further, run orders # 1, 2, 7, 10, 12, 14 & 15 are just close to the mean of the control limits. Therefore, all the points are acceptable and within the control limits of the chart.

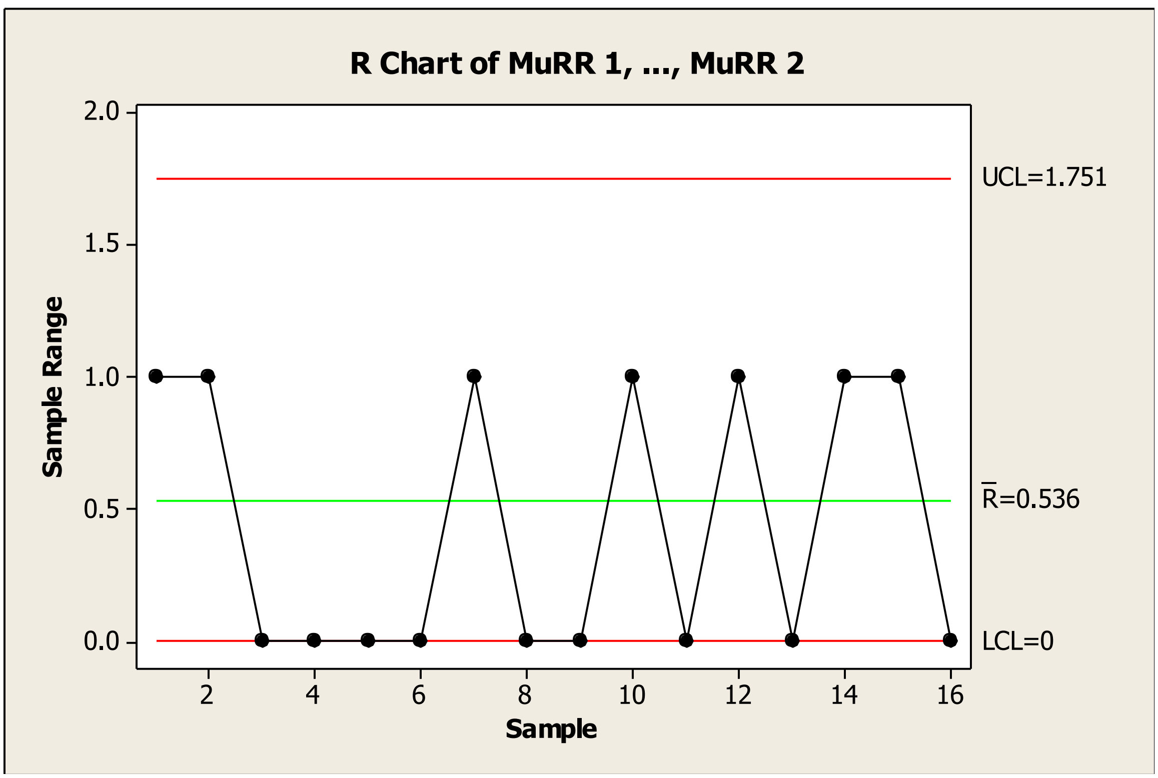


Figure 20: R Chart for Av. MuRR (Fractional Factorial DOE)

Figure 22 below shows the Pareto Chart for fractional factorial design for pallet testing. Pareto Chart is a statistical technique in decision making that is used for the selection of a limited number of tasks that produce significant overall effect. It provides a general idea of how majority of the problems or defects are produced by a few causes. It is a very useful tool to help determine which effects are active. The chart displays the absolute value of the effects, and draws a reference line on the chart. Any effect that extends past this reference line is potentially important. So, in Figure 22 below, the effects BD and B are significantly important because they extend past the reference line. This means that Reader Location - Pallet Orientation combination and Pallet Orientation are the most critical factors and impact the reliability of pallet packaging. The effects F, AE and ABD have the least impact on pallet packaging. This means that the factors: Tag Placement on Pallet, Tag Placement on Package-Tag Placement on Box and Tag Placement on Package-Reader Location-Pallet Orientation do not impact pallet packaging. The remaining factors and factor-factor interactions may or may not impact the pallet packaging depending upon the layout of the scenarios.

