Optimization of Material Flow by Lean Tools and RFID Integration into a Vendor-Involved eKanban System

by

Yang Wang

Submitted to the Department of Mechanical Engineering
in partial fulfillment of the requirements for the degree of

Master of Engineering in Advanced Manufacturing and Design
at the
MASSACHUSETTS INSTITUTE OF TECHNOLOGY

February 2021

Signature of Author:____
Yang Wang
Department of Mechanical Engineering
January 15, 2021

Certified by:____
David E. Hardt
Ralph E. and Eloise F. Cross Professor of Mechanical Engineering
Thesis Supervisor

Certified by:____
Stephen C. Graves
Abraham J. Siegel Professor of Management, Sloan School of Management
Thesis Supervisor

Accepted by:____
Nicolas Hadjiconstantinou
Professor of Mechanical Engineering
Chairman, Committee for Graduate Students

This page is intentionally left blank.

Optimization of Material Flow by Lean Tools and RFID Integration into a Vendor-Involved eKanban System

by

Yang Wang

Submitted to the Department of Mechanical Engineering
in partial fulfillment of the requirements for the degree of
Master of Engineering in Advanced Manufacturing and Design

Abstract

To survive in the global marketplace today that is more dynamic and complex than ever, companies must have a proper and up-to-date material flow design to ensure agile and resilient operations. The importance of monitoring and controlling flow has been made even more apparent with the recent COVID-19 pandemic.

Therefore, this work aims to study the material flow system at a leading global manufacturing company, identify problems and gaps in its process, and leverage lean manufacturing methodologies and RFID technology to optimize the material flow of an electronic Kanban (eKanban) system that involves third-party vendors. This thesis outlines a systematic problem-solving approach, starting with process visualization through Value Stream Mapping (VSM), problem identification by issue tree, and benefit analysis via simulation modeling. System design of a Radio-Frequency Identification (RFID) network is performed at both rack-level and item-level by testing RFID hardware, tags, and various system setups. A web interface is developed for data integration and visualization. The successful pilot run demonstrates the effectiveness of the optimized system in eliminating waste and increasing operational efficiency and provides a guide for a full-scale implementation.

Thesis Supervisor:	David E. Hardt
Title:	Ralph E. and Eloise F. Cross Professor of Mechanical Engineering
Thesis Supervisor:	Stephen C. Graves
Title:	Abraham J. Siegel Professor of Management

This page is intentionally left blank.

Acknowledgments

I would like to take this opportunity to extend special thanks to everyone who contributed to the success of this project. This thesis and my unforgettable experience at MIT would not have been possible without you.

First, I would like to gratefully acknowledge the support and resources made available to me by MIT. Thank you, Professor David Hardt and Professor Stephen Graves, for being my thesis advisors and for your mentorship, patience, and insightful guidance throughout the thesis project. Thank you, Jose Pacheco, for your constant support, enlightening career advice, and great project coordination.

Next, I would like to thank my project partners at MIT. Thank you, Daniel, Shum, and Robyn, for our excellent collaboration, endless discussion, and genuine encouragement to each other over the past year. It is you who made this long journey vivid and fulfilling.

I would also like to thank Waters Corporation for sponsoring this project. Thank you to Michael Fogwill, Joseph Michienzi, and Jaaffar Ismail for making this project possible and providing me the necessary resources. Thank you to my project supervisor, Sonya Wilson-Thomas, for granting me creative freedom and always being supportive and patient. Thank you to Burt Bliss, Carl Tracy, Matthew Howland, Marc Costa, Paul Beggs, Linda Douglas, Kerwin Cross, and Dan Sweeney for the countless hours of discussion and valuable feedback that made this project successful.

Finally, I would like to express gratitude to my parents for your love and unconditional support.

This page is intentionally left blank.

Table of Contents

This page is intentionally left blank.

List of Figures

List of Tables

This page is intentionally left blank.

List of Abbreviations

Abbreviation	**Description**
AEN	Ambient Electromagnetic Noise
AI	Artificial Intelligence
API	Application Programming Interface
CSS	Cascading Style Sheets
CV	Computer Vision
dBm	Decibel Milliwatts
eKanban	Electronic Kanban
EPC	Electronic Product Code
ERP	Enterprise Resource Planning
FCC	Federal Communications Commission
FDA	Food and Drug Administration
FFCA	Full Faraday Cycle Analysis
GUI	Graphical User Interface
HD	High Density
HPLC	High-Pressure Liquid Chromatography
HTML	Hypertext Markup Language
HTTP	Hypertext Transfer Protocol
IMA	Immediate Maintenance Activity
IoT	Internet of Things
JIT	Just-In-Time

KS	Kanban Size
LC	Liquid Chromatography
LD	Low Density
MRP	Material Resource Planning
MS	Mass Spectrometry
NPI	New product Introduction
OUT	Order-Up-To
PLCM	Path Loss Contour Mapping
PO	Purchase Order
POU	Point-of-Use
RF	Radio Frequency
RFID	Radio-Frequency Identification
SKU	Stock-Keeping Unit
SNR	Signal-to-Noise Ratio
SOP	Standard Operations Procedure
SST	Safety Stock Target
Stdev	Standard Deviation
TPM	Total Productive Maintenance
TPS	Toyota Production System
UPLC	Ultra-High Pressure Liquid Chromatography
VSM	Value Stream Mapping
WIP	Work-in-Progress

Chapter 1

Introduction

1.1 Motivation and Statement of Purpose

The global market today is more dynamic and complex than ever. Manufacturing companies are facing increased pressure and having difficulty adapting to the external dynamic changes happening every day. To survive in this competitive global market, manufacturing companies must invest in a proper and up-to-date material flow design to ensure agile but resilient operations across all production-related departments. Companies must understand the material flow along its whole production process, identify underlying issues that constrain or misdirect the material flow, and optimize the material flow system accordingly with various technological and organizational advances, including more efficient data collection technologies and well-defined Standard Operating Procedures (SOP).

To gain deep insights into the current challenges faced by the manufacturing industry, the material flow process and related operations at a leading global manufacturing company, Waters Corporation, are studied in detail. The complex nature of the company's organizational structure and its product and services portfolio leads to huge challenges in its operations. Wastes are generated across the manufacturing process; capacities are often not fully utilized or limited; inventory levels are poorly controlled, causing frequent out-of-stock or material overflow conditions.

The purpose of this thesis, therefore, is to understand the material flow in a major factory of this large manufacturing company, identify key problems and gaps that limit the material flow, and leverage lean Six Sigma manufacturing methodologies and Radio-Frequency

Identification (RFID) technology to improve the overall efficiency and effectiveness of its material flow.

1.2 Objective

The objective of this project is to explore opportunities to optimize material flow through the Waters Milford facility, increase material availability, and reduce overall cost. To achieve this goal, the project team analyzed the current material flow process, identified key issues and gaps, and proposed, developed, and implemented a practical solution that outlines the future direction of a corporate-scale upgrade of the material flow process.

1.3 Scope

The scope of this thesis is to study the inefficiencies and wastes within the electronic Kanban (eKanban) system that Waters Corporation uses to procure and transport high-value parts from several suppliers. We did a pilot implementation of a novel, RFID-based eKanban solution with the existing eKanban suppliers and stock-keeping units (SKUs).

1.4 Task Division

This thesis is based upon a group project conducted by Robyn Lee [1] and the author, aiming to study and optimize the material flow at Waters Corporation from different perspectives. As the project team carried out the initial system investigation and analysis in close collaboration, portions of each of these theses' first chapters will be similar. After identifying fundamental problems, we divided the group project into two parts, with Lee's thesis focusing on solutions surrounding the conveyor belt congestion problem and this thesis focusing on developing a solution to the eKanban manual scanning problem.

1.5 Thesis Outline

This thesis consists of nine chapters. Chapter 1 defines the goals and scope of the project. Chapter 2 introduces the background information of the studied company, Waters Corporation. Chapter 3 presents the basic concepts and knowledge of lean manufacturing that are used in this study. Chapter 4 describes the problem statement. Chapter 5 discusses the methodology used to analyze and improve the eKanban system. Chapter 6 and Chapter 7 detail the system design of a rack-level and an item-level RFID solution, respectively. Chapter 8 describes the development of a web interface that integrates and interprets the RFID data. Chapter 9 reviews the whole project and provides a roadmap of future work and recommendations for Waters Corporation.

This page is intentionally left blank.

Chapter 2

Background

2.1 Waters Corporation

Founded by Jim Waters in 1958, Waters Corporation is a global analytical instrument company specializing in test equipment and measurement solutions for both industrial and academic research uses. Water is a leader of innovation in chromatography, mass spectrometry, and thermal analysis system solutions, and the company's product portfolio can be widely found in the pharmaceutical industry, material sciences, as well as chemical, food and environment sciences market. The company also maintains a global support and service network and provides other software-based products and laboratory automation solutions. In fiscal year 2019, net sales of the company's products and services totaled $2.1 billion, of which 45% came from sales of instrument systems, 19% came from chemistry consumables and 36% from service [2].

Figure 2-1: A typical chromatography system produced by Waters Corporation [3]

As a result of Waters' large product families, more than 7,000 employees work in 31 countries, including 15 manufacturing facilities, 3 distribution centers, with products available in more than 100 countries. At the company's headquarters, the Milford, Massachusetts facility operates most of the assembly steps for their products, including all major assembly operations, and currently focuses on and produces 1,500 distinct products. The complex nature of the company's organizational structure and its product and services portfolio leads to challenges in its operations today.

2.2 Waters™ Product Lines

In 2019, 64% of Waters' net sales came from products including instrument systems and chemistry consumables. The company's product family comprises two primary lines: Liquid Chromatography (LC) and Mass Spectrometry (MS). This part introduces these two product lines and their underlying technology.

2.3.1 Liquid Chromatography

Liquid chromatography (LC) is a separation technology in analytical chemistry used to separate a sample mixture into individual components. Upon contact with adsorbent material in a mobile (liquid) or stationary (solid) phase, the individual components will interact with the adsorbent material differently based on their different affinity for the mobile or stationary phase. For example, the mixture to be separated is injected into a solvent stream and loaded onto the top of the column. The different components in the sample mixture pass through the column packed with stationary solid phase such as porous particles at different rates due to differences in their affinity for the mobile liquid phase and the stationary solid phase, leading to the separation of the components as they flow out of the column. Depending on the pressure used in the separation process, the technique can be featured as high-pressure or high-performance liquid chromatography (HPLC) and ultra-high pressure liquid chromatography (UPLC) with 3 and 1000 bar respectively.

Since LC instruments and columns are two indispensable parts of this technology, Waters' products can be found in manufacturing, research laboratories, and hospitals where the technology is applied. The company's LC instruments and accessories, including HPLC systems, UPLC systems, and chromatography columns, are mainly produced in its Milford facility.

2.3.2 Mass Spectrometry

Mass spectrometry (MS) is an analytical technology used to measure the mass-to-charge ratio of one or multiple ionized molecules in a sample. The MS instruments ionize molecules by bombarding them with electrons. Once ionized, the ions are sorted and separated according to mass-to-charge ratio by magnetic and electric fields. The separated ions are then measured and presented as a mass spectrum, a plot of intensity of the mass-to-charge ratio. The measurement results can then be used to calculate the exact molecular weight of the sample components and further determine the chemical identity of the components.

The company's MS instruments and accessories are mainly produced in its Wilmslow, England and Wexford, Ireland facilities.

2.3 Waters-MIT Collaboration

Beginning in 2013, MIT and Waters Corporation have been collaborating annually on a variety of projects in areas ranging from manufacturing process control, operations improvements, supply chain optimization to research and development. Each year, a team of MIT students in the Advanced Manufacturing and Design program comes to one of the many sites of Waters, works with a broad range of departments, identify opportunities for improvement, and brings fresh outside perspectives to the long-established and successful company, driving innovation and contributing to its long-term success.

This year, two projects were conducted in different areas, with two students working on each. Vinakollu [4] and Hsu [5] work on improving ion transfer efficiency by evaluating the capillary geometry for the MS system. Lee [1] and the author focus on studying and improving the material flow at the Waters Milford facility.

Chapter 3

Lean Manufacturing: Basics

Lean manufacturing describes a systematic way of running manufacturing operations using a set of rigorous tools and management practices to eliminate non-value added wastes and improve efficiency. The roots of the revolutionary production process are from the Toyota Production System (TPS), developed by Toyota in Japan. The term “Lean” was first introduced by John Krafcik in 1988 when he was studying at MIT under James Womack, who then further defined and developed this idea and outlined the five key principles to lean manufacturing in the book *Lean Thinking* [6]:

- Value: Value can only be defined by the customer and it is only meaningful when expressed in terms of a specific product which meets the customer’s needs at a specific price at a specific time
- Value stream: The set of actions required to bring a product through the three critical management tasks of problem solving, information management and physical transformation
- Flow: The continuous movement of a product through value added processes
- Pull: The customer drives the production and “pulls” the line rather than building to stock or pushing the line
- Perfection: Focus on continuous improvement to drive value in the value stream and to move towards states of flow and pull.

In today’s fast-paced, volatile and ever-changing global marketplace, it is becoming increasingly important for manufacturing companies that aim at long-term success to adopt lean methods to eliminate waste, optimize processes.

3.1 Material and Information Flow: Why Are They Important

In manufacturing, material flow means the movement of physical goods through the production chain from inbound to outbound, including transportation of raw materials, components, work-in-progress (WIP) inventory, and final products.

Information flow, on the other hand, describes the movement of information between people, processes and systems. It centers on transmitting orders, updating material status such as location and quantity, indicating material dynamics, e.g., consumption and demand.

Lean manufacturing requires that material and information flow always work closely with each other: Material flow optimization cannot be accomplished without acquisition and analysis of accurate data from information flow. Information never flows correctly without a well-performing material flow.

Currently, material flow is vaguely defined, and information flow is opaquely visible at many traditional manufacturing companies including Waters Corporation. It not only generates wastes and constrains and hinders the efficiency of the production process, but also brings enormous difficulty to production planning and supply chain coordination.

Production planning in manufacturing companies does not work without a well-defined, well-understood material flow process. As their product and service portfolio become more and more diversified and complex nowadays, the material flow becomes more divergent throughout the whole production process. As a result, many traditional manufacturing companies do not have a clear understanding of how their material flows from inbound arrival to outbound shipment. This raises a huge challenge to the production planning department as production planning would only make sense and be accurate if the planner truly understands how much of what material flows to which process for how long.

A poorly managed information flow is an obstacle to efficient supply chain coordination for manufacturing companies. In companies where there is a lack of information transparency or availability, the supply chain and procurement system heavily rely on certain experienced employees whose resources, connections and skills become unavailable after they leave the company for some reasons such as retirement. As such, underlying issues may not appear until individuals leave the company without conveying their ad hoc fixes and knowledge formally to others within the company.

Material and information flows interact closely with the supply chain coordination and production planning process for manufacturing companies. Achieving harmony between them is a key success factor for any manufacturing company, and efficiently managing the material flow is the starting point.

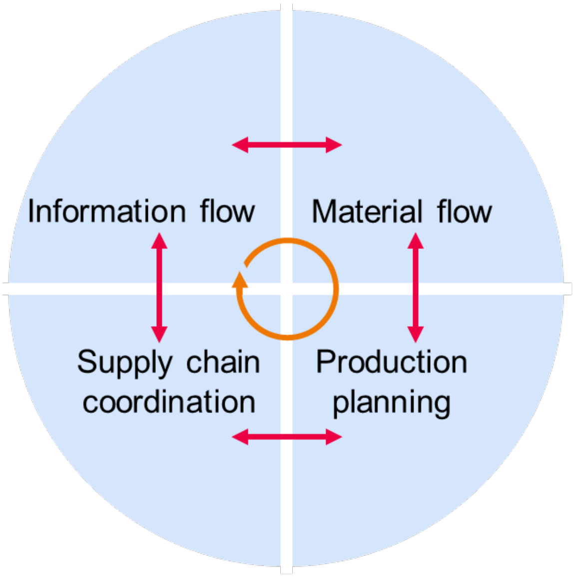


Figure 3-1: Material and information closely interact with company's operations

3.2 Value Stream Mapping (VSM)

Value stream mapping (VSM), or material and information flow mapping called by Toyota, is a lean tool that helps lean practitioners identify, visualize and reduce waste in the manufacturing process.

First developed by Toyota in the early 80s, the successful implementation in its assembly factories made the VSM an industry best practice. The concept was further developed by Mike Rother and John Shook in the book *Learning to See* [7], introducing the tool to a wider audience outside of Toyota and making it accessible to American manufacturing companies. Since then, VSM has been adopted by many companies to analyze and improve operations efficiency.

VSM is a good starting point to help management and engineers recognize waste, identify its causes and propose solutions. It begins with a flowchart that documents every material and information flow process. Depending on the application needs, different variables such as inventory type, cycle time, number of workers, batch size, etc. are displayed at each process. Critical steps are then identified with qualitative or quantitative issues highlighted, such as delays, restrictions, inefficiencies, excess inventories or redundant actions. As VSM visualizes all these issues and their corresponding critical processes, it is easy for management and engineers to communicate, develop process improvement plans and give guidance towards the future desired operations.

3.3 Just-in-Time

A Just-in-Time system, as the name tells, describes a system that produces the right items at the right time in the right amounts at the right quality, meeting customer demand exactly. It originated in Japan owing to the natural lack of resources and space in this country, as a JIT system plans a manufacturing process in such a way that there is little to no manufacturing material inventory held at the production site. As an important lean manufacturing principle, JIT has been widely applied to many manufacturing companies worldwide, although different terms are used to describe this lean methodology, such as “short-cycle manufacturing” used by Motorola and “continuous-flow manufacturing” used by IBM.

A typical methodology that uses JIT manufacturing principles is the pull-system.

3.4 Push vs Pull

Traditionally, many manufacturing companies operate in a push system, where process input materials and components are ordered and pushed through the production processes to produce products based on customer demand forecast or downstream process demand anticipation. A push production system typically produces products in large quantities or batches and ties up a significant amount of capital in inventory and WIP.

An ideal JIT production, on the other hand, tends to produce only so many products that the customer actually needs. The ultimate goal is one-piece material flow, which is desired by many manufacturing companies including Waters. This can be achieved by a pull system.

Being the opposite of the traditional push system that uses anticipation-based replenishment, a pull system uses consumption-based replenishment. In a typical pull system, the customer order process withdraws a given amount of needed parts from a supermarket, and the supplying process produces to replenish what was just withdrawn. A Kanban system is a typical pull system.

3.5 Kanban

Developed by Toyota's Taiichi Ohno after visiting and getting inspired by a U.S. supermarket, a Kanban system is a common and simple-to-implement system for controlling the material flow in production and inventory management as part of JIT and lean manufacturing principles. Kanban is a Japanese term for "signboard", a physical card that contains critical information that regulates the production to meet customer needs exactly in product type, time, quantity and quality.

The critical function of a Kanban is to trigger activities upstream in a given manufacturing process. It activates material movement when people from the downstream process come to the upstream process to withdraw the right quantity of parts at the right time. As a result of this withdrawal, the preceding process produces only enough parts to replace those withdrawn. Being a closed-loop, pull production system, a typical Kanban system works from the finished goods or, in other words, customer demand, backward, as shown in the following figure.

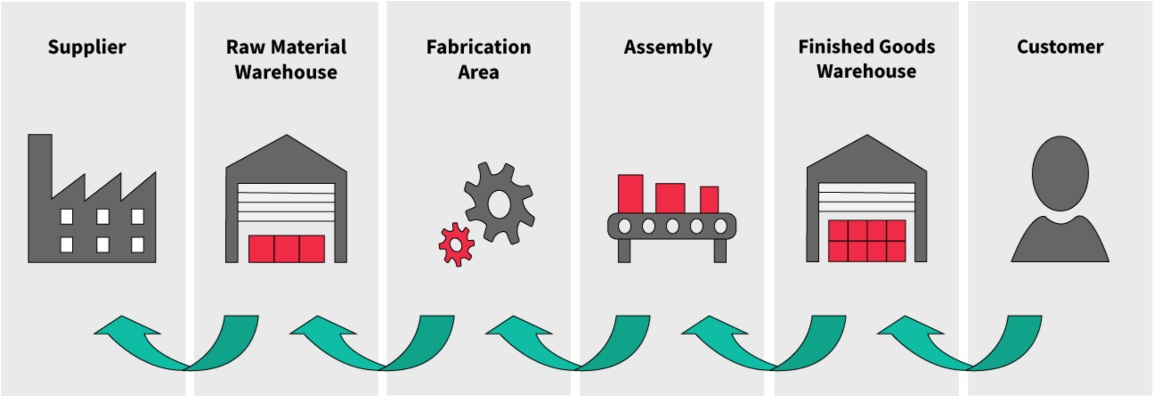


Figure 3-2: A typical Kanban system

A Kanban system helps in the elimination of waste and maximization of value. In general, a manufacturing system is best regulated when material flows in and out of a given process smoothly and rationally. If process inputs, i.e., material from upstream, arrive before needed, excess WIP, redundant inventory and unnecessary costs occur. If process outputs, i.e., finished or semi-finished goods, are produced before needed by the downstream process, similar costs and wastes related to overproduction occur. With a Kanban system, however, manufacturing processes can be synchronized all the time, in which way wastes are eliminated and the interest of stakeholders and customers is maximized.

However, the Kanban system is not universally applicable. First, from the aspect of the supply side, the Kanban system requires a smooth and agile supply, if vendors are involved in the system. Thus, it is less suited to the production process with remote and inflexible vendors, in which case high transportation cost and lead time variability are inevitable. Second, in respect of the demand side, the Kanban process expects steady, repetitive demand and production flow. Frequent changes in demand may render the system ineffective. Therefore, the Kanban process is less suitable for companies where demand in product volumes and mixes fluctuate significantly over time.

3.6 eKanban

Historically, the manual Kanban system has been used based on physical cards. However, a loss or misplacement of a Kanban card can lead to material shortage or inventory overflow. Also, an upstream supplier will not be triggered until the physical Kanban card reaches the upstream station. As companies are moving to the era of global and distributed manufacturing with operations, suppliers and contract manufacturers across continents in today's global marketplace, the traditional Kanban system no longer meets the needs of some global players in the manufacturing industry.

An eKanban, or electronic Kanban system, on the other hand, provides opportunities to further support continuous and lean material flow processes on a global scale by electronically maintained Kanban cards. Compared to traditional Kanban card systems, an eKanban system allows an efficient material flow process through real-time and digital Kanban signals that triggers instantaneous replenishment messages to the upstream process or supplier.

As a result of its potential for increased efficiency, more and more manufacturing companies start using the eKanban system to help them expand their operational footprint and drive digitalization transformation today.

This page is intentionally left blank.

Chapter 4

Problem Statement

In this chapter, the current state of the material flow process at Waters Milford facility is analyzed, critical problems are identified and categorized by root cause, and a problem statement is presented.

4.1 Facility Overview and Analysis

This section aims to understand and define the most up-to-date material process flow at Waters Milford facility. Materials investigated in this study include input materials such as semi-finished product (e.g., stainless steel tubes for consumables) and purchased parts (e.g., sheet metal chassis for instruments), as well as output products (e.g., instruments and spare parts).

Enormous amount of material flows through Waters Milford facility every day, typically 25,000 to 50,000 parts per day. These can range from small screws, plastic and metal parts to large heavy housings and motors. There are 20 people from various departments moving the material multiple times per day.

The Milford facility is the global headquarters of Waters with more than 1,500 employees. As mentioned in Chapter 2, among the three major facilities, the Milford facility mainly produces LC instruments and accessories, including HPLC systems, UPLC systems, and chromatography columns while the other two facilities in Wilmslow, England and Wexford, Ireland mainly produce MS instruments and accessories.

Today, most of Waters' less critical, low-value-added components and operations are outsourced to local and overseas manufacturers, so that the Milford facility can focus on critical, high-value-added manufacturing processes and final assembly operations in order to maintain a strong engineering know-how and protect key process secrets. The two main operations, manufacturing of chromatography columns and final assembly of HPLC and UPLC analytical instruments are performed in the following three primary production-related areas at the Milford facility:

1) The 50,000 square-foot Global Machining Center that staffs over 200 professionals and has 90 state-of-the-art machines. Operating 24 hours a day with two shifts and 6 days every week, the Global Machining Center produces over 3 million parts every year, mostly critical and high-precision components for consumables like columns and valves;
2) The 29,000 square-foot Advanced Instrument Assembly & Accessory Kitting Operation area in which over 130,000 high-value-added products including analytical instruments, consumables, and accessory kits are assembled annually;
3) And the 8,500 square-foot Clean Room for optics, micro valves, and critical parts needed by the assembly process.

Based on the nature of operations performed in each area and to simplify understanding, the 1st area, Global Machining Center, is referred to as the Machine Shop, and the 2nd and 3rd areas, Advanced Instrument Assembly & Accessory Kitting Operation and Clean Room, are referred to as the Assembly/Production area further in this thesis. Over 80 assemblers and specialists and nearly 40 engineers work in the Assembly/Production area 8 hours a day with one shift and 5 days every week.

To gain an overview of the current material flow at Waters Milford facility, a detailed facility tour throughout all operational areas is conducted along with a large number of meetings, interviews and discussions with site managers and various stakeholders from diverse functional teams. The tour and talks greatly helped the project team understand how various materials flow into, within, and from Waters Milford facility. To visualize the holistic process, a material flow map is developed and illustrated below. Each stage through which material flows is explained in detail.

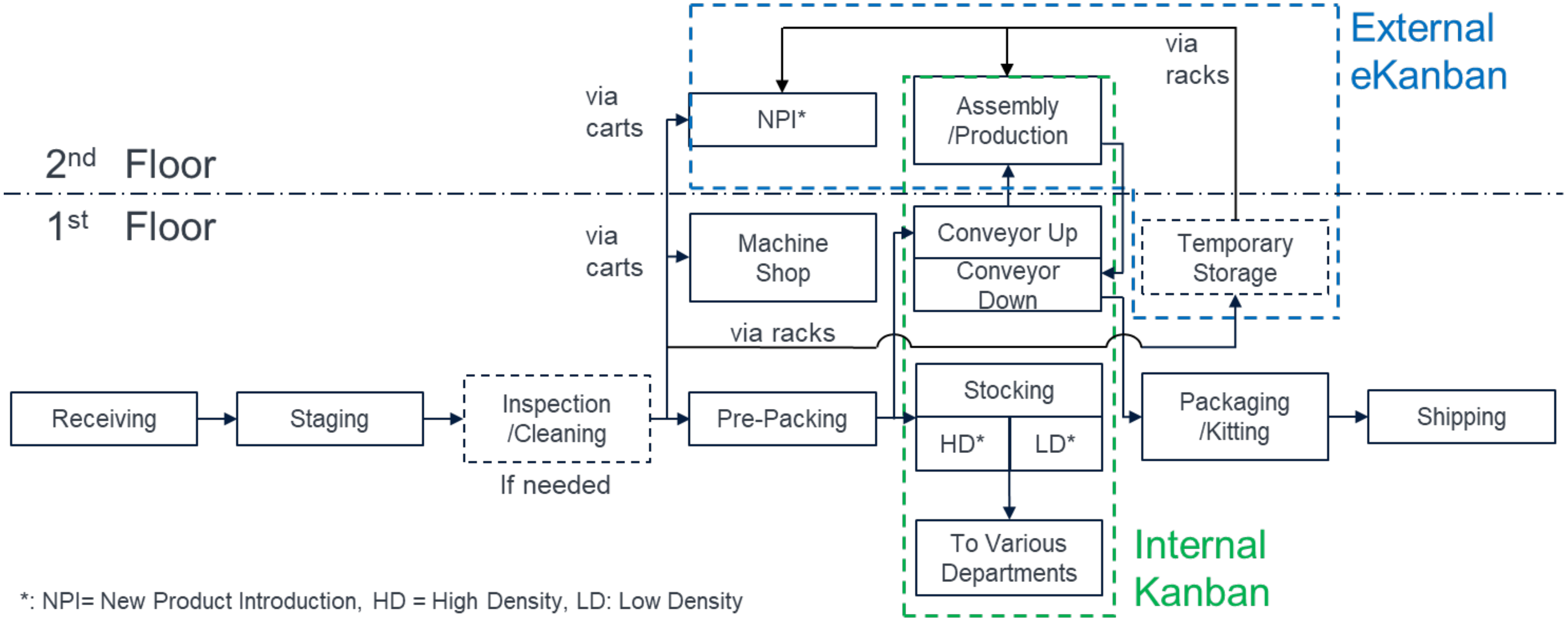


Figure 4-1: Material flow map at Waters Milford facility

Receiving:

As can be seen from the map, input materials including semi-finished product such as stainless-steel tubes, and purchased parts such as sheet metal chassis are delivered and confirmed in the receiving area. This is the only location where materials flow into Waters Milford facility.

Staging:

The received materials are then transported to the next location, the staging area, or the landing zone, an intermediate storage area where materials are scanned and booked into the internal MRP system used by Waters. At this point, the physical material movement is first recorded electronically. Depending on whether additional actions are needed, the material will be handled differently at the end of this step.

Inspection/Cleaning:

Extra actions may be needed if the materials are marked with special characteristics. Materials that require Immediate Maintenance Activity (IMA) such as parts with critical dimension or tolerance requirements will be sent for inspection before further movement, while metal materials such as stainless steel will be sent to the Critical Cleaning area for a special chemical treatment called passivation, which removes free iron from the surface. A protective oxide layer that increases corrosion resistance will be formed, which is critical to the quality of the high-value product Waters produces.

Storage Locations:

Incoming materials are then transported to various locations in three different ways:

1) Materials ordered for NPI or Machine Shop are directly delivered via carts and stored there accordingly;
2) Certain incoming materials such as high-value sheet metal kits from specific vendors are delivered directly to assembly & production or NPI areas via racks, with or without being temporarily stored on the first floor;
3) Assembly Point-Of-Use (POU) parts and other excess materials are pre-packed before being transported to the assembly/production area and warehouse, respectively.

Stocking:

Materials that are not needed immediately are stocked in the warehouse. Depending on the frequency the materials are needed in the future, they are stocked in the High Density (HD) or the Low Density (LD) area of the warehouse. With an internal order through SAP, stocked material will be moved to locations where they are needed.

Conveyor belt:

A two-way conveyor belt system is used for internal transportation of incoming materials as well as outgoing, finished products at Waters Milford facility. On the one hand, incoming, pre-packed materials are delivered to the assembly/production area in bins through the upwards conveyor belt. On the other hand, finished goods (e.g., instruments and spare parts) are brought down from the assembly/production area through the downwards conveyor belt, before they are kitted, packaged, and finally shipped to end customers.

As shown in Figure 4-1, two material flow systems are used at Waters Milford facility, namely, the internal Kanban system and the external eKanban system.

The material movement processes enclosed by the green dotted line in Figure 4-1 make up the internal Kanban system, a material flow procedure working on a “pull” manufacturing principle. The Kanban cards are checked twice a day, ensuring a quick response to internal material demand and a continuous material flow. The Kanban system mainly includes frequently used parts for machining, testing, and assembly such as hardware, spare parts and small consumables.

The external eKanban system, enclosed by the blue dotted line in Figure 4-1, describes a similar “pull” material flow system, yet with a limited number of Waters’ vendors involved, who are located in nearby areas and are therefore able to react to factory demand quickly. The eKanban system mainly includes material flow process of high-value instruments and the purchased parts and product for their assembly. After being confirmed in the receiving area, purchased parts from these vendors are directly delivered to the assembly/production area by vendors without being stored or inspected. The assembly/production area deploys Total Productive Maintenance (TPM) that empowers the operators to carry out in-process inspection and failure analysis while performing the assembly work.

As these two systems form the whole material flow process, the project team is split here and will analyze the overall material flow of the company from the perspective of internal Kanban and external eKanban. A detailed study of the internal Kanban system can be found in Lee's thesis, whereas this thesis focuses on studying the external eKanban system.

4.2 How eKanban Is Supposed to Work at Waters Now

An eKanban system provides opportunities for an efficient material and information flow process through electronically maintained Kanban cards, electronic and remote Kanban review, and digital data transfer and storage, when designed and implemented properly. As a result, Waters decided to deploy the eKanban system several years ago with the following process logic. Figure 4-2 illustrates how the eKanban process is supposed to work at Waters Milford facility step by step.

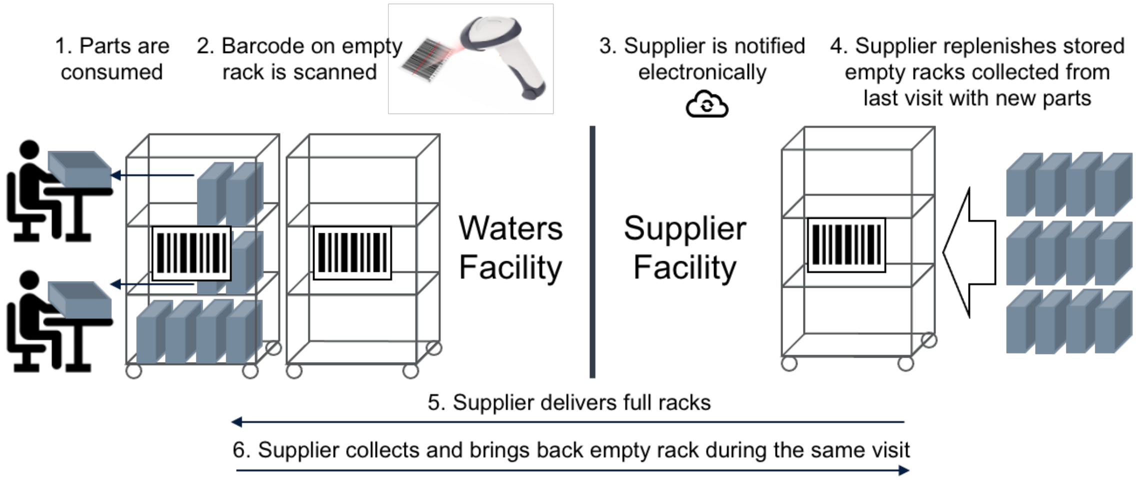


Figure 4-2: Operating principle of the eKanban system at Waters

Racks filled with different types of purchased parts are stored on the assembly/production area and are consumed by various units. When all parts in a rack have been consumed, the empty rack is moved to the temporary holding area nearby on the same floor (see Figure 4-3). At the same time, the barcode on the empty rack is supposed to be scanned by either an operator, an assembly supervisor or a floor manager, using a hand-held barcode scanner. The supplier of that part type should then be notified electronically instantly and starts preparing new parts to refill the stored empty racks collected from the last delivery visit with new parts. After the demanded number of parts are loaded into racks, the supplier delivers the full racks to Waters Milford facility and, during the same visit, collects and brings back empty racks stored in the temporary holding area.