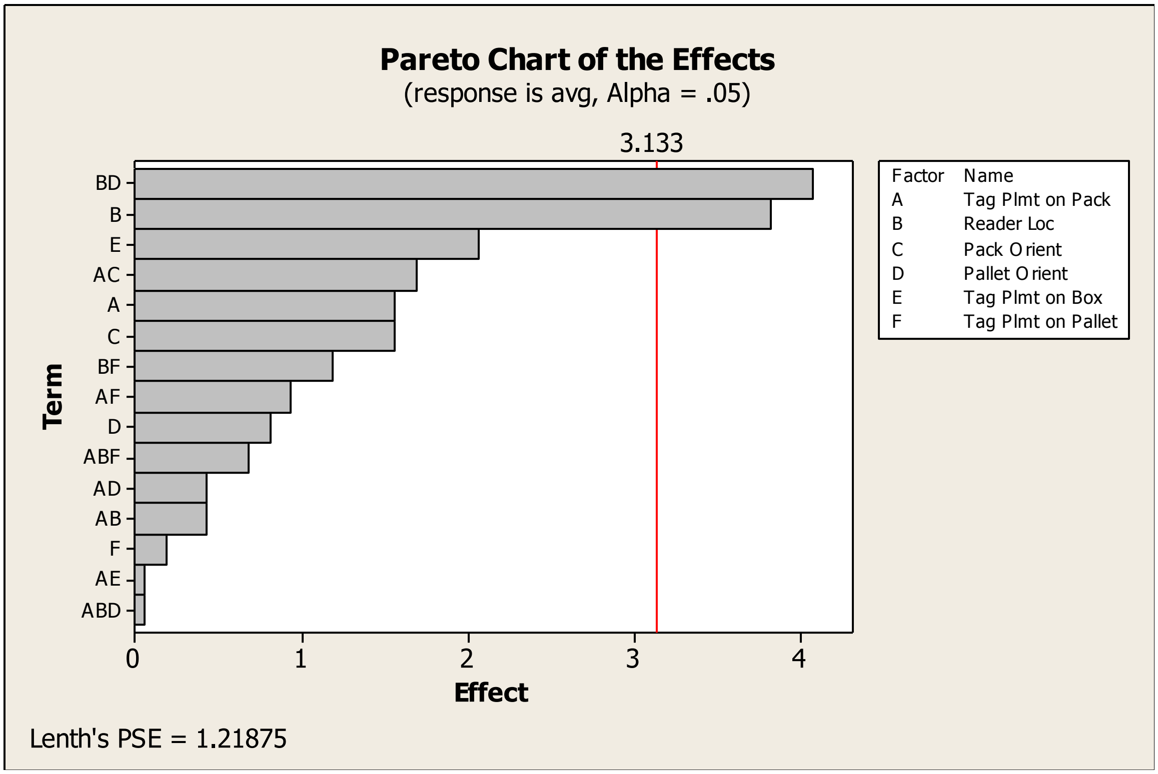


Figure 21: Pareto Chart for Fractional Factorial Design

Figure 23 below shows the matrix of interactions plot for fractional factorial design for pallet testing. An interactions plot is a plot of means for each level of a factor with the level of a second factor held constant. In this case, the raw response data used to draw the interactions plot is the average of the means of the response variable (MuRR) for each level of a factor. Interaction plots are useful for judging the presence of interaction. Interaction is present when the response at a factor level depends upon the level(s) of other factors. Parallel lines in an interactions plot indicate no interaction. The greater the departure of the lines from the parallel state, the higher the degree of interaction. To use interactions plot, data must be available from all combinations of levels.

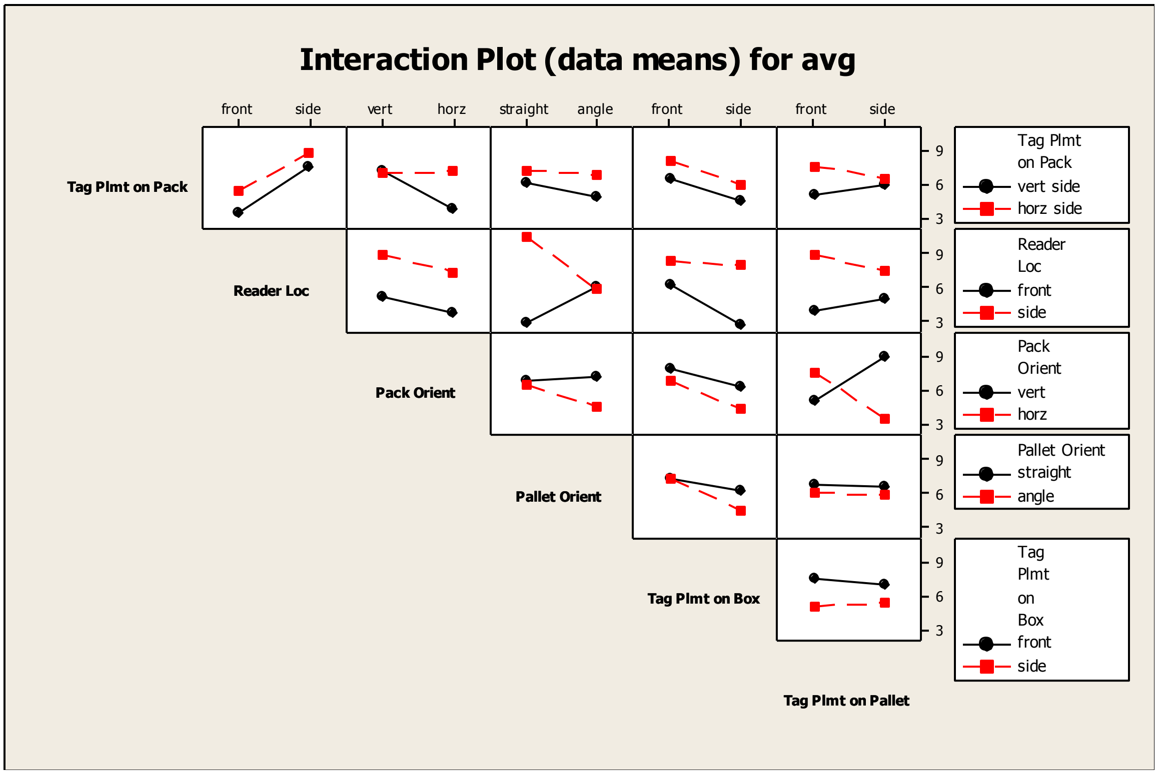


Figure 22: Interactions Plot for Fractional Factorial Design

The following conclusions are given by the matrix of interaction plots for fractional factorial design:-

- Reader Location – Pallet Orientation is the most significant interaction. The MuRR changes drastically when the Pallet Orientation is changed from straight to angle depending upon the level of the Reader Location.
- Package Orientation – Tag Placement on Pallet is the next important interaction. The MuRR changes drastically when the Tag Placement on Pallet is changed depending upon the level of Package Orientation.
- Tag Placement on Box is the next important factor. The MuRR changes significantly when Tag Placement on Box changes from front to side.

- Tag Placement on Package – Package Orientation is the next important interaction. The MuRR changes significantly when Package Orientation changes from vertical to horizontal depending upon the level of Tag Placement on Package.
- Tag Placement on Package – Tag Placement on Pallet is the next important interaction. The MuRR changes when Tag Placement on Pallet changes from front to side depending upon the level of Tag Placement on Package.
- Pallet Orientation – Tag Placement on Pallet is the least important interaction. The MuRR does not change with the change in the levels of either factor.
- Tag Placement on Package – Tag Placement on Box is the next least significant interaction. The MuRR does not change with the change in the levels of either factor.
- Tag Placement on Pallet is the next least significant factor. The MuRR does not change when Tag Placement on Pallet changes from front to side.
- Tag Placement on Package – Reader Location is the next least significant interaction. The MuRR does not change with the change in the levels of either factor.

Figure 24 below shows the main effect plots for fractional factorial design. The objective of using main effects plot is to identify the significant levels of the factors and interactions identified by using Pareto Chart and Interaction Plots above.