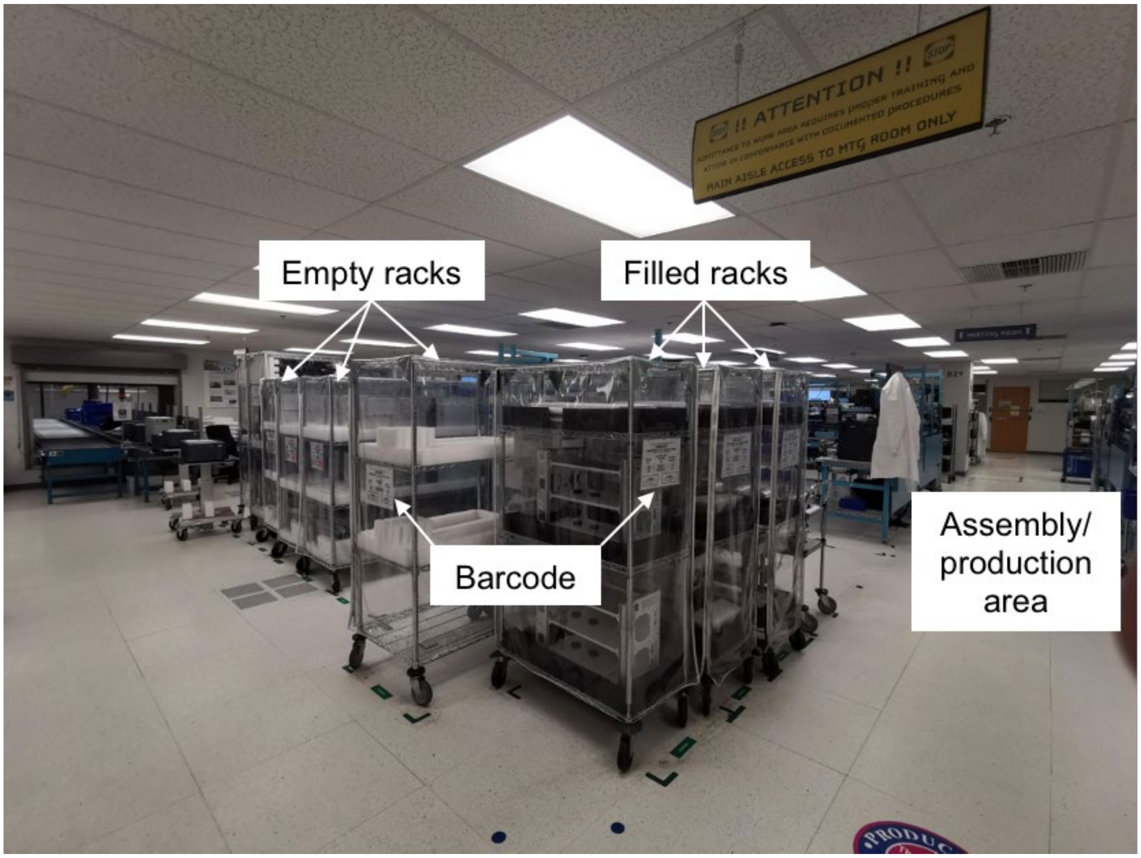


Figure 4-3: Filled and empty racks in the assembly/production area

However, the eKanban process at Waters today does not work exactly as designed. This discrepancy between actual and design is due to both systematic design flaws and unsatisfactory implementation. These issues are investigated and discussed in the next part.

4.3 Problem Identification through VSM

Today, material flow is often not well specified or standardized, and information flow is often invisible at many traditional manufacturing companies including Waters Corporation. This not only generates wastes and constrains and hinders the efficiency of the production process, but also creates enormous difficulty for production planning and supply chain coordination. Although the eKanban system is supposed to streamline the material and information flow, there are a number of issues and gaps that makes the current eKanban process at Waters less effective than designed.

Therefore, to analyze the process flow of the eKanban system used at Waters currently, a high-level value stream map is created that visualizes both information flow and material flow in the current state (see Figure 4-4).

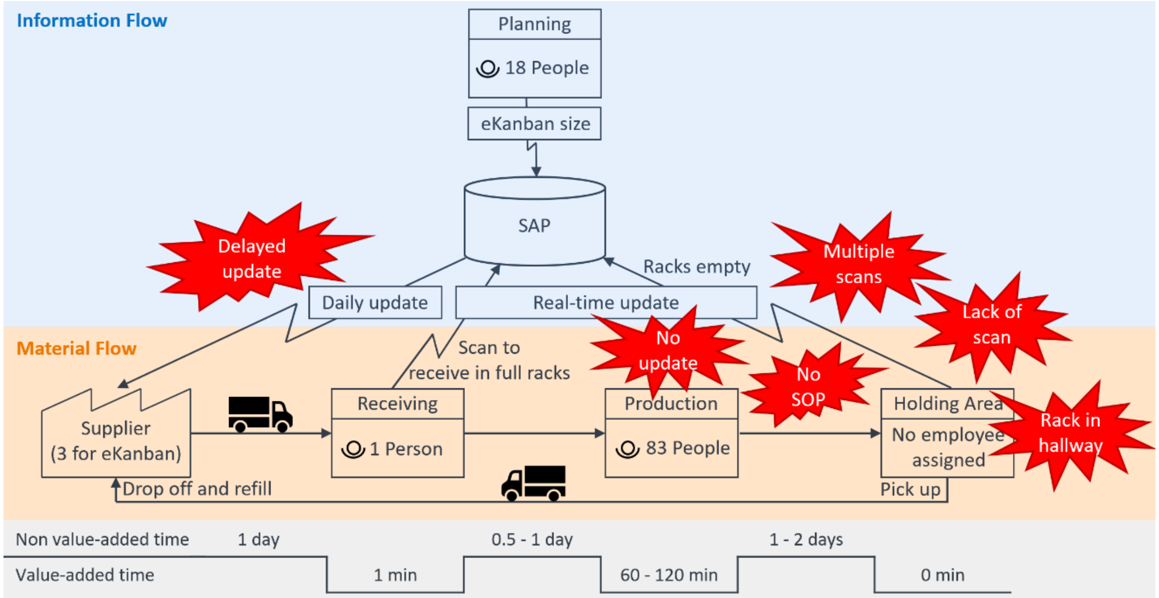


Figure 4-4: Value stream map of the current eKanban process

The map divides the eKanban process into several key subprocesses managed by various departments within and outside the factory and presents their close interaction with each other, including production department (including various subunits), planning department, and supplier. According to the eKanban process design introduced in Chapter 4.2, after all parts in a rack have been consumed, the empty rack is moved to the temporary holding area nearby on the same floor and the barcode on the empty rack is supposed to be scanned by either an operator, an assembly supervisor or a floor manager. The supplier of that part type is then notified electronically through the Supplier Portal that is connected to SAP and then refills the stored empty racks collected from the last delivery visit with new parts. After the demanded number of parts are loaded into racks, the supplier delivers the full racks to Waters Milford facility and, during the same visit, collects and brings back empty racks stored in the temporary holding area. The racks are confirmed in the receiving areas at Waters and then delivered to the assembly/production area.

However, the eKanban process at Waters today does not work exactly as it is designed and supposed to. After close observation and several rounds of interviews with stakeholders, discussions with floor workers, and a variety of other on-site investigations, the following six key issues and gaps are identified and highlighted in red as shown in the VSM, followed by detailed current state and root cause analyses:

1) Lack of scan: Sometimes no one performs a scan operation when a rack becomes empty.
2) Multiple scans: Sometimes multiple employees perform multiple scan operations when a rack becomes empty.
3) No SOP: No standard operating procedure (SOP) is documented or in use.
4) Delayed information update for suppliers: The supplier portal that allows suppliers to access material demand information only gets updated on a daily basis, causing an information delay for suppliers.
5) No material information update from the production stage: Material flows through the production process without any information flow, causing an information gap for the planning department.
6) Irregular material storage: Some eKanban racks in both full and empty states are stored in the corridor entering the assembly/production floor, rather than next to the workplace (full racks) or in the designated holding area (empty racks).

First, the first three issues (lack of scan, multiple scans, and no SOP) can be attributed into one root cause, namely, the current flawed manual scanning process. Closer observation and interviews reveal that the current eKanban system shows no sign of whether an empty rack has been scanned or not. This confuses the employees on the assembly/production floor and gives them no information on whether one should scan it. As no documented SOP is available, everyone who sees an empty rack may scan it. As a result, a significant amount of time is often wasted communicating and clarifying this simple action, and an empty rack could be either not scanned or scanned multiple times by the end of the day. The suppliers are thus very confused about the actual amount of material consumed and how many new racks they should deliver. Often, the suppliers need to proactively ask for material information updates during the day so they would be able to prepare the right amount of material. Without prompt communication, not only does the supplier have problems planning their production schedule, capacity, and shipment accordingly, but most importantly, the supplier may deliver an extra amount of material or not deliver at all, leading to inventory overflow or even production shutdown, respectively.

Second, the following two issues (delayed information update for suppliers and no material information update from the production stage) can be traced back to the root cause of an opaque information flow process that makes the current eKanban system less efficient in two respects. First, it causes an information gap for suppliers. The current supplier portal is only updated with material information once a day at night. Any material demand and feedback are not reflected on the supplier portal and further in their MRP system in real time, as the suppliers' MRP system captures data from the supplier portal. This results in very limited and delayed access to material information by the suppliers. Internal teams at Waters tried to solve this issue by sending an email to the supplier once an empty rack is scanned. This works on a temporary basis and only if the suppliers' employees are told to make shipment on email request only and ignore their MRP system. But the discrepancy between the email request and material information shown in their MRP system often confuses the suppliers. As employees tend to trust and rely on data shown in the MRP system rather than emails, the temporary solution does not work very well. Second, the opaque information flow also causes an information gap for the internal planning department at Waters. Accurate and agile production and procurement planning require prompt material information updates throughout the whole operation process. However, since no information update is provided on the production floor, material information such as inventory level and the number of work-in-progress (WIP) parts are invisible to planners, leading to the extra effort needed by the planning department to ensure an evenly distributed production capacity and a steady production rhythm.

The last issue, namely, the irregular material storage is caused by the limited storage space for eKanban racks in the temporary holding area on the assembly floor. As Waters' product list becomes more and more diversified and customized, the demand for high-value SKUs that are purchased and delivered via eKanban is growing. Given the narrow and constricted room in the assembly & production area on the second floor, some eKanban racks are now left in the corridor entering assembly area. Furthermore, a foreseeable expansion of future operations requires a new design of an official eKanban storage area for the incoming material on the first floor. This is also in line with the company's health and safety policies during the COVID-19 pandemic era, which might last longer than expected.

Therefore, these six key issues can be categorized into three root causes: flawed manual scanning process, opaque information flow process, and limited storage space (see Figure 4-5).

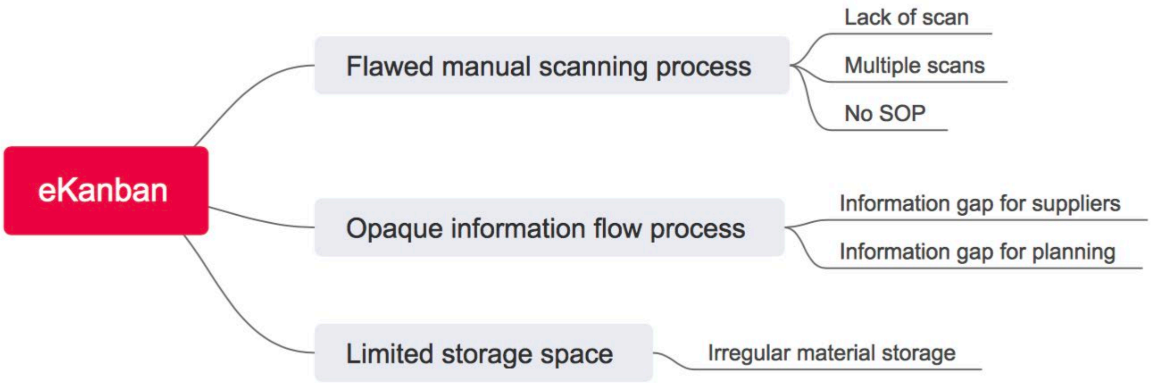


Figure 4-5: Problem attribution via issue tree

4.4 Problem Statement

We conclude that the problems of the eKanban system at Waters are

1) The manual scanning process is causing inaccuracy and ineffectiveness of material flow and the corresponding risks of production shutdown, backlog, and high inventory cost. Significant inconsistency exists between material flow and information flow. At the end of each material flow cycle, human errors emerge from the manual scanning process that serves as the bridge between those two flows. These human errors cause timing inaccuracy and delay the information flow, which then results in an inaccurate and ineffective physical material flow;
2) The lack of transparency of the information flow is causing difficulties in internal production planning and external supply chain coordination, damaging the relationship with suppliers;
3) The limited storage space is causing irregular material storage and inventory shrinkage and limiting the potential of an expansion of material flow through eKanban.

A tree diagram is created to show the root cause analysis and illustrate the problem statement in five levels including underlying issues, reflection on information flow, reflection in material flow, operational issues, and operational loss. See Figure 4-6.

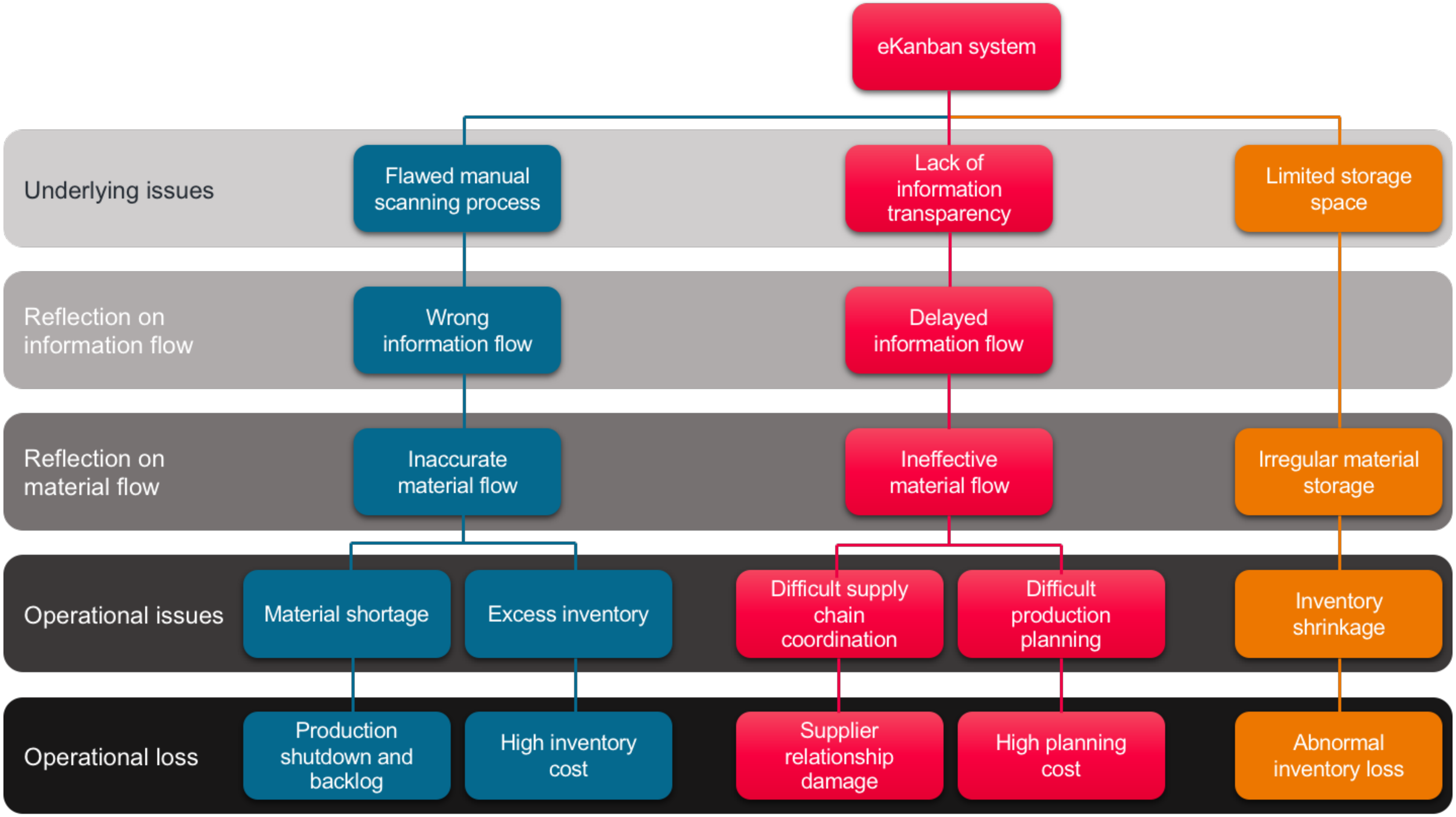


Figure 4-6: Tree diagram for root cause analysis

This page is intentionally left blank.

Chapter 5

Methodology for System Improvement

In this chapter, methodologies used to improve the current eKanban system are described and compared. Regarding the eKanban issues discussed in Chapter 4, a short-term and a long-term solution are proposed to resolve these issues in different phases.

In the short term, process improvement relies on process standardization through the implementation of standard operating procedure (SOP). We expect that the current eKanban with a standardized working procedure will result in fewer human errors, although they cannot be fully eliminated. The short-term solution does not take into account the expansion of the eKanban system and the corresponding need for extra storage space, given the special market conditions in the COVID-19 pandemic. The short-term solution includes SOPs in three versions:

1) COVID-temporary
2) Current state with manual scanning
3) Future state with automated process

In the long term, on the other hand, an efficient, effective, and scalable eKanban system is ensured by implementing advanced material tracking technology with a newly designed storage space and information system. The long-term solution includes three main parts:

- Selection, evaluation and designation of a supplier interface area as expanded storage space for the eKanban materials
- Design of an automated eKanban material flow tracking system leveraging new technologies to replace the current flawed manual scanning process
- Development of a transparent information flow process that eliminates information gaps across departments and supply chains

5.1 Short-Term Plan: Implementation of SOP

In the short term, SOPs are implemented to reduce human error generated from the current eKanban manual scanning process. In particular, clear, detailed, and easily understandable work guidance is documented covering the following points:

- A brief introduction of the scanning process and a clarification of the consequences of each related action
- A clearly defined and assigned responsibility for the scanning action for assembly operators
- An examination obligation and a responding procedure for assembly supervisors
- Clearly defined locations and time slots for related actions

The implemented SOPs are not included in this thesis due to confidential reasons.

5.2 Long-Term Plan: Methodology for Eliminating Human Errors

As discussed in Chapter 4, human errors emerging from the flawed manual scanning process are the root cause of a series of material flow issues observed, including material shortage and inventory overflow. With the previous study and discussion, it is understood that the flawed manual scanning process is closely tied with the current eKanban system. It is therefore essential to justify the advances of the eKanban system before diving into improving it. If the eKanban does not prove its advantages over other alternatives, it would be worth considering rescinding the use of the eKanban system. Thus, to study the effectiveness of the eKanban system, some alternative purchasing methods are proposed and investigated.

5.2.1 Manual Purchase Order (PO)

Purchase Order (PO) represents the most traditional and common way of material procurement in manufacturing companies. With a PO, purchasing personnel usually place large orders manually based on demand and production projections created by the planning and production departments. Therefore, it requires close and meticulous collaboration and coordination between several cross-functional teams. Purchasing by PO also requires holding a relatively large amount of safety stock on-site to avoid material shortages, resulting in a large amount of excess material stocked as inventory at Waters Milford facility. Besides, the parts purchased by PO are delivered in massive packages (see Figure 5-1); therefore, extra labor hours are needed for unpacking, sorting and reloading in containers or on pallets used by the production department.

Figure 5-1: Materials purchased by PO in massive packages, requiring extra labor hours for unpacking, sorting and reloading before they become ready to use.

The lead time, defined as the time from the moment the vendor gets an order to when the material gets delivered, is generally longer with PO since the vendor does not know when the order will come in and must produce and ship a large number of parts at once given a PO. However, we will assume that purchasing eKanban parts by PO has the same lead time as the other methods in this thesis, taking into account the long-time cooperation between Waters and the three local eKanban vendors, the conservative finished goods inventory level held by the vendors, and the very short delivery distances.

5.2.2 Physical Kanban

The physical Kanban card system is another common method used to purchase material from external vendors. As a typical pull system, materials are only purchased and delivered from the last stage when a given amount of material has been consumed in the current stage, triggering a pull signal for replenishment. To involve the vendor, a three-bin Kanban system is the best practice that connects different departments: one bin on the production floor where material demand is created; one bin in the factory storage where materials are held; and one bin in the supplier's storage.

However, the three-bin Kanban system has a major operational disadvantage: it requires the supplier to conduct the Kanban review on-site. If the supplier is located far away, the manufacturing company and the supplier must negotiate and determine an appropriate review period together, as the Kanban card system requires the supplier to be physically present at the plant for the physical review. Ideally, the review should be conducted on a daily basis or more often, as it provides greater flexibility in order quantities and helps reduce inventory. If the review period is longer, more inventory has to be held by the manufacturing company to compensate for the risks of out-of-stock caused by late reviews.

5.2.3 eKanban

An eKanban system is a novel approach that digitalizes the information flow of a typical Kanban system. Similar to a Kanban card system, manufacturing companies plan a limited amount of Work-in-Progress (WIP) parts they want to keep based on their space on the production floor and estimated production rate. Like a physical Kanban card system, material demand in eKanban is conveyed to suppliers through a pull signal, yet in real time electronically without an on-site Kanban review.

5.2.4 eKanban or Not – Simulation Modeling for Comparison

To evaluate the three purchasing methods introduced and justify the benefit of implementing the eKanban system, they are compared from the perspective of material availability and inventory level held as these are the two factors that concern the production managers and planners at Waters the most.

There is a natural trade-off between material availability and inventory level held. Sufficient research has been conducted that shows factory inventory level and order quantity are proportional to the review period. It is therefore easy to understand that the eKanban system has the apparent advantage in terms of a fast and digital review that can be performed in the supplier's absence while the inventory information and material replenishment requests are conveyed in milliseconds, resulting in absolute savings in inventory holding.

However, a detailed study of the effectiveness of an eKanban system considering both material availability and inventory level is still lacking. Therefore, to quantify the potential benefit of an eKanban system and get a more in-depth insight into the effect of different purchasing systems used at Waters, a MATLAB model is developed to simulate various operation scenarios using different purchasing systems, leading to a detailed cost/benefit analysis.

First, incoming materials are categorized into two groups, as shown in Table 5-1 below. Group A represents those standard materials that have a high daily demand and relatively low demand variation. Given the commodity nature of these materials, they have a fairly short lead time. Group B, on the other hand, represents those more customized materials with low daily demand, high demand variation, and corresponding longer lead time. In actual production at Waters, the portfolio of purchased parts is more complicated, but most of them fall into these two segments.

Table 5-1 also shows the parameters assigned to these two groups for simulations. These are simplified incoming material characteristics that roughly represent the difference between these two groups. While group A has a daily demand of 100 units with a standard deviation (Stdev) of 10 units (10% of daily demand) and a lead time of 1 day, group B has a significantly lower daily demand of 10 units with a relatively higher standard deviation of 3 units (30% of daily demand) and a lead time of 3 days.

Table 5-1: Two representative material groups for the simulation model. Lead time here is defined from the vendor's point of view as the time from the moment the vendor gets an order to when the material gets delivered and is assumed to be the same for all purchasing methods.

	Incoming material group A	Incoming material group B
Daily demand [unit]	100	10
Stdev demand [unit]	10	3
Lead time [day]	1	3

For each material group, the four most representative operation scenarios that use different purchasing systems are simulated through the MATLAB model, including

1) eKanban with a pre-defined Kanban size (KS)[1]
2) Physical Kanban with the same KS as eKanban
3) Physical Kanban with no backlog by adjusted KS
4) Purchase order (PO)

In the first scenario, material inventory information is shared directly with suppliers in a digital way through an eKanban system, leading to an instant eKanban review and prompt trigger of material replenishment. When the production floor has consumed a certain amount of material and the empty racks are returned to the holding area, the supplier gets that information instantly and starts preparing material for delivery with no delay. The replenishment arrives in the corresponding lead time (1 day for A or 3 days for B).

In the second and the third scenarios, a physical Kanban card system is simulated where an on-site Kanban review needs to be conducted by the supplier. Imagine a supplier

---

[1] It is worth mentioning that the Kanban size (KS), in the sense we use it here, refers to the minimum order quantity that includes both average demand and safety stock per period (here: per day). For example, if daily demand is 100 units and safety stock is 30, the Kanban size is 130.

delivering high-volume components on a daily basis within the eKanban system. On the first day, the production floor consumes a quantity of materials and the empty bins are returned to the storage location. On the morning of the second day, the supplier delivers materials and simultaneously reviews the physical Kanban cards attached to the empty bins from the last cycle. During the same visit, the empty bins are collected and returned to the supplier operation to be filled. On the third day, the empty bins are refilled and delivered, causing a one-day delay in addition to the normal lead time.

The difference between the second and the third scenario lies in whether the backlog is eliminated. Since the physical Kanban card system creates a one-day delay in material delivery, out-of-stock and a corresponding production backlog can occur, given the daily demand variation. While the second scenario, with the backlog risks, uses the same fixed safety stock target and thus holds the same level of inventory as the first scenario, in the third scenario the safety stock target is adjusted to eradicate backlog.

In the fourth scenario, a PO is simulated. The PO at Waters can be seen as a Kanban system with a more extended review period of 5 days, i.e., a business week, as it merely replenishes the inventory to a fixed position with a large order of material in a periodic manner using an Order-Up-To (OUT) policy.

To summarize, several fundamental assumptions of the simulation model include:

- eKanban and Kanban have the same review period (here: daily)
- eKanban order happens on the same day; Kanban order happens the next day (one-day delay)
- Purchase order has longer review and order period (here: 5 days)
- Same Kanban size for both material groups for ease of comparison
- Inventory simulated here is the end-of-day inventory after a day of operations. The theoretical average end-of-day inventory is equivalent to safety stock
- Backlog is created when the end-of-day inventory falls below zero, meaning the replenishment at that day does not fulfill the material demand
- Each simulated unit represents a container or a rack that contains multiple parts

Each simulation runs 1000 days, representing four years given each year has 250 business or production days. The levels of inventory and backlog resulting from material shortage are compared.

Scenarios Simulation – Material Group A

The simulation results of the first scenario, eKanban, are shown in Figure 5-2 below. The average inventory held is 30 units, much lower than the average material demand of 100 units, while no stockout or production backlog occurs as a result of a safety stock target (SST) of 30 units. Note that the inventory level shown in blue is the on-hand net inventory.

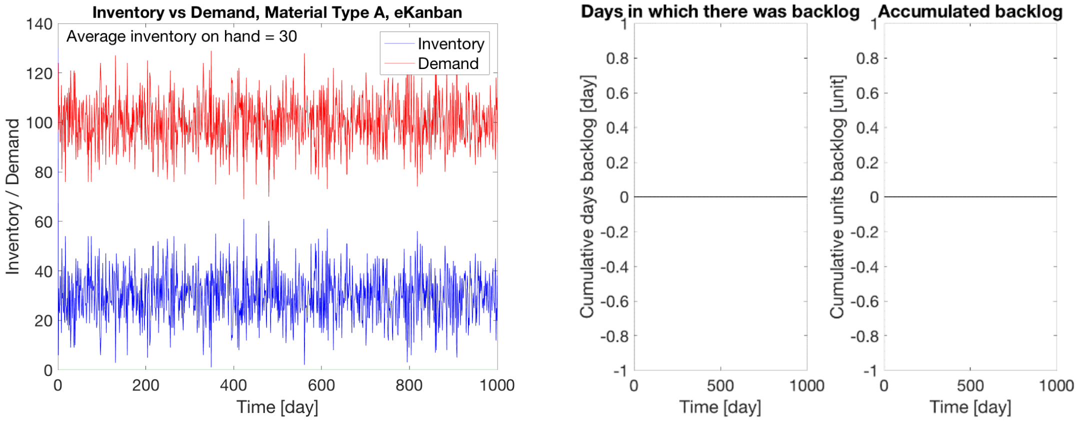


Figure 5-2: Inventory and backlog run charts for the first scenario (eKanban), material group A. The average (end of day) net inventory is 30 units and no backlog occurred.

The simulation results of the second scenario are shown in Figure 5-3 below. The average inventory held, 30 units, is the same as the eKanban scenario since the same safety stock target is used. Because of the one-day delayed material delivery, out-of-stock is not avoidable, and we observed an average cumulative production backlog of 16 days out of 1000, i.e. on 1.6% of the days, and the average shortfall on these days was about 6 units[2], i.e. 6% of the daily demand.

---

[2] The average shortfall values are rounded to integers in the sense we observe the inventory here.

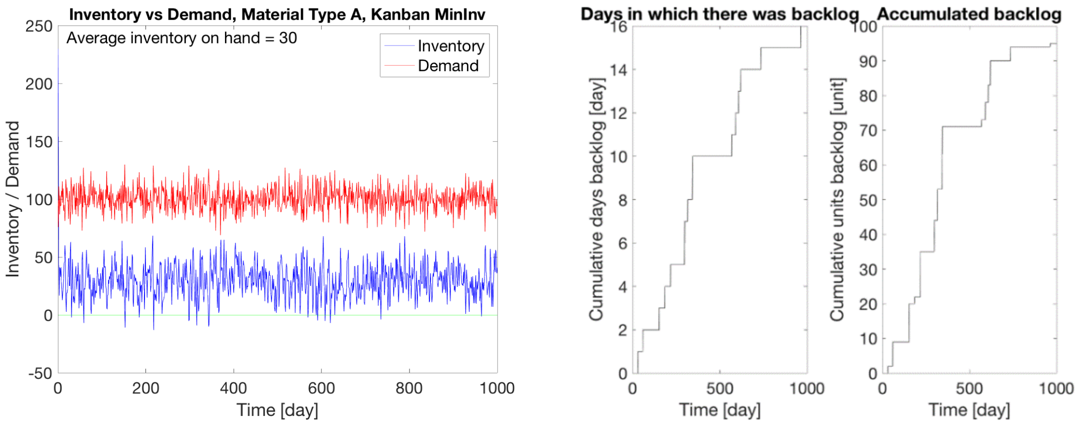


Figure 5-3: Inventory and backlog run charts for the second scenario (Physical Kanban), material group A. The average inventory held is 30 units with a cumulative backlog of 16 days out of 1000 and the average backlog on these days was about 6 units (95 units divided by 16 days).

The simulation results of the third scenario are shown in Figure 5-4 below. To eliminate the backlog observed in the second scenario, the safety stock target is set to 50 units.

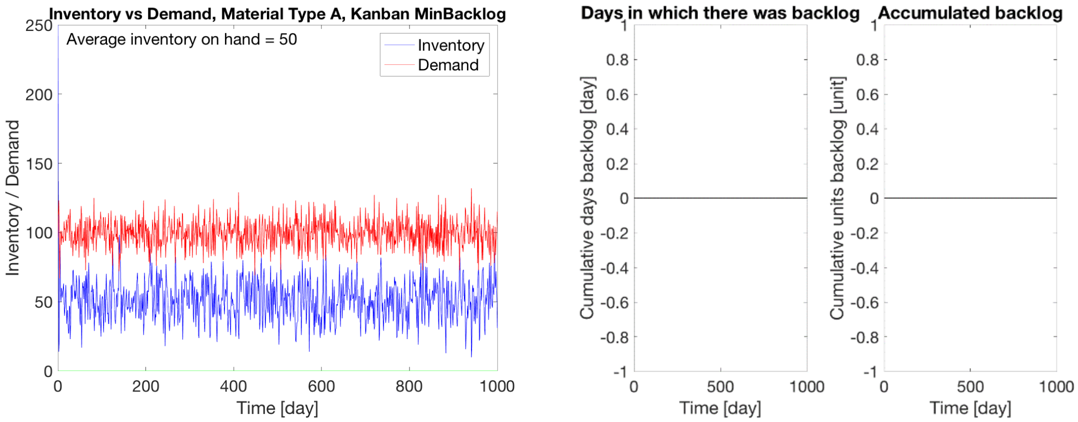


Figure 5-4: Inventory and backlog run charts for the third scenario (Physical Kanban with no backlog), material group A. The average net inventory is 50 units without any backlog.

The simulation results of the fourth scenario are shown below in Figure 5-5. The PO is the most conservative way of purchasing materials; every order is made with the goal that no backlog will occur. In this scenario, therefore, no backlog is expected as a result of placing bulk orders and holding more inventory: we set the order-up-to level to 590 which results in an average inventory of 290 units.