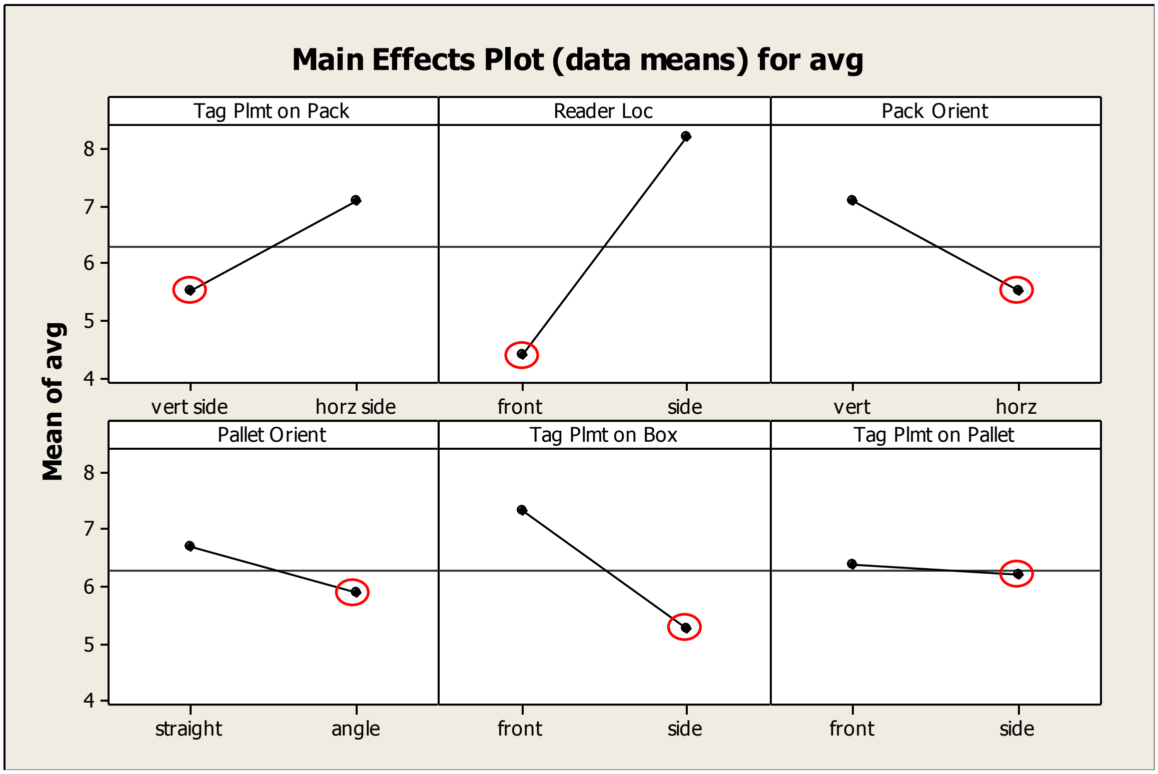


Figure 23: Main Effects Plot for Fractional Factorial Design

The following are the conclusions of main effects plot in conjunction to the analysis of Pareto Chart and Interactions Plot: -

- Reader Location – Pallet Orientation (Estimated Level: Front – Horizontal)
- Reader Location (Estimated Level: Front)
- Tag Placement on Box (Estimated Level: Side)
- Tag Placement on Package (Estimated Level: Vertical Side)
- Package Orientation (Estimated Level: Horizontal)
- Reader Location – Tag Placement on Pallet (Estimated Level: Front – Side)
- Tag Placement on Package – Tag Placement on Pallet (Estimated Level: Vertical Side – Side)
- Pallet Orientation (Estimated Level: Angle)

- Tag Placement on Package – Reader Location – Tag Placement on Pallet (Estimated Level: Vertical Side – Front)
- Tag Placement on Package – Pallet Orientation (Estimated Level: Vertical Side – Angle)
- Tag Placement on Package – Reader Location (Estimated Level: Vertical Side – Front)
- Tag Placement on Pallet (Estimated Level: Side)
- Tag Placement on Package – Tag Placement on Box (Estimated Level: Vertical Side – Side)
- Tag Placement on Package – Reader Location – Pallet Orientation (Estimated Level: Vertical Side – Front – Angle)

Figure 25 below shows the estimated effects and coefficients table for the full factorial design. This table is used to develop a mathematical model to validate the significant levels given by the main effects plot. From the Figure 25 below, the coefficients for the regression model can be calculated. Since, MuRR was used to estimate the effect of each factor therefore the regression equation that describes the relationship between avg. MuRR and factors for pallet testing is given by:

Avg MuRR (Min) = 6.28 - 2.03 BD + 1.91 B - 1.03 E

It can be seen from the model that the factors impacting pallet testing are significant with p-Value lesser than 0.05. Also, the plot points fit the fitted line adequately; therefore, it can be assumed that the model is appropriate.

Factorial Fit: avg versus Tag Plmt on Pack, Reader Loc, ...

Estimated Effects and Coefficients for avg (coded units)

Term	Effect	Coef
Constant		6.281
Tag Plmt on Pack	1.562	0.781
Reader Loc	3.813	1.906
Pack Orient	-1.562	-0.781
Pallet Orient	-0.813	-0.406
Tag Plmt on Box	-2.063	-1.031
Tag Plmt on Pallet	-0.188	-0.094
Tag Plmt on Pack*Reader Loc	-0.438	-0.219

```
Tag Plmt on Pack*Pack Orient          1.687   0.844
Tag Plmt on Pack*Pallet Orient        0.438   0.219
Tag Plmt on Pack*Tag Plmt on Box     -0.062  -0.031
Tag Plmt on Pack*Tag Plmt on Pallet  -0.937  -0.469
Reader Loc*Pallet Orient             -4.063  -2.031
Reader Loc*Tag Plmt on Pallet        -1.188  -0.594
Tag Plmt on Pack*Reader Loc*         -0.062  -0.031
  Pallet Orient
Tag Plmt on Pack*Reader Loc*         -0.688  -0.344
  Tag Plmt on Pallet

Predictor     Coef  SE Coef      T      P
Constant    6.2813   0.4911  12.79  0.000
BD         -2.0312   0.4911  -4.14  0.001
B           1.9062   0.4911   3.88  0.002
E          -1.0312   0.4911  -2.10  0.058
```

Figure 24: Estimated Effects and Coefficients for Full Fractional Design

The model is significant with S = 1.96453 and R^2 – Value = 75.3%. Both these values indicate that the model fits the data well. The objective of the mathematical model is to determine the levels of factors to have minimum Av. MuRR. The mathematical equation is developed in a three step procedure. In the first step, a general mathematical equation is developed. In the second step, the significant levels of the factors are determined in terms of -1 (low) and +1 (high). The third step represents the final equation with significant levels.