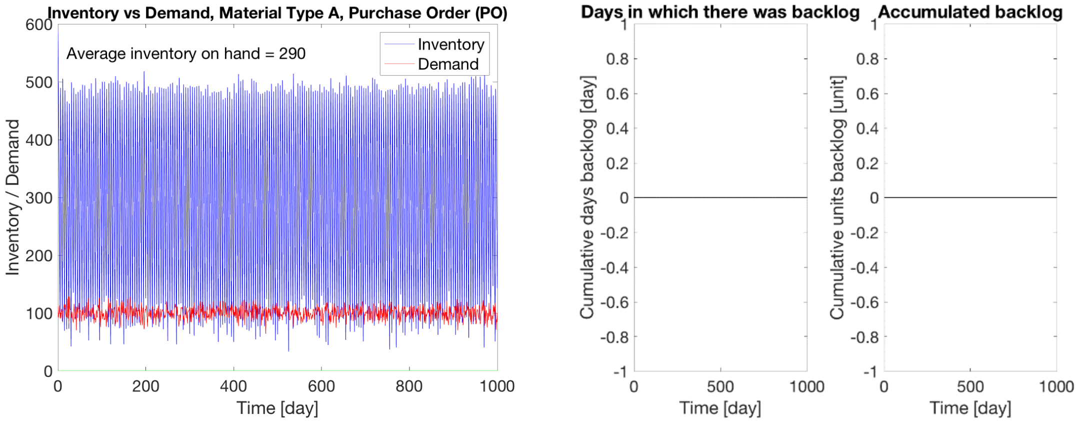


Figure 5-5: Inventory and backlog run charts for the fourth scenario (PO), material group A. The average inventory held is 290 units without any backlog.

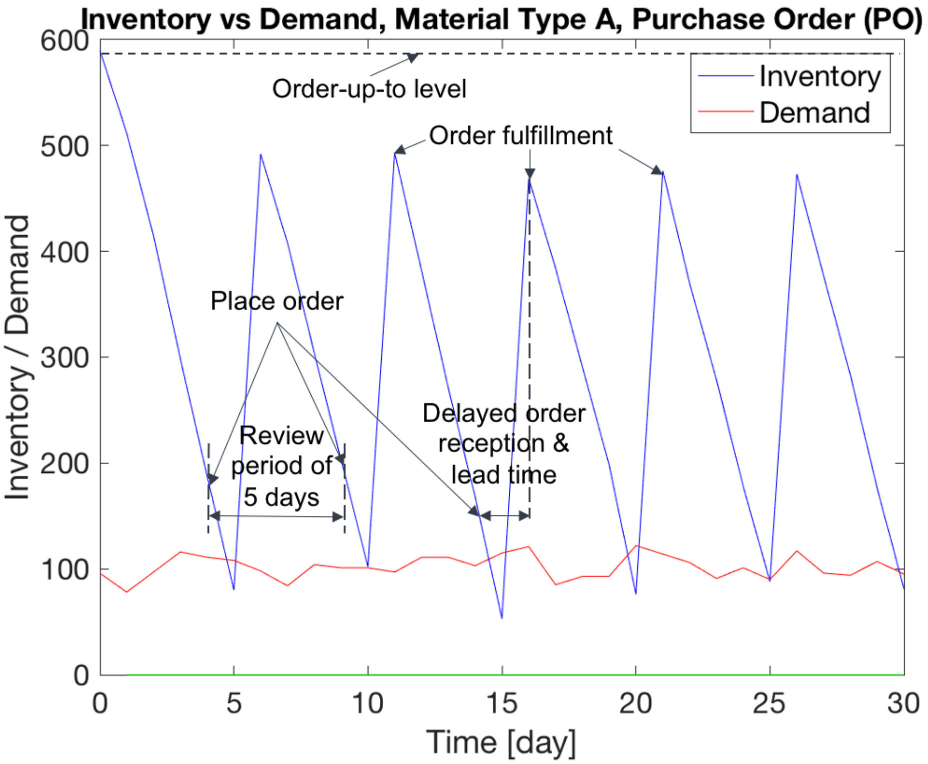


Figure 5-6: PO 30-day inventory vs. demand dynamics plot. The PO is simulated to have a review period of 5 days using the Order-Up-To (OUT) policy. After each review, the vendor gets the order with one-day delay and deliver the material in two days (one-day delayed order reception plus one-day lead time)

Figure 5-6 above shows the inventory dynamics in a shorter period of 30 days with more details. As can be seen, the PO is simulated to have a review period of 5 days using the OUT policy. After each review, the vendor gets the order with one-day delay and deliver the material in two days (one-day delayed order reception plus one-day lead time).

Table 5-2 summarized the results of the four simulated scenarios in material group A. Inventory and backlog are compared across different case scenarios. For material group A, the eKanban scenario delivers the best results with no backlog and the lowest average inventory level. The traditional physical Kanban system with delayed material delivery has a significantly higher probability of out-of-stock when the same safety stock target as eKanban is used, while the eKanban does not have a backlog issue. If no backlog is desired for the physical Kanban system, 67% more inventory must be held to fully eliminate the backlog. Furthermore, 967% of the inventory needed for the eKanban scenario must be held if PO is used, leading to significantly higher inventory holding costs, although not quantifiable owing to limited access to cost data.

Table 5-2: Inventory and backlog simulation results for material group A. The eKanban scenario delivers the best results with no backlog and the lowest average inventory level. The physical Kanban having the same average inventory as the eKanban case has a significantly higher probability of out-of-stock, which can be eliminated by significantly raising the inventory position. The PO scenario keeps the highest average inventory as expected, making it uneconomic regarding inventory holding costs.

	eKanban - Benchmark	Phys. Kanban - Same SST	Phys. Kanban - no backlog	PO
Daily demand [unit]	100	100	100	100
Stdev demand [unit]	10	10	10	10
Lead time [day]	1	1	1	1
Review period [day]	1	1	1	5
Digital review?	Yes	No	No	No
Average inventory	30 (100%)	30 (100%)	**50 (167%)**	**290 (967%)**
% of days backlog occurs	0	**1.6%**	0	0
% backlog on daily demand	0	**6%**	0	0

It is worth mentioning that despite the higher inventory holding costs caused by PO, this traditional purchasing method often has its own advantages such as lower transportation costs and lower purchase costs per unit of material, as vendors tend to offer quantity discounts for larger purchases. In the case of the eKanban system at Waters, however, these cost advantages are not significant for two reasons. First, the transportation costs advantages associated with the less frequent orders placed by PO is insignificant given the fact that the current three local eKanban vendors are located in close proximity and have very short transportation distances. Second, Waters enters into annual purchasing agreements with the eKanban vendors to approximate the annual purchase quantities at the beginning of each fiscal year, which also results in quantity discounts offered by the vendors.

Scenarios Simulation – Material Group B

To simplify the cross-group comparison between material group A and B, the same safety stock target (equal to 3 times the daily demand standard deviation) is used for the benchmarking scenario, eKanban, and the second scenario, physical Kanban, while for the other two scenarios used, we adjust the safety stock targets to eliminate the backlog.

The simulation results of the first scenario, eKanban, shows an average inventory of 9 units, close to the average material demand of 10 units. We observed an average cumulative production backlog of 34 days out of 1000, i.e. on 3.4% of the days, and the average shortfall on these days was about 3 units, i.e. 30% of the daily demand. See Figure 5-7.

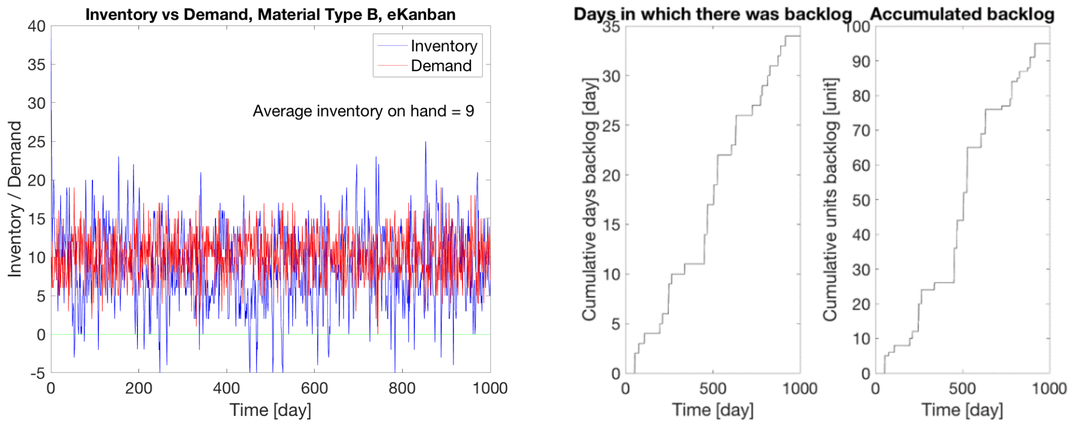


Figure 5-7: Inventory and backlog run chart for the first scenario (eKanban), material group B. The average inventory held is 9 units with a cumulative backlog of 34 days out of 1000 and the average backlog on these days was about 3 units (94 units divided by 34 days).

With the same average inventory on hand, the simulation results of the second scenario show a higher rate of backlog, which is accumulated to a backlog of 60 days out of 1000, and the average backlog on these days was about 3 units, i.e. 30% of the daily demand, as a result of the one-day delayed material delivery. See Figure 5-8.

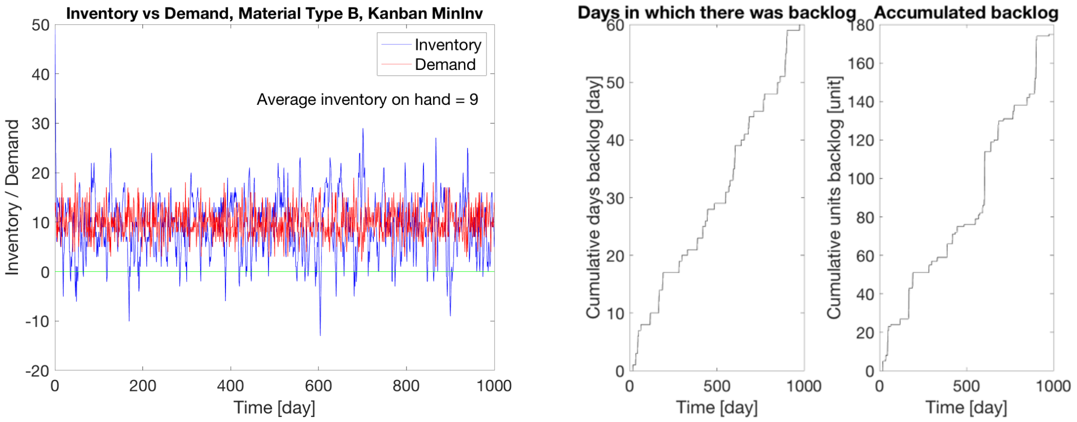


Figure 5-8: Inventory and backlog run chart for the second scenario (Physical Kanban), material group B. The average inventory held is 9 units with a cumulative backlog of 60 days out of 1000, and the average backlog on these days was about 3 units (173 units divided by 60 days).

To eliminate the backlog in the second scenario, the safety stock target in the third scenario is adjusted to 24 units of material B, according to the simulation shown in Figure 5-9 below.

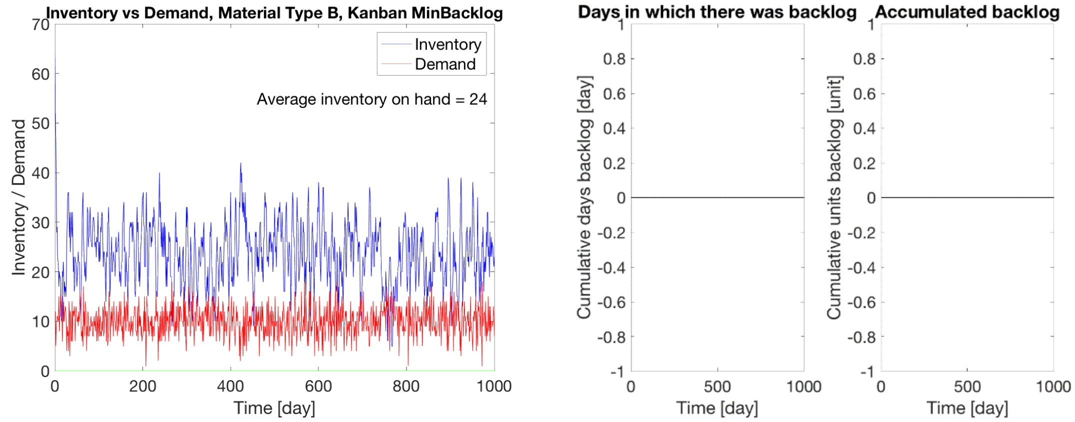


Figure 5-9: Inventory and backlog run chart for the third scenario (Physical Kanban with no backlog), material group B. The average inventory held is 24 units without any backlog.

Having a more extended review period, the fourth scenario PO has the order-up-to level of 99 units which results in an average inventory of 49 units. See Figure 5-10 below.

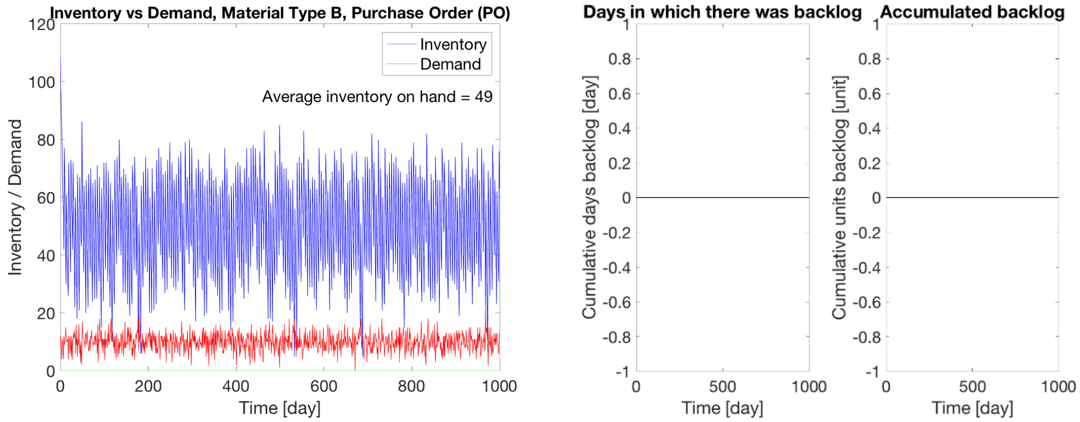


Figure 5-10: Inventory and backlog run chart for the fourth scenario (PO), material group B. The average inventory held is 49 units without any backlog.

Table 5-3 summarized the results of the four simulated scenarios in material group B. Inventory and backlog levels are compared across different case scenarios. The eKanban scenario delivers the best results with no backlog and the lowest average inventory level.

Similar to material group A, the traditional physical Kanban system with delayed demand fulfillment has a significantly higher probability of out-of-stock when the same safety stock target as eKanban is used (5.8% compared to 3.4%). Elimination of backlog requires 267% of the inventory needed for eKanban, rendering the physical Kanban system less economic. Furthermore, 544% of the inventory needed for eKanban must be held if PO is used, leading to significantly higher inventory holding costs.

Table 5-3: Inventory and backlog simulation results for material group B. The eKanban scenario delivers the best results with no backlog and the lowest average inventory level. The physical Kanban having the same average inventory as the eKanban case has a significantly higher probability of out-of-stock, which can be eliminated by significantly raising the inventory position. The PO scenario keeps the highest average inventory as expected, making it uneconomic regarding inventory holding costs.

	eKanban - Benchmark	Phys. Kanban - Same SST	Phys. Kanban - no backlog	PO
Daily demand [unit]	10	10	10	10
Stdev demand [unit]	3	3	3	3
Lead time [day]	3	3	3	3
Review period [day]	1	1	1	5
Digital review?	Yes	No	No	No
Average inventory	9 (100%)	9 (100%)	**24 (267%)**	**49 (544%)**
% of days backlog occurs	3.4%	**5.8%**	0	0
% backlog on daily demand	30%	30%	0	0

To summarize, the MATLAB simulation model shows a superior inventory performance of the eKanban system as it can reduce the probability of backlog or reduce the severity of backlog while lowering inventory levels. Therefore, the eKanban system is proven to be more effective than other purchasing methods in terms of avoiding material shortage and reducing inventory level. Thus, we shall shift the investigation focus to the methodology for material tracking for eKanban.

5.3 Long-Term Plan: Methodology for Material Tracking for eKanban

As a properly designed eKanban system is proven to work better than its alternatives through process simulation, it is worth considering improving the effectiveness of the eKanban by implementing advanced, automated material tracking technologies to replace the current manual scanning process. Therefore, three different material tracking methods that help monitor and keep track of the material flow throughout the whole eKanban process are introduced and compared, including the current barcode system.

5.3.1 Barcode

A barcode is a sequence of parallel bars representing encoded data that is readable and interpretable by an optical device such as a scanner. To read and send the signal to a computer, the scanner uses a beam of light to scan the parallel black lines with various widths and spaces (see Figure 5-11). As the barcode system has been used as standard product tracking technology in industries such as manufacturing, retail and logistics for over several decades, the technology is mature, inexpensive and easy to implement.

Figure 5-11: How barcode works. The scanner uses a beam of light to read the barcode comprised of parallel black lines with various widths and spaces and then send it to the computer through a wireless network.

5.3.2 Computer Vision

Computer vision, often abbreviated as CV, is a powerful and compelling type of artificial intelligence (AI) techniques that trains computers to process images or optical objects and make the visual world interpretable and understandable by machines. Computer vision can be well applied to the field of material tracking, given the availability of the right camera equipment, encoded signs or labels such as barcodes or QR codes that contain material information, and a specially designed algorithm. A computer vision-based material tracking system is able to capture material movement action or location information autonomously with no human interaction necessary, provided a well-designed algorithm and sufficient training.

5.3.3 Radio-Frequency Identification (RFID)

Since Radio-Frequency Identification (RFID) was first introduced to industry several decades ago, it has been recognized as an efficient material tracking and data capture technology. RFID refers to a wireless system that uses electromagnetic fields to remotely capture radio frequency (RF) waves and identify digital data encoded in transponders or RFID tags attached to objects. The RFID tag, together with the antenna and the RFID reader, form an RFID system. Unlike barcode scanners and camera-based material tracking systems, the RFID system does not need to “see” the information carrier but uses an electromagnetic field to communicate with it.

The working principle of an RFID network is illustrated in Figure 5-12. A reader generates electrical signals through an antenna connected to it. An antenna converts the electrical signals into RF waves used to broadcast the RF signals. Activated by electromagnetic energy emitted by the antenna, an RFID tag is induced to transmit data signal stored in it back to the antenna that is connected to the reader. The reader then receives signals from the antenna, decodes it and sends it to a computer or a cloud database where the data is stored and evaluated.

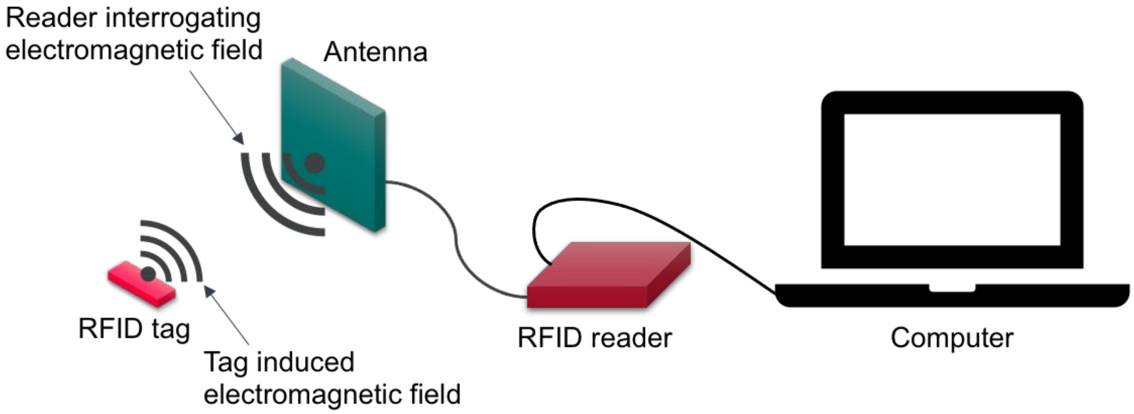


Figure 5-12: How RFID works. After being activated by the electromagnetic field generated by the antenna, the information stored in the RFID tag is read by the antenna and then sent to the reader, which decodes the information and sends it to the computer.

5.3.4 Why RFID?

After introducing all three alternatives for tracking material flow, they will be compared in this section and the most appropriate one will be selected for further study.

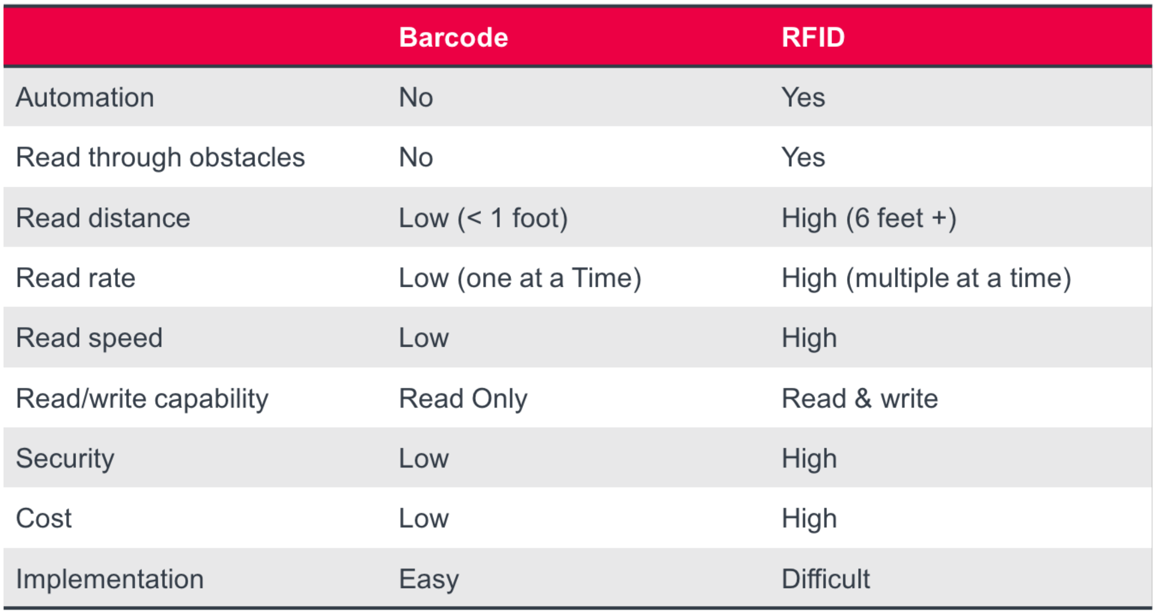
The first alternative to be excluded is computer vision. Although the technology itself looks very promising, there are three reasons to eliminate this technology from the list:

1) A more in-depth investigation shows that the effective range that a camera can read an image such as a QR code is relatively constrained. Given the size of the rack, a very limited number of racks can be managed by a single camera, and therefore, multiple camera systems are needed for one application location, resulting in an uneconomic camera-rack ratio;
2) Experience and expertise are required in coding, algorithm design, machine learning, and computer graphics. As the focus of this thesis lays on material flow from a lean perspective, CV related expertise lacks within the project team; the maintenance of the system can be a pain for a company with little personnel who have related experience or expertise;

3) The camera system with CV is highly customized. The pilot project may provide only limited guidance for in-house engineers with no domain knowledge to manage and upgrade the system in the future. An expansion of the pilot project may be difficult in terms of both a technical and a financial perspective.

Therefore, the focus lays on the comparison between RFID and barcode systems. Both technologies have been widely used in industries such as retail, logistics and manufacturing for data collecting and material tracking for a long time. However, knowing the major differences between RFID and barcode is critical to choose the technology that works more efficiently and effectively at Waters. Table 5-4 below compares these two technologies from some critical perspectives that influence the efficiency and effectiveness of a material flow.

Table 5-4: Barcode vs. RFID



	Barcode	RFID
Automation	No	Yes
Read through obstacles	No	Yes
Read distance	Low (< 1 foot)	High (6 feet +)
Read rate	Low (one at a Time)	High (multiple at a time)
Read speed	Low	High
Read/write capability	Read Only	Read & write
Security	Low	High
Cost	Low	High
Implementation	Easy	Difficult

- **Automation**: A barcode system requires operators to complete the scanning process for each labeled item. An RFID system, on the other hand, is completely automated once up and running. It requires no human involvement to collect the data and therefore eliminates human errors.

- **Read speed**: Barcode scanning is slow as it requires line-to-line to read the information and an accurate alignment is required. An RFID system is able to complete the reading process within milliseconds autonomously, offering tremendous time-saving opportunities.
- **Read range**: A barcode system requires the scanner to maintain a line-of-sight and stay very close, usually several inches, with the code in order to scan it, while an RFID system can perform reading from a long distance. A passive RFID tag can be read up to 40 feet if the system is set up properly.
- **Read rate**: Barcodes are designed to be scanned one at a time, whereas many RFID tags can be read simultaneously, allowing speedy batch reading.
- **Read/write capability**: A barcode can only be read, and the data can never be changed once created. An RFID tag can be read, rewritten, modified or updated as needed in different material flow stages in a manufacturing company.
- **Security**: A barcode is easy to reproduce or counterfeit, while an RFID tag is difficult to replicate, providing a secure environment for the information stored in.
- **Cost**: The cost of RFID tags and readers are significantly higher than barcode labels and scanners, given the more complex nature of the RFID technology.
- **Implementation**: RFID implementation is significantly more complicated and time-consuming than a barcoding system as it involves more site evaluation, hardware testing work, and fail-safe consideration.

Now it is understood that RFID provides better opportunities for material flow improvement at Waters from most practical aspects except cost and implementation difficulty.

Admittedly, the cost of an RFID system is higher than the barcode as the readers and the tags are provided by limited manufacturers and the technology has not yet been as popular as the barcode system. However, costs have fallen tenfold in the past two decades [8] and the trend continues. With the increasing RFID applications in industry these days, economies of scale are driving the unit cost down every day, making an RFID system even more affordable.

It is also true that the implementation of an RFID system is more challenging than that of a barcode system. The system design, setups, and testing of an RFID network is more complicated, time-consuming, and requires certain technical know-how compared to implementing a barcode system. Besides, a barcode system provides a simple fail-safe measure by giving the operator instant feedback such as a beep sound after each successful scan, while unsuccessful reading of the RFID tag is hard to notice. To address these difficulties, this thesis will explore the opportunities of integrating fail-safe measures into the RFID network, for example, by using slack light or buzzer indicators or a real-time data visualization interface, and will discuss and document the system design, setups, and testing work of a pilot RFID system in detail, providing guidance for future large-scale implementations at Waters Corporation and other manufacturing companies.

To summarize, although cost and implementation are two challenging points, the focus of this study is to eliminate human error and achieve full material flow transparency, and the author and related stakeholders at Waters believe the benefit of an RFID system would outweigh its cost and this is the right direction to go. In the next two chapters, therefore, the system design and implementation of the rack-level and item-level RFID networks will be discussed respectively.

This page is intentionally left blank.

Chapter 6

Solving the Immediate Issues: Rack-Level System Design and Implementation

To solve the three issues discussed in Chapter 4, including a flawed manual scanning process, lack of transparency of the information flow, and limited storage space, a rack-level RFID solution is proposed and developed. The design and implementation of the system are detailed in this chapter.

In most applications in industry, RFID is deployed at the item-level, meaning the tags are placed on the individual items to track their movement, locations, etc. However, an item-level implementation in the eKanban process at Waters Milford facility would face three challenges:

- **Technical challenge**: The current eKanban system is mainly used for metal parts that can interfere with RF waves and RFID tags. An item-level implementation would require specific metal-compatible RFID tags that cost significantly more and require a much longer testing phase.
- **Organizational challenge**: A new numbering & serializing scheme for incoming goods must be designed by Waters if an item-level system is to be used. Such a structural, large-scale disruption to the current system might face significant resistance.
- **Coordination challenge**: An item-level RFID implementation would require a significant effort in coordination and negotiation with suppliers, as they would need to affix an RFID tag on each product they ship to Waters, requiring extra, uneconomic labor hours.

Therefore, taking these challenges into account, the most appropriate solution for the current situation is a rack-level RFID implementation. At rack-level, we can demonstrate the benefits of implementing RFID in the eKanban system at Waters by replacing the barcodes and scanners with RFID tags and readers, requiring no structural change to the operating model of the current eKanban system while eliminating the human errors. In this way, the immediate issues can be resolved quickly without internal resistance in the organization from various stakeholders. Once people see and understand the benefit of the rack-level RFID, a smooth transition to an item-level implementation will become possible.

Regarding the three issues discussed in Chapter 4, the rack-level solution includes

1) Design of a new storage area for eKanban parts on the first floor
2) System design of a rack-level RFID network
3) Development of a transparent information flow process

The first two parts are detailed in this chapter, while the last part is realized through data integration and visualization based on an RFID network, as documented in Chapter 8.

6.1 Site Selection and Design

The starting point of designing and implementing an RFID system is site location selection and design. As extra storage space needs to be newly designed and determined, it is worth considering deploying an RFID network directly at the new storage location. In the future, the new storage location with an RFID network will become an "interface" area where suppliers replenish materials in full racks while bringing back the empty racks returned from the assembly line.

Figure 6-1 shows the floor map of the first floor, including operation areas such as receiving, high-density storage, kitting, warranty & repair, incoming inspection and part of machining.

The receiving area and the lift to the assembly floor are marked out in particular, as they are the key locations along the material flow of eKanban parts at Waters.

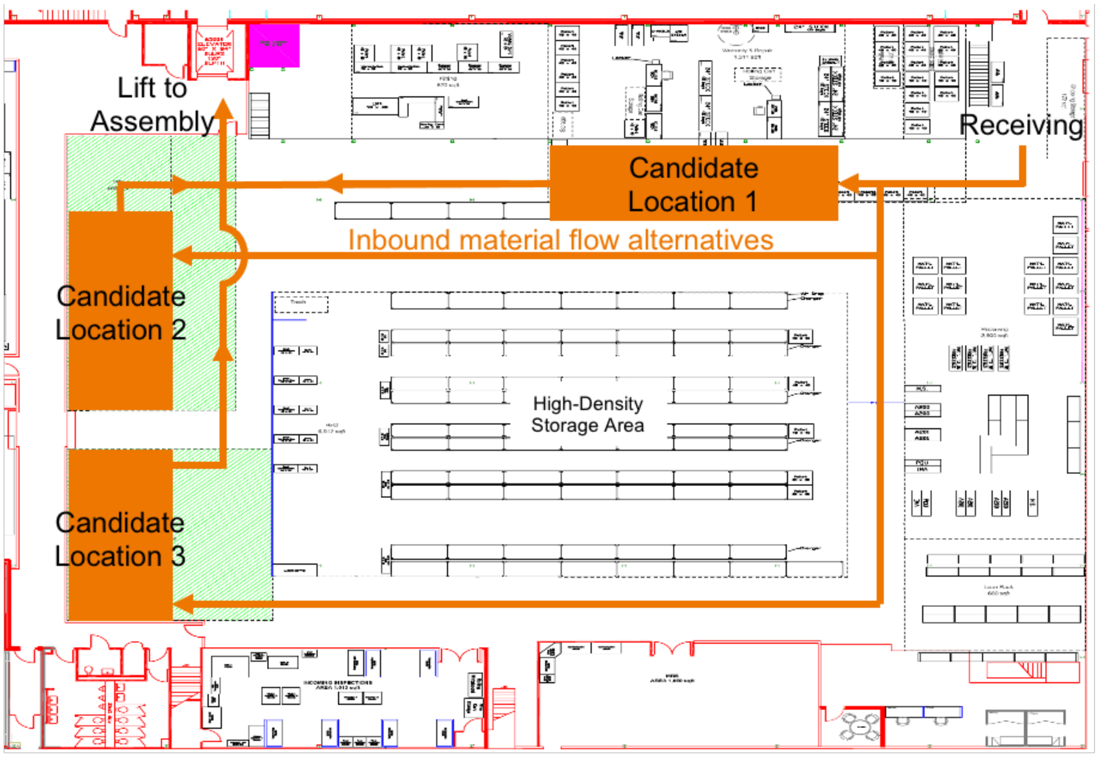


Figure 6-1: Floor map and three candidate locations. Arrows represent inbound material flow alternatives through each candidate location.

The areas marked orange are the candidate locations currently free and can potentially be used as a supplier interface area with an RFID network. Each of them has an area of around 47 to 55 m^2. Given that the size of an eKanban rack is about 0.75 m^2, each location would be capable of storing approximately 60 racks, taking space for necessary aisles into consideration.

About 20 racks are currently stored on the second floor where assembly and production occur, including 10 "kit" types with an average of 2 racks per kit type. Note that a "kit" is a group of SKUs; for example, a sheet metal kit includes a body, a cover and side panels. Therefore, the new storage space on the first floor provides a significant capacity increase for the eKanban system. To optimize the use of the new storage space, the following scheme is designed.