Step 1 – General mathematical model:

Avg. MuRR = 6.28 – 2.03 (Reader Location * Pallet Orientation) + 1.906 (Reader Location) – 1.031 (Tag Placement on Box) + 0.844 (Tag Placement on Package * Package Orientation) + 0.781 (Tag Placement on Package) – 0.781 (Package Orientation) – 0.594 (Reader Location * Tag Placement on Pallet) – 0.469 (Tag Placement on Package *Tag Placement on Pallet) -0.406 (Pallet Orientation) – 0.344 (Tag Placement on Package * Reader Location * Tag Placement on Pallet) + 0.219 (Tag Placement on Package * Pallet Orientation) – 0.219 (Tag Placement on Package * Reader Location) – 0.094 (Tag Placement on Pallet) – 0.031 (Tag Placement on Package * Tag Placement on Box) – 0.031 Tag Placement on Package * Reader Location * Pallet Orientation)

Step 2 – Mathematical equation in terms of -1 (low) and +1 (high):

Avg. MuRR = 6.28 – 2.03 (-1) * (-1) + 1.906 (-1) – 1.03 (+1) + 0.844 (-1) *(+1) + 0.781 (-1) – 0.781 (+1) – 0.594 (-1) * (-1) – 0.469 (-1) – 0.344 (-1) * (-1) * (-1) +0.219 (-1) * (-1) – 0.219 (-1) * (-1) – 0.094 (-1) – 0.031 (-1) * (+1) – 0.031 (-1) * (-1) * (-1)

Step 3 – Final Mathematical Equation:

Avg. MuRR = 6.28 – 2.03 – 1.906 – 1.03 – 0.844 – 0.781 – 0.781 – 0.594 – 0.469 + 0.344 + 0.219 – 0.219 – 0.094 + 0.031 + 0.031

Avg. MuRR = - 1.872 (which is minimum)

Chapter 5

Conclusion

Chapter 5 summarizes the major conclusions of this thesis and provides the "Guidelines for RFID Ready Facility" with the prime focus in the area of packaging. Finally it discusses the scope of future research in this area.

5.1 Summary of Research

The main purpose of this thesis is to develop the functional guidelines for an RFID ready facility. RFID is a scenario sensitive technology, as discussed in Chapter 1. Therefore, the companies willing to install this technology should first identify and understand the impact of potential factors related to RFID technology and the physical infrastructure where it has to be implemented. Further, a guided pilot study followed by test experiments can determine:

- How much potential does the RFID technology holds for the scenario?
- Will RFID technology be a success or a failure for the scenario?
- If a success, how much profit will RFID technology generate along with the other benefits?

In order to achieve this objective, this thesis proposes a methodology for RFID implementation in the area of packaging. The methodology used in this research illustrates the procedure to select the potential factors and to classify the factors based on their sensitivity. Further the DOE methodology explains how to plan the experiments by keeping the non – significant factors constant and varying the potentially significant factors. The experimental approach followed for RFID packaging in this thesis can be used for other scenarios as well, for example: manufacturing, warehousing, transportation, recycling, distribution, etc. MINITAB is used to validate the physical results and to check the stability of the RFID settings provided by the experimental output. MINITAB is the widely used statistical tool in the industry and it eliminates any additional effort needed by the end user to perform statistical analysis.

In the nutshell, if the company is considering implementing RFID technology in any of its facilities or departments, this thesis will help the company to select the best method of RFID implementation by providing the "Guidelines for RFID Ready Facility".

5.2 RFID Ready Facility Guidelines

This section provides the RFID functional guidelines for:

- RFID Package Tagging
- RFID Box Tagging
- RFID Pallet Tagging

Table 26 below represents the functional guidelines for RFID package tagging. The first column of the table represents the setup factors. The second column of the table represents the experimental results correspond to the respective setup factor. The last column of the table represents the RFID operational guidelines for each factor.

Table 26: Functional Guidelines for RFID Package Tagging

	Setup Factor	Experimental Result	Guidelines
1.	RFID Reader	1. The RFID reader when placed at corner position provides better tracking results than other positions. This is mainly due to ample visibility of the products to the reader at corner position. Therefore, the products remain in the reader range for a longer period of time. 2. The RFID reader sustained constant tracking with the following configuration:- • Reader Power – 9db	1. There is an extensive range of RFID readers available for industrial use. Therefore, the reader selection should be based on the type of environment, reader frequency and the sample size of the products. 2. The initial trials tell us what configuration best matches with reader's operating conditions. It has been observed that RFID readers at medium power and high frequency deliver most

		• Tracking Frequency – 2.5 seconds.	desirable results for the products that are close in read range. But if the distance between the products and reader is too far, then RFID readers at high power and low frequency deliver better results.
2.	Conveyor Operation	1. The two levels of conveyor speed were considered in DOE: low (50m/s) and high (100m/s). High speed of conveyor at 100m/s delivered good tracking results in the experiments.	1. The speed of conveyor should be set high when the RFID reader is at corner location because products are in the range of the reader for a longer time period. Consequently, the speed of conveyor should be low when the RFID reader is at front position because it will facilitate the products to be in read range for long time period.
3.	Package Orientation	1. The package when placed vertically on the conveyor loop provides better tracking results. The vertical position of the package brings horizontal side of the package upfront RFID reader and therefore, provides a good platform where RFID tags are visible.	1. The orientation of package should be selected according to the location of RFID reader and should be kept constant unless there is any change in reader location. 2. The vertical position should be selected if the geometry of the package is cubic. Package orientation can change for different geometric shapes.
4.	Package placement	1. The corner location of RFID reader receives maximum exposure when the package is placed straight resting on the vertical side.	1. Package placement was found to have significant effect on RFID packaging. The range of the reader is an important factor that determines the location of

			the package on conveyor loop.
5.	Tag Placement	1. The best results were observed in the experiments when the tags were placed on the horizontal side of the package. This is because the horizontal position of package is upfront RFID reader and the tags are placed in the center of the horizontal position so that there is no interference between RFID tags when the products reach the corner of conveyor loop.	1. The tag placement is based on the package material, number of products to be tagged, RFID reader configuration and conveyor speed.