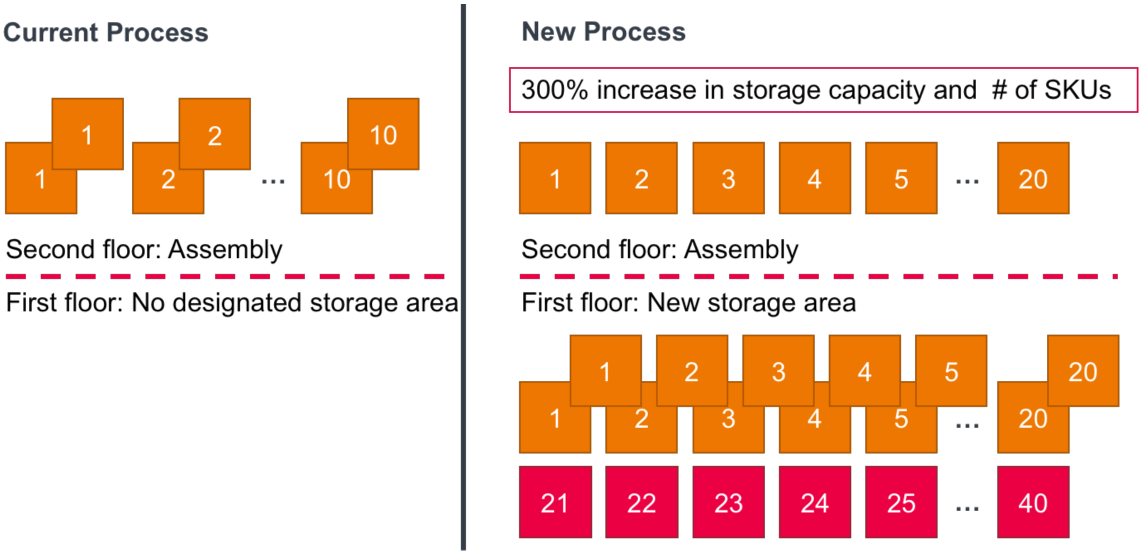


Figure 6-2: Comparison between the current and newly designed eKanban process. Each box represents an eKanban rack. Numbers indicate different kit types. Nos. 1 to 20 (orange) are high-demand types, while Nos. 21 to 40 (red) are low-demand. The new process increases storage capacity from 10 to 40 kit types and from 20 to 80 racks, representing an expansion by 300%

Figure 6-2 compares the storage capacity of the current and newly designed eKanban process. Each box represents a rack, and each number describes a kit type. The current process has 10 kit types with 2 racks per kit type for a total of 20 racks. With the additional storage space on the first floor, the newly designed process will allow a total of 80 racks with 20 racks on the assembly floor and 60 racks in the new storage area. As illustrated on the right of the figure, the new process design divides different kit types into two categories: 20 high-demand, fast-consuming kit types colored in orange, with one rack being stored on the assembly floor and two racks in the interface area; and 20 low-demand, low-consuming ones colored in red, with one rack being stored in the interface area. These two categories add up to a mixed portfolio of 40 kit types in total to be incorporated in the eKanban process in the future, representing a 300% increase in eKanban storage capacity and the number of SKUs incorporated in the eKanban process.

6.2 Site Technical Assessment

After selecting the candidate sites and designing the interface area, the next step is to evaluate the technical feasibility of deploying an RFID network at them and selecting the most appropriate candidate site to proceed with. Without a proper evaluation and corresponding technical adjustment of the deployment location, RFID's power and benefit cannot be fully utilized.

The technical site assessment is completed by a combination of the Full Faraday Cycle Analysis (FFCA) and the Path Loss Contour Mapping (PLCM) in this thesis. The former represents the identification of the sources of noise and interference at each candidate site and the determination of the best RF interrogation locations, while the latter gives insight into the details of a given interrogation zone so that an optimized configuration is possible.

6.2.1 Ambient Electromagnetic Noise and Full Faraday Cycle Analysis

To determine the technical feasibility of deploying RFID at each candidate site, environmental noise and its potential interference with the desired RF signal must be determined first. The environmental noise in the radio frequency world is characterized by the Ambient Electromagnetic Noise (AEN). The AEN describes a group of electrical and magnetic waves that are emitted by certain electrical devices. In a typical manufacturing environment, these include conveyors, electric doors, sorting machines, infrared scanners, real-time location systems, alarm motion detectors, and site radio communication devices. These devices contribute differently to the degree of AEN at each site depending on their relative locations and power settings. It is therefore important to determine the relative noise level compared to the RF signal level at each candidate site and the effect on the RF signal interrogation zone.

The FFCA is a technical process that gathers time-dependent AEN data regarding the electrical and magnetic waves in a site environment over a full business cycle in which all typical operations occur. Since the RF communications in the U.S. use a specific frequency band between 902 MHz to 928 MHz, a spectrum analysis over this range will be conducted at each candidate site where setting up an RFID interrogation zone is desired. The FFCA is conducted over this range as a whole instead of separating this band into single frequencies (channels) because the Federal Communications Commission (FCC) requires that no device operating across this band stay for more than 400 milliseconds at each channel and that the device keeps moving through each channel. This process is called frequency hopping.

As shown in Figure 6-3, the FFCA is conducted at all three candidate sites using an RF spectrum analyzer. A small tripod is used to hold the spectrum analyzer at an appropriate vertical position on a plastic cart, ensuring continuous measurement over a long period of time.

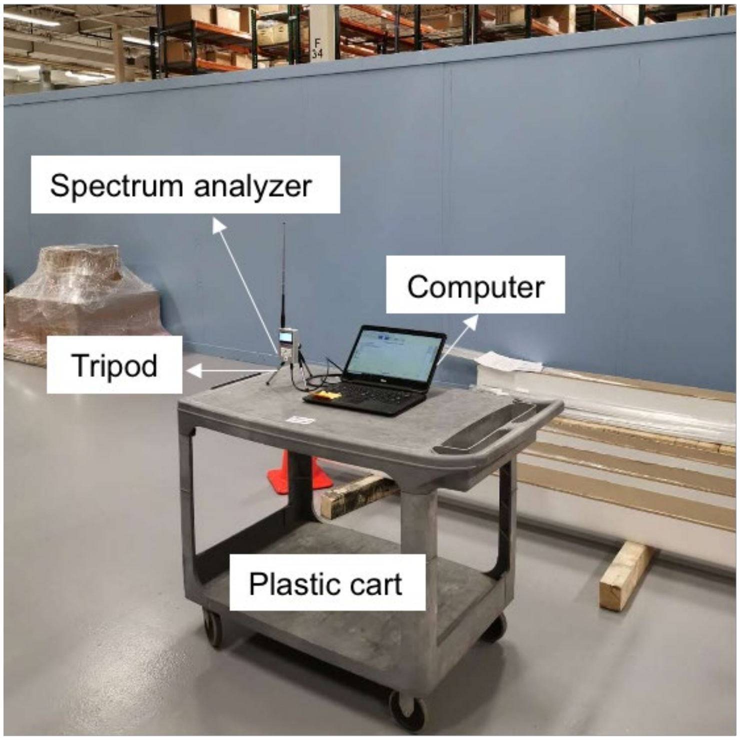


Figure 6-3: Full Faraday Cycle Analysis test setup at a candidate location, including a spectrum analyzer held by a tripod vertically on a plastic cart, and a computer. The measurement lasted four hours collecting AEN data over a full operation cycle.

The measurement lasted four hours at each candidate site collecting AEN data over a full operation cycle, i.e., a full shift as the facility goes through all its normal business operations. Measurement span is set between 890 to 950 MHz, broader than the frequency band of RF communications to ensure detection of signal interference close to but not included in the band of interest. The measurement results of candidate location 1, which represents the worst noise environment, are shown below.

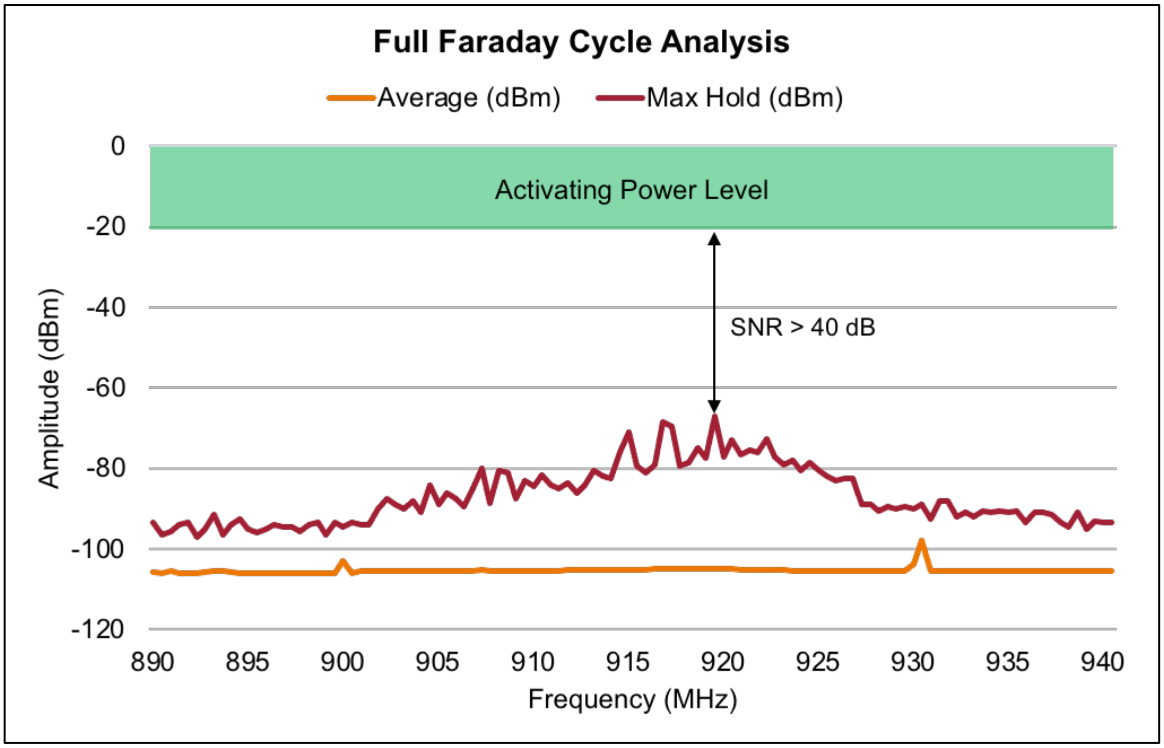


Figure 6-4: Full Faraday Cycle Analysis result. The amplitudes are in decibel milliwatts (dBm), a measure of the signal power. The Average shows the average power at each frequency over the entire sampling time of four hours, whereas the Max Hold is the maximum value recorded at each frequency over the same period. Given that the power to activate a tag is normally above -20 dBm [9], the minimum signal-to-noise ratio (SNR) as shown here is 47 dBm. The two constant blips shown by the Average around 900 and 930 MHz (outside the RF spectrum) result from slight interference from nearby phone transmitting towers, as these are frequencies reserved for mobile and fixed phone communications [10].

As can be seen from Figure 6-4, the amplitudes of AEN are shown in decibel milliwatts (dBm), a measure of the signal power. Two data capture modes are used and compared: the mode Average shows the average power at each frequency over the entire sampling time of four hours, whereas the mode Max Hold is the maximum value recorded at each frequency over the same period. The results show that the average strength of the RF waves that propagate through the potential interrogation zone over the RF frequency band is below -105 dBm, representing the level of electromagnetic noise during regular operations, while the peak is -67 dBm, indicating the extreme level of electromagnetic interference over this band when specific machines or devices are running. Closer scrutiny reveals the barcode scanning process and forklift operations are two major reasons for the peak noise levels. These are relatively weak interferences, and industry experience shows that the minimum required power input to activate a UHF tag is 10 μW (-20 dBm) [8]. At the peak noise level, the signal-to-noise ratio (SNR) is larger than 40 dB, indicating a difference in power of more than 10,000 times. The high SNRs show that the RFID network will be able to distinguish received signals as legitimate information that should be listened to and ignore noise signals on the same spectrum. Table 6-1 summarized noise level in terms of average and peak values and the SNR at each candidate location.

Table 6-1: AEN noise level and SNR at each location. The high SNRs suggest that the noise levels observed are neglectable.

Candidate location	Noise average	Noise peak	SNR
1	-105	-67	47
2	-105	-69	49
3	-106	-70	50

Figure 6-5 is the histogram of signal frequency distribution, generated using the FFCA results at a candidate location. It shows that over 99.9% of the sampling period, regular operational radio communications over the RF frequency band are powered below -90dBm. This results in a signal-to-noise ratio of 70 dB, large enough to ignore the effect of environmental noise on the future RFID network.

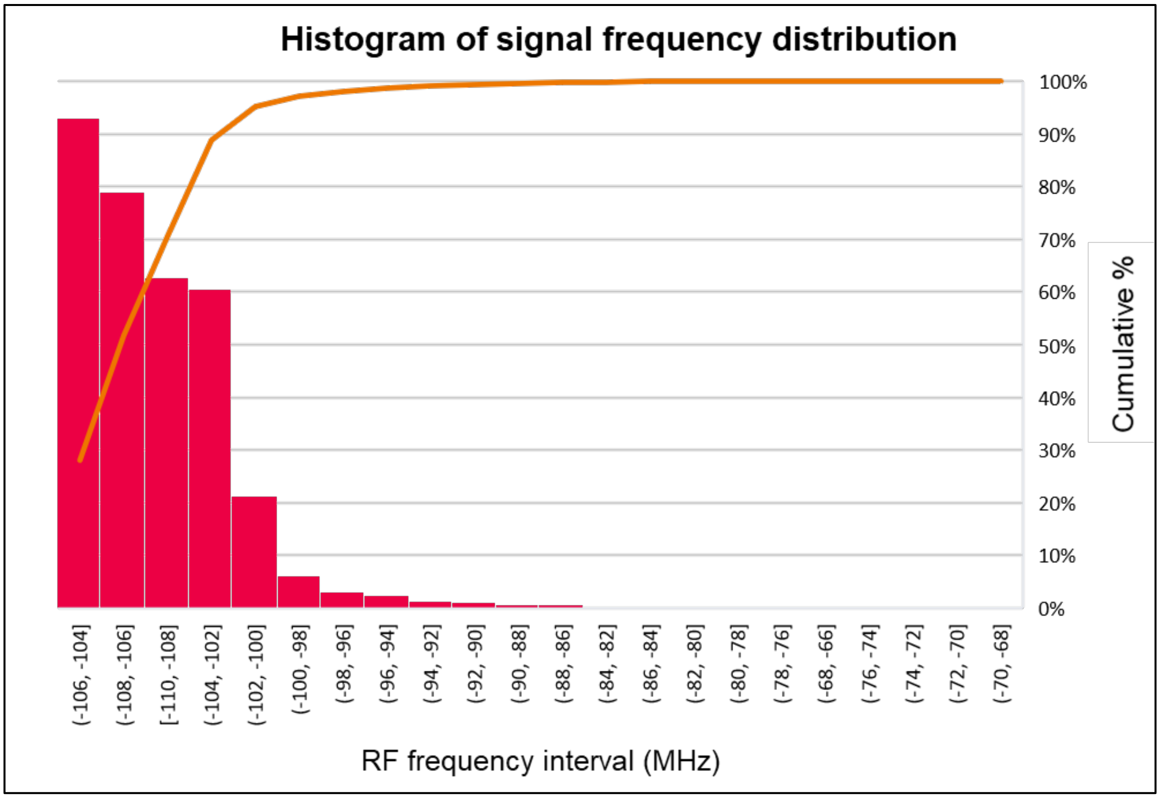


Figure 6-5: Histogram of signal frequency distribution. Over 99.9% of the sampling period, radio communication happened over the RF frequency band below -90 dBm.

Therefore, it can be concluded that the environmental noise during the regular operations at all three candidate sites is insignificant and these are good locations for deployment of RFID networks. A technical adjustment or noise compensation measure is not necessary.

6.2.2 Path Loss Contour Mapping

After identifying the degree and the sources of dynamic environmental noise and its effect by the FFCA, the next step is to perform the Path Loss Contour Mapping (PLCM) to get insights into the effect of static objects on a given interrogation zone so that it can be fine-tuned and configured for optimal performance.

In a manufacturing environment, local objects often cause loss of RF signals as they may absorb or reflect the RF signal. Therefore, the design of the interrogation zone and the configuration of RFID readers should consider the loss of RF signal in certain locations or directions. PLCM is such a technique that aims to create a contour map of RF signal strength in a specific location and helps understand how the actual RF signal propagates compared to how ideal signals behave.

The test setup for PLCM is shown in Figure 6-6. The spectrum analyzer is attached to a tripod one meter above the ground, an RF antenna is connected to an RFID reader and then placed one meter away from the spectrum analyzer. Receiving control signals from the reader, the antenna generates RF waves and broadcasts RF signals. Signal strength is measured in 8 circular directions by rotating the antenna around the spectrum analyzer while keeping the distance between the antenna and the spectrum analyzer constant.