Table 27 below represents the functional guidelines for RFID box tagging. These guidelines indicate the best configurations of package and box with an objective to block the RFID tags on the package and to enable the visibility of RFID tag on the box.

Table 27: Functional Guidelines for RFID Box Tagging

	Setup Factor	**Experimental Result**	**Guidelines**
1.	Package Orientation	1. The physical and statistical results indicate that vertical orientation of the package delivers maximum RFID reliability. This is because the RFID tags are blocked when the packages are placed facing vertical to each other.	1. The most stable method to block the tags when placed inside the box is to embed the RFID tag on the vertical surface of the package and to place the package vertically inside the box. This orientation of the package blocks the visibility of RFID tags and only the outer tag on the box is detected.
2.	Box Orientation	1. The physical results indicate that both angle and straight orientations of the	1. The level of Box Orientation depends on the Tag Placement on Box.

		box deliver maximum RFID reliability depending upon the level of Tag Placement on Box. 2. The statistical results indicate that straight orientation of the box delivers maximum RFID reliability. 3. Box Orientation – Tag Placement on Box is the most significant interaction.	2. The best orientation of the box is angle when the tag is placed on the side of the box. This configuration enables RFID tag to be more visible to RFID reader. 3. The best orientation of the box is straight when the tag is placed on the front of the box. This configuration enables the position of RFID tag directly facing RFID reader therefore provides better stability.
3.	Tag Placement on Box	1. The physical and statistical results indicate that the Tag Placement on Box can be either on the front or side of the box. 2. The tag placed on the front of the box with straight orientation delivers the same RFID reliability when the tag is placed on the side of the box with angled orientation of the box. 3. This is because in either configuration, the RFID tag is facing the RFID reader.	1. The tag can be placed either on the front or side of the box if the geometry of the box is cubic. 2. The Tag Placement on Box is significant with Box Orientation.
4.	Tag Placement on Package	1. The physical and statistical results indicate that the tag placement on vertical side of package delivers maximum RFID reliability. 2. This is because the vertical side of the package is not visible to the RFID reader and therefore the tags embedded on the vertical side are not detected by the reader.	1. Tag Placement on the package should be such that the RFID tags are not visible to the RFID reader. 2. The vertical position of the package is the best to embed RFID tags if the number of packages inside the box is more than two.

Table 28 below represents the functional guidelines for RFID pallet tagging. These guidelines indicate the best configurations of package, box and pallet with an objective to block the RFID tags on both the package and box so that the RFID tag on the pallet is visible.

Table 28: Functional Guidelines for RFID Pallet Tagging

	Setup Factor	Experimental Result	Guidelines
1.	Tag Placement on Pallet	1. The physical and statistical results indicate that tag placement on the side of pallet delivers maximum RFID reliability. 2. The level of Tag Placement on Pallet depends on the level of Pallet Orientation. 3. The tag should be placed on the side and the orientation of the pallet should be at an angle facing RFID reader.	1. Tag Placement on the pallet should be such that the RFID tag should face RFID reader. 2. It has been observed in the experiments that even if the RFID tag is placed on the side of the pallet, it will deliver maximum RFID reliability if the pallet is placed at an angle facing the reader. This is because it provides ample visibility to the tag in front of the reader.
2.	Tag Placement on Box	1. The physical and statistical results indicate that the tag placement on the side of the box delivers maximum RFID reliability. 2. The tag should be placed on the side of the box and the box should be placed vertically inside the pallet. This configuration blocks all the tags on the box.	1. Each box placed inside the pallet consists of multiple packages. Therefore, Tag Placement on Box is the most crucial factor to determine the stability of RFID readability. 2. The tag should be placed on the box in such a manner so that the tags on the packages remain hidden and the tag on the pallet is visible. 3. The best configuration is to align the RFID tag on the box with the tags on the packages and keep the same orientation of both the packages and box. These

			configurations will intact the tag visibility on the pallet without any interference with other tags.
3.	Pallet Orientation	1. The physical and statistical results indicate that Pallet Orientation depends on the Reader Location. 2. The statistical results indicate that the angled orientation of the pallet delivers better RFID reliability provided the tags are placed on the side of the pallet with reader location upfront pallet.	1. It is very important to align Pallet Orientation with Reader Location and Tag Placement on Pallet. For example, if the tag is placed on the front of pallet with straight orientation of pallet but the reader location is on the side then there are more chances of missing the tag detection on pallet. Therefore, Tag Placement on Pallet, Pallet Orientation and Reader Location should be carefully aligned achieve maximum tag visibility on the pallet. 2. The pallet orientation should be such that the RFID tag on the pallet receives ample visibility in front of RFID reader.
4.	Package Orientation	1. The physical and statistical results indicate that the horizontal package orientation delivers maximum RFID reliability. 2. Package Orientation depends on Tag Placement on Package.	1. The package orientation should be such that the RFID tags on the package are not visible to RFID reader. 2. The best strategy is to keep the package orientation vertical if the tags are placed on the horizontal side of package or vice-a-versa.
5.	Tag Placement on Package	1. The physical and statistical results indicate that the tag should be placed on the vertical side of the package.	1. The tags should be placed on the vertical side of the package and the packages should be placed horizontally inside the pallet. 2. Tag placement on package

			should be aligned with package orientation and box orientation.
6.	Reader Location	1. The physical and statistical results indicate that the front reader location delivers maximum RFID reliability. 2. This is because when the tags are placed on the side of the pallet and the orientation of the pallet is at an angle then the front position of reader provides ample visibility to the RFID tag on the pallet.	1. The reader location is one of the most significant factors to determine RFID reliability. This is because it is more complex to caliber RFID tag configurations of multiple tags rather than adjusting reader location. 2. The RFID tags on the packages and boxes should not be detected by the RFID reader other than the tag on the pallet. 3. The best configuration is to place the tag on the side of pallet and box and reader location to the front.

5.3 Summary of Research Results with respect to Problem Statement

The objective of this study was to:

- Conduct experiments by using DOE as core methodology to develop the functional guidelines for an RFID ready facility
- Compare the physical and analytical results of DOE
- Develop the general guidelines for an 'RFID Ready Facility'

All the above objectives have been achieved through the course of this research work. The methodology in this research provides a structured framework to classify the potential factors impacting RFID infrastructure and to plan the Design of Experiments based on the type of factor – level configuration. It also provides a methodology to validate the results of the experimentation in order to sustain the goals for a longer period of time. Finally, the MINITAB tool helps the implementer to compare the physical and analytical results and also determine the best RFID implementation strategy that will maximize the profits.

5.4 Future Work

The next step in this research can be focused in combining physical experiments with computer aided simulations. The simulation models of the complex physical scenarios can be created to understand how RFID technology behaves in such scenarios. If the study finds the lag between the physical experiments and computer simulations then this research can be enhanced to understand the bottleneck in the simulation model. One of the benefits of using computer simulations with physical experiments is that the potential factors impacting RFID infrastructure can be iterated and replicated millions of times which otherwise is never possible with physical iterations.

The other area in which the future research in this topic can focus is to test different types of materials in categories of packages, boxes and pallets. In the present research, DOE was conducted using same type of material of packages, boxes and pallets. At the next level heterogeneous materials can be used to fill the packages as well as for the material of packages. These physical scenarios can be combined with computer simulations to validate the reliability of RFID infrastructure.

Lastly, based on the results of physical and simulation models, mathematical algorithms can be created along with IT applications to automate the RFID infrastructure. These algorithms can be modified according to the needs of the scenario where RFID technology is to be implemented, thereby, resulting in standard operating procedures and sustainability for RFID implementation.

List of References

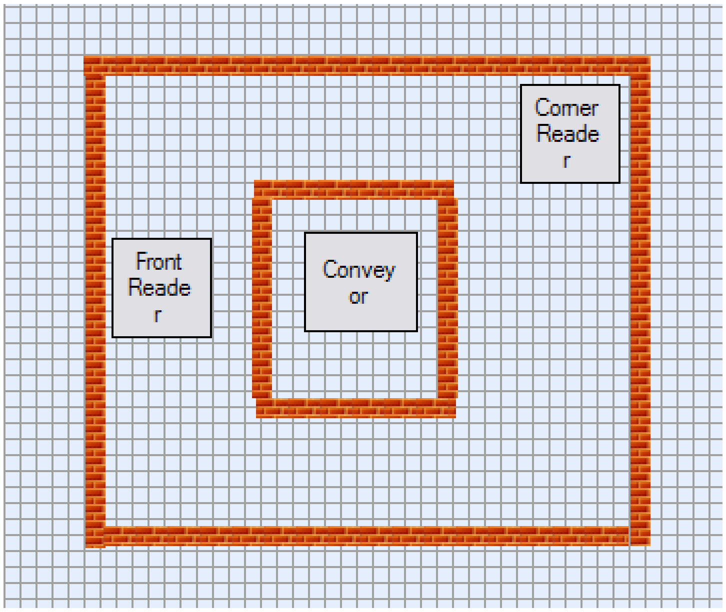
1. [Does RFID Reduce Out of Stocks, 2007, Bacheldor, Beth (2008-01-11).
2. "Sam's Club Tells Suppliers to Tag or Pay http://www.rfidjournal.com/article/articleview/3845/1/1/. Retrieved 2008-01-17]
3. www.acq.osd.mil
4. Daniel W. Engels (Reserach Director, A.-I. L., 2004, "Packaging and RFID Incorporating RFID in the Real World." Pack Expo International.
5. Chang - Xue (Jack) Feng. "An experimental Study of the Impact of Turning Parameters on Surface Roughness", *IIE Conference*
6. *Gildas Avoine and Philippe Oechslin., 2005, "RFID Traceability: A multilayer Problem", Financial Cryptography and Data Security*
7. Jonathan Ryan Thomas Falls, 2006, "The Effect of Conveyor Speed, Packaging Materials and Product on the Readability of Radio Frequency Identification Trabsponders"
8. EPC Global Tag Data Standard
9. LaMoreaux,D.Robert. 1995. Verification. In Barcodes and other Automatic Identification Systems. Leatherhead: Pira International
10. Markland. Robert E., Shawnee K. Vickery and Robert A. Davis. Operations Management. South Wetern College Publishing, Cincinnati, 1995
11. Michelle Renee Ryan. 2002. "A model for the Implementation of a Radio Frequency Identification System into a Warehouse Environment"
12. Twede D. & Parsons B. 1997. Distribution Packaging for Logistical Systems: A Literature Review. Pira, UK.
13. Lockamy, A., 1995 A Conceptual Framework For Assessing Strategic Packaging Decisions, The International Journal of Logistics Management, Vol.6, Issue 1, pp 51-60.
14. Mazen Saghir. 2004. "The Concept of Packaging Logistics"
15. Lambert D.M., Stock J.R., & Ellram L.M. (1998) Fundamentals of Logistics Management.McGraw-Hill, Singapore.
16. Saghir, M. and Jönson, G., 2001. Packaging Handling Evaluation Methods in the Grocery RetailIndustry, Packaging Technology and Science. 14(1): 21-29
17. Intermec 2003. "Supply Chain RFID; How it Works and Why it Pays". Intermec White Paper Online
18. Jeffrey Robert Tazelaar. 2004. "The Effect of Tag Orientation and Package Content on the Readability of Radio Frequency Identification (RFID) Trabsponders"
19. L.K Bandyopadhyay, S.K. Chaulya, P.K. Mishra, Wireless Communication in Underground Mines, RFID-Based Sensor Networking.
20. B. atkin and R. Leiringer, (2006), RFID Applications in Construction and Facilities Planning, itcon.org.
21. Pala, Z., 2007, Automation with RFID Technology as anapplication: Parking Lot Circulation Control (MSc), YuzuncuYil University,Van.
22. Glover, B., Bhatt, H., 2006. An Introduction to RFID, Chap. 1RFID Essentials. 1. O'Reilly. 276
23. Zeydin PALA and Nihat INANC, 2007, Smart Parking Applications Using RFID Technology, RFID Eurasia, 2007

24. Li Zhekum, Rajit Gadh and B.S Prabhu, 2004, Applications of RFID Technology and Smart Parts in Manufacturing, ASME 2004.
25. Johnson D., 2002, “RFID tags improve tracking, quality on Ford line inMexico,” CONTROL ENGINEERING 49 (11), pp. 16-16.
26. N.C. Wu, M.A.Nystrom, T.R. Lin, 2006, Cjallenges to Global RFID Adoption, ScienceDirect
27. Finkenzeller, K., 2003. RFID Handbook—Fundamentals and Applications in Contactless Smart Cards and Identification, second ed. Wiley, New York.
28. Alien, 2002. RFID Primer. Rev A
29. Mullen, D., 2004a. RFID Technology Overview. Global Aviation Forum, AIM.
30. Mullen, D., 2004a. RFID Technology Overview. Global Aviation Forum, AIM.
31. Ornauer, J., Michielsen, E., Rerisi, E., 2004. RFID Integration Services Markets, 2004 Q1. Allied Business Intelligence.
32. Taguchi, G.Elsayed, E.A, and Hsiang., 1989 "Quality Engineering in Production Systems", McGraw-Hill, New York.
33. Zillur Rahman and Faisal Talib., 2008, "A Study of Optimization of Process by Using Taguchi's Parameter Design Approach", The Icfai University Press
34. R. Radharamanan. "Quality Improvement of a Production Process Using Taguchi Methods", IIE Conference
35. Codruta Dura and Claudia Isac., 2009, "Using Taguchi Methods to Improve the Production Process Quality: A Case Study", Total Quality Management, Vol.20, No.11, 1189 - 1212
36. Douglas C. Montgomery. "Design and Analysis of Experiments", 17, 166.
37. Kwol - Leung Tsui., 1996 "A Critical Look at Taguchi's Modelling Approach for Robust Design", Journal of Applied Statistics, Vol.23, No.1, 81 - 95.
38. Piccilli, M.R, Balestrassi, P.P, Paiva, A.P., 2010, "Crack Avoidance in Steel Piston Rings Through the Optimization of Process and Gas Nitriding Parameters", International Journal of Advanced Manufacturing Technology.
39. P.P Balestrassi, E. Popova, A.P Paiva., 2009, "Design of Experiments on Neural Network's Training for Nonlinear Time Series Forecasting", Journal of Neurocomputing, ELSEVIER.
40. http://www.alientechnology.com/tags/index.php
41. Vanessa Lima, Pedro Balestrassi, Anderson Paiva., 2010, "Radio Frequency Braodband Amplifiers Performance Optimization : An Experimental Approach", IEEE Transactions on Microwave Theory and Techniques.
42. Kackar, R.N., 1985 "Off-line Quality Control, Parameter Design, and the Taguchi Method", Journal of Quality Technology, 17 (4), 176 - 188.

Appendix A

Lab Layout

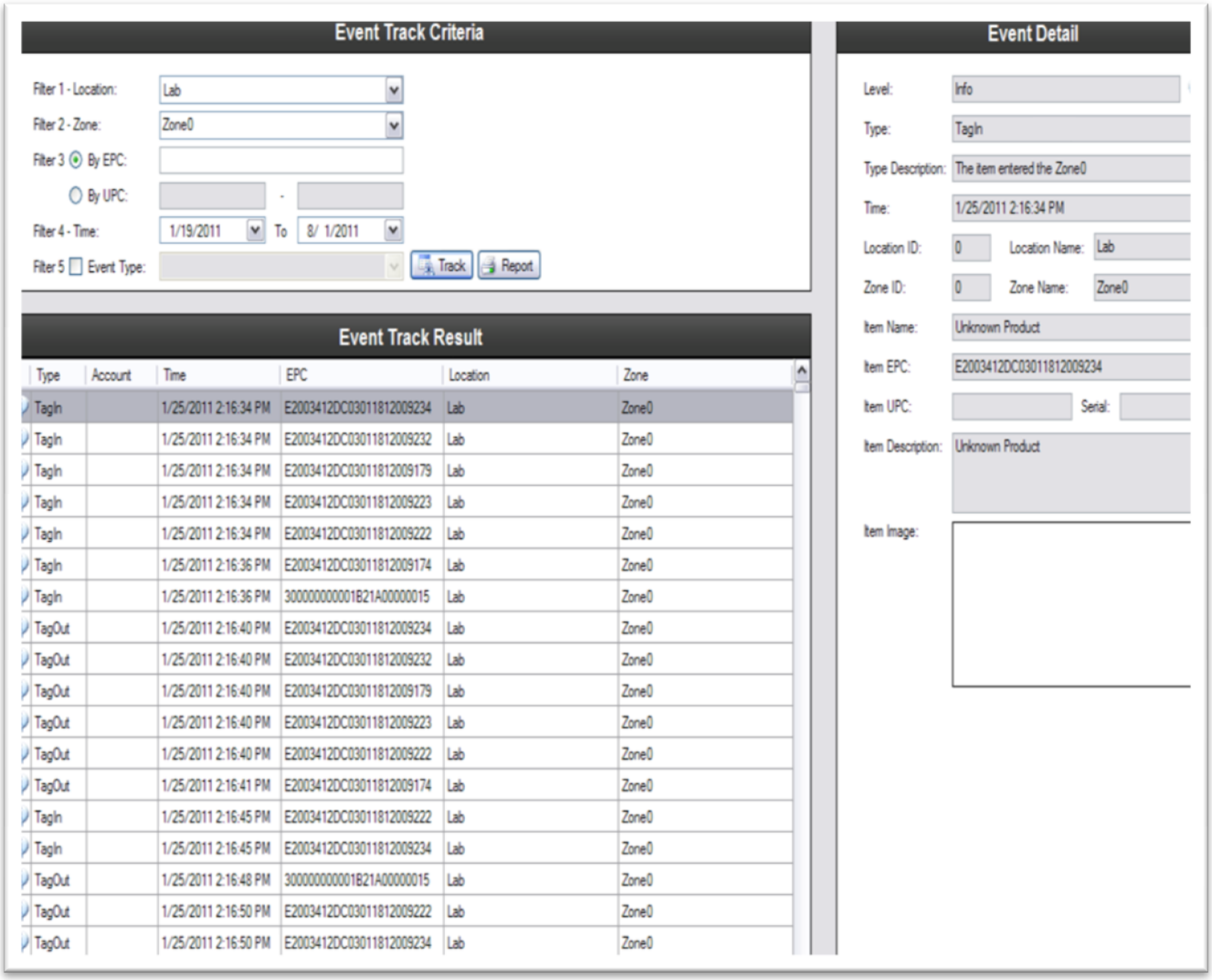
Blueprint of Lab



UT RFID Laboratory

Appendix B

Event Track Layout



Sample RFID Data 1

Type	Account	Time	EPC	Location	Zone
TagIn		1/25/2011 2:16:34 PM	E2003412DC03011812009234	Lab	Zone0
TagIn		1/25/2011 2:16:34 PM	E2003412DC03011812009232	Lab	Zone0
TagIn		1/25/2011 2:16:34 PM	E2003412DC03011812009179	Lab	Zone0
TagIn		1/25/2011 2:16:34 PM	E2003412DC03011812009223	Lab	Zone0
TagIn		1/25/2011 2:16:34 PM	E2003412DC03011812009222	Lab	Zone0
TagIn		1/25/2011 2:16:36 PM	E2003412DC03011812009174	Lab	Zone0
TagIn		1/25/2011 2:16:36 PM	300000000001B21A00000015	Lab	Zone0
TagOut		1/25/2011 2:16:40 PM	E2003412DC03011812009234	Lab	Zone0
TagOut		1/25/2011 2:16:40 PM	E2003412DC03011812009232	Lab	Zone0
TagOut		1/25/2011 2:16:40 PM	E2003412DC03011812009179	Lab	Zone0
TagOut		1/25/2011 2:16:40 PM	E2003412DC03011812009223	Lab	Zone0
TagOut		1/25/2011 2:16:40 PM	E2003412DC03011812009222	Lab	Zone0
TagOut		1/25/2011 2:16:41 PM	E2003412DC03011812009174	Lab	Zone0
TagIn		1/25/2011 2:16:45 PM	E2003412DC03011812009222	Lab	Zone0
TagIn		1/25/2011 2:16:45 PM	E2003412DC03011812009234	Lab	Zone0
TagOut		1/25/2011 2:16:48 PM	300000000001B21A00000015	Lab	Zone0
TagOut		1/25/2011 2:16:50 PM	E2003412DC03011812009222	Lab	Zone0
TagOut		1/25/2011 2:16:50 PM	E2003412DC03011812009234	Lab	Zone0
TagIn		1/25/2011 2:17:04 PM	300000000001B21A00000015	Lab	Zone0
TagOut		1/25/2011 2:17:13 PM	300000000001B21A00000015	Lab	Zone0
TagIn		1/25/2011 2:17:37 PM	300000000001B21A00000015	Lab	Zone0
TagOut		1/25/2011 2:17:45 PM	300000000001B21A00000015	Lab	Zone0

Sample RFID Data 2

Type	Account	Time	EPC	Location	Zone
TagOut		1/27/2011 12:33:17 PM	E2003412DC03011812009233	Lab	Zone0
TagOut		1/27/2011 12:33:17 PM	300000000001B21600000011	Lab	Zone0
TagOut		1/27/2011 12:33:17 PM	E2003412DC03011812009181	Lab	Zone0
TagOut		1/27/2011 12:33:19 PM	E2003412DC03011812009236	Lab	Zone0
TagIn		1/27/2011 12:34:32 PM	300000000001B21C00000017	Lab	Zone0
TagIn		1/27/2011 12:34:38 PM	300000000001B21900000014	Lab	Zone0
TagOut		1/27/2011 12:34:39 PM	300000000001B21C00000017	Lab	Zone0
TagOut		1/27/2011 12:34:46 PM	300000000001B21900000014	Lab	Zone0
TagIn		1/27/2011 12:35:04 PM	300000000001B21C00000017	Lab	Zone0
TagIn		1/27/2011 12:35:09 PM	300000000001B21900000014	Lab	Zone0
TagOut		1/27/2011 12:35:10 PM	300000000001B21C00000017	Lab	Zone0
TagOut		1/27/2011 12:35:16 PM	300000000001B21900000014	Lab	Zone0
TagIn		1/27/2011 12:36:33 PM	E2003412DC03011808005243	Lab	Zone0
TagIn		1/27/2011 12:36:33 PM	300000000001B21A00000015	Lab	Zone0
TagIn		1/27/2011 12:36:35 PM	E2003412DC03011808005242	Lab	Zone0
TagIn		1/27/2011 12:36:35 PM	E2003412DC03011812009176	Lab	Zone0
TagIn		1/27/2011 12:36:36 PM	E2003412DC03011812009224	Lab	Zone0
TagIn		1/27/2011 12:36:38 PM	E2003412DC03011812009236	Lab	Zone0
TagIn		1/27/2011 12:36:38 PM	E2003412DC03011812009219	Lab	Zone0
TagOut		1/27/2011 12:36:40 PM	300000000001B21A00000015	Lab	Zone0
TagIn		1/27/2011 12:36:40 PM	E2003412DC03011812009233	Lab	Zone0
TagIn		1/27/2011 12:36:40 PM	E2003412DC03011808005241	Lab	Zone0
TagOut		1/27/2011 12:36:42 PM	E2003412DC03011808005243	Lab	Zone0

Vita

Amoldeep Singh Jaggi was born in Jalandhar, Punjab, India. He graduated in 2007 with a Bachelor's degree in Mechanical Engineering. He came to University of Tennessee, Knoxville in 2009 to persue his Master's degree in the Industrial Engineering. He joined Dr. Rupinder Singh Sawhney as a Graduate Research Assistant and worked on more than ten different projects over the course of two years. Amoldeep is currently completeing his master's degree in Industrial Engineering.