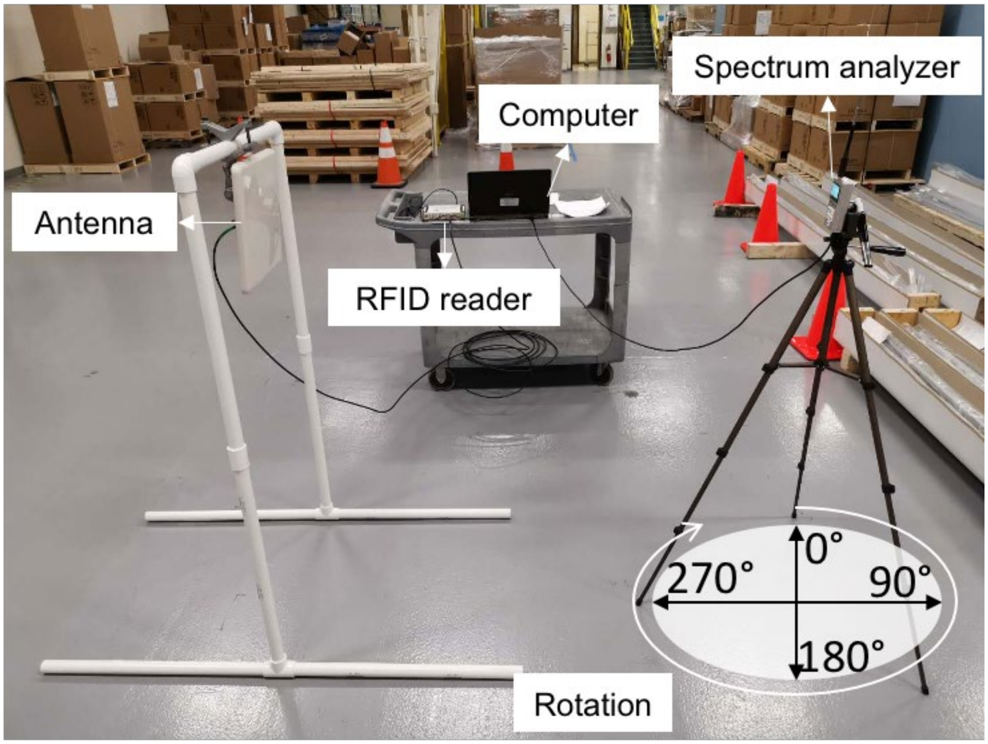


Figure 6-6: PLCM test setup. The antenna converts the electrical signals received from the reader into RF signals. Signal strength is measured by the spectrum analyzer in 8 circular directions by rotating the antenna around the spectrum analyzer. Picture shows the antenna facing at 270°.

Figure 6-7 left shows the measurement results of PLCM. It can be seen that RF signals at 90° and 270° are significantly weaker. Closer scrutiny reveals that metal goods stored in those two directions may absorb and reflect RF signals (see Figure 6-7 right). These results suggest that the antenna should be mounted in a position where it does not face or back against large metal shelves or massive metal goods. At this location specifically, it is appropriate to mount the antenna facing 0° or 180°.

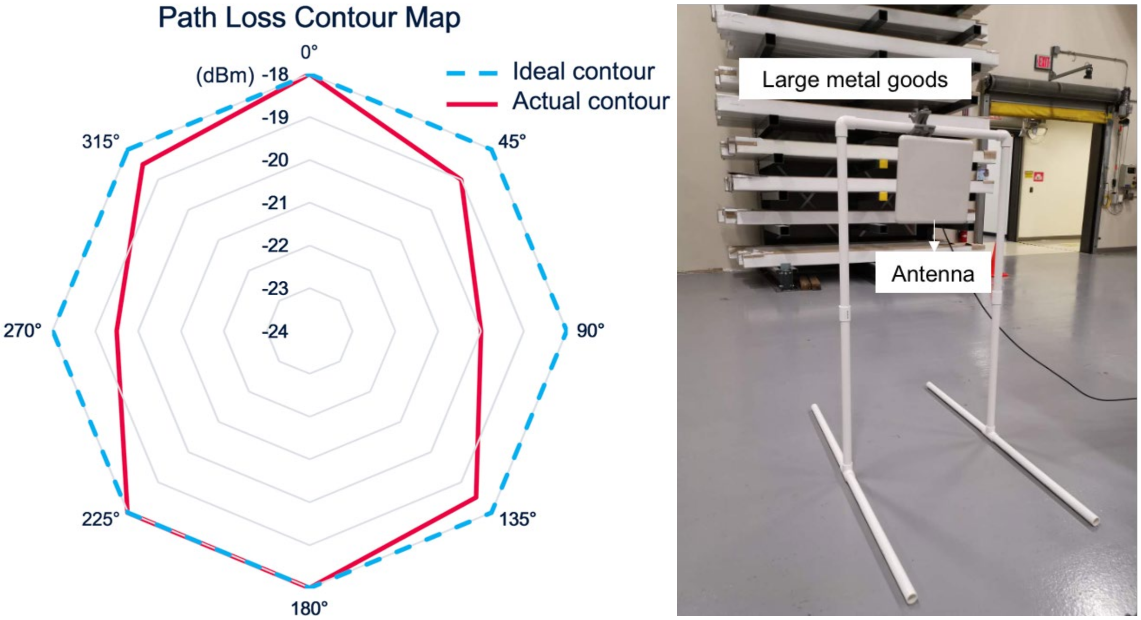


Figure 6-7: Measured path loss contour map (left) and interfering metal goods (right). RF signals at 90 ° and 270 ° are significantly weaker owing to metal goods stored in those two directions absorbing and reflecting RF signals.

6.3 System Design

6.3.1 What Comprises an RFID System for Waters?

As we introduced in Chapter 5, a typical RFID system consists of three key components: an RFID tag, a reader, and an antenna. See Figure 6-8.

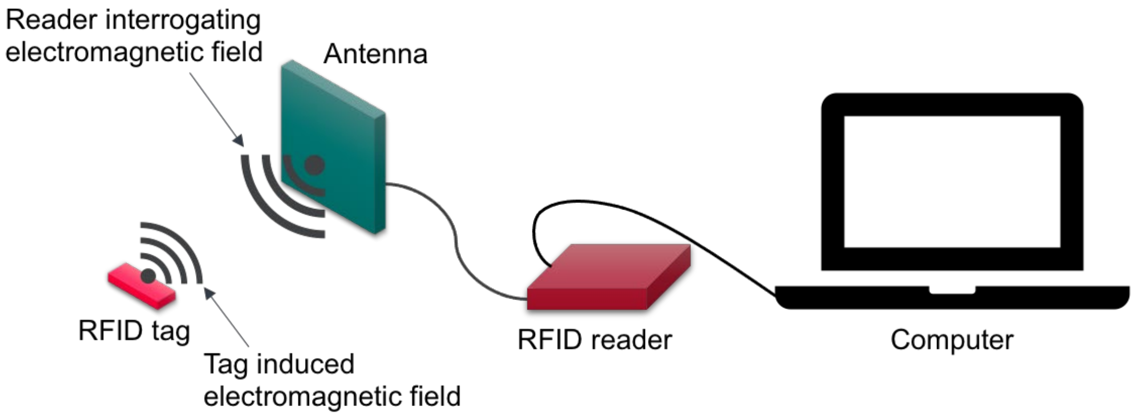


Figure 6-8: Key components of an RFID system

The RFID tag, also called the transponder, carries the encoded digital information of the items they are attached to and plays the most important role in industrial applications as their performance can vary within a wide range for different use cases. A typical RFID tag consists of four key components:

1) A face: a thin layer that covers the antenna and chip, usually made of transparent or white plastic, or paper;
2) A chip, usually an integrated circuit that is used to store the unique encoded information about the tag and the product it is attached to, such as electronic product code (EPC), so that it can be read, identified, tracked, or modified by RFID readers from a distance;
3) A tag antenna: usually a metal wire that transmits and receives radio waves. This internal antenna receives energy from the RF waves generated by the external antenna-reader couple and uses this energy to activate the RFID chip. The activated RFID chip then sends a signal back to the reader through the RFID antenna connected to the chip;
4) A substrate: a thin layer of transparent material that holds the antenna and chip together. Material and thickness can vary depending on the specific application scenario.

An exploded view of a typical RFID tag is illustrated in Figure 6-9.

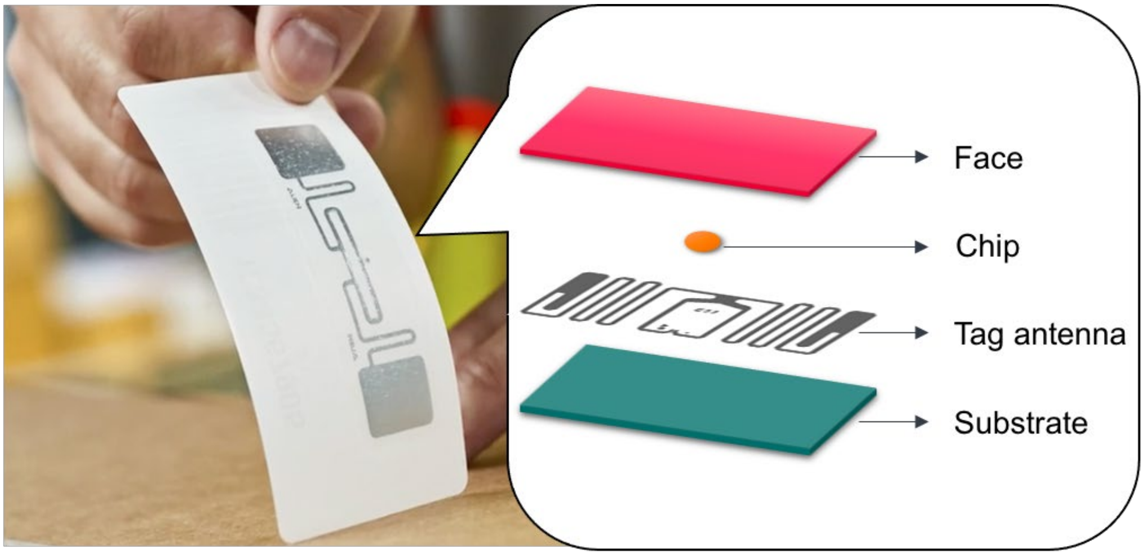


Figure 6-9: An exploded view of a typical RFID tag

Depending on different application scenarios, it is very important to select the right type of RFID tag with an appropriate combination of all four components, especially the tag antenna and substrate, as they significantly affect reading performance in different usage scenarios. The next few sections describe the tag selection process and the determination of antenna pattern, without which a proper RFID network cannot be designed.

6.3.2 Tag Selection

One challenge to successful RFID implementation in the eKanban system at Waters is metal interference with radio communication. The materials transported through the eKanban process are mostly metal parts. As metal parts are heavy, the carts or racks carrying them are also made of metal, ensuring stable and safe transportation. Although RFID works well in most application scenarios, e.g., on wood, plastic, cardboard, and glass, attaching RFID tags on a metallic surface can be problematic. A metallic surface can actively absorb and reflect RF waves and the energy they carry, detuning the RFID tags or creating interference with them by changing their radiation pattern, input impedance, radiation efficiency, and resonant frequency [11]. The interference in the communication between the tag and the reader can significantly undermine performance.

To make RFID applications more adaptable in such situations, several manufacturers have designed specific RFID tags that work in proximity to metal. Unlike paper label RFID tags, metal-mount RFID tags have a spacer built in the substrate to shield the tag antenna from touching the metal directly, for example, by a thin layer of foam. This makes the metal-mount tags larger, thicker, and more complex to produce. Given the higher cost of these tags specially designed to work on metallic surfaces, industry applications are limited in scope. Traditionally, on-metal RFID tags are used for high-value asset identification and logistics tracking by labeling laptops, mobile phones, medical devices, servers, and vehicles in a variety of industries. However, with the recent developments in RFID technology, costs have been greatly reduced, making on-metal RFID applications more affordable and popular.

To select the most appropriate type of RFID tag, thirteen commercially available passive UHF RFID tags were tested, including paper label tags and hard tags (sealed by plastic shell to protect the functional RFID inlay from harsh environments), with various combinations of chip, antenna, and substrate design, as shown in Figure 6-10.

Figure 6-10: RFID tags with different sizes, built-in antenna shape, and coverage materials were tested to ensure a diversified and representative sample pool.

Tests are conducted on two metrics. First, the read sensitivity of each tag type is tested by measuring the minimum antenna power output required to activate the tag with a test range of 10 to 30 dBm, or in other words, 0.01 to 1 Watt. Second, the read rate of each tag type is tested at a fixed antenna power output of 30 dBm, indicating how many read transactions per second a particular tag can perform given a fixed input signal. A higher read rate represents a more frequent communication between the tag and the antenna, and therefore a higher chance of successful read transaction in any scenario. For the rack-level implementation, in particular, this is a good metric for testing tag reading performance, as only one tag per rack is used and the traditional test of reading completion time will be completed in less than one second for most tag types, making it difficult to determine the difference in the performance of different tags.

The test setup is shown in Figure 6-11. Tests are conducted by placing the antenna in front of the tag type and attaching each tag type on a steel mesh piece held by a tripod, simulating the real case for eKanban racks. All tests are completed with a fixed tag-antenna distance of 1 meter. Read sensitivity and read rate of each tag type are measured by the antenna. The test results are illustrated in Figure 6-12.

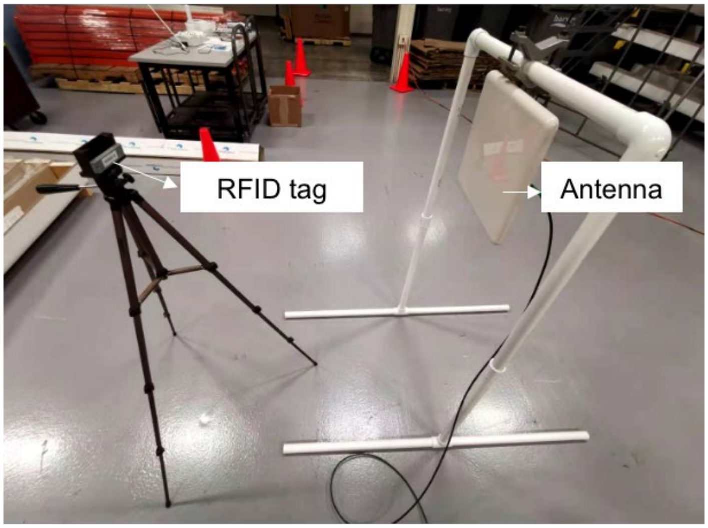


Figure 6-11: Tag selection test setup. The antenna and the RFID tag being tested are placed face to face. Read sensitivity and read rate is measured for each tag type.

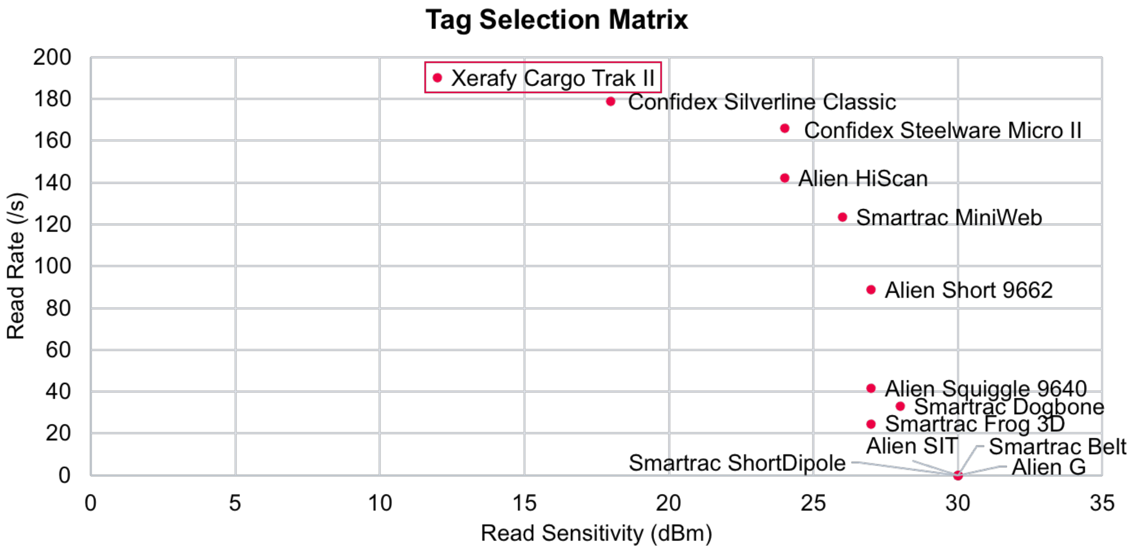


Figure 6-12: Tag selection matrix is used to select the best performing tag type. Each point represents a tag type's performance in two metrics. On the horizontal axis, read sensitivity of each tag type is obtained by measuring the minimum activating antenna power output. On the vertical axis, read rate is measured at a fixed antenna power output of 30 dBm. A well-performing tag type should have both high read sensitivity (low activating power output) and high read rate.

As shown by the test results in the tag selection matrix, the tag type "*Xerafy Cargo Trak II*" is clearly the best performer in respects of both read sensitivity and read rate, and thus, selected as the tag type for the rack-level RFID implementation.

6.3.3 Determination of Antenna Radiation Pattern

Antennas create electromagnetic fields to emit radio waves. Electromagnetic radiation is dipole radiation, meaning the strength of the radio waves from the antenna shows directional or angular dependence. Therefore, the antenna radiation pattern of both the RFID antenna and the in-tag antenna must be determined in order to design the most appropriate relative position of tag and antenna.

The radiation pattern of the selected tag type, *Xerafy Cargo Trak II*, is provided by the tag manufacturer [12] and illustrated in Figure 6-13. As can be seen from the plot, the antenna read ranges are determined at a number of angles, normalized to the longest range and given in percentage. The maximum read range is found at 12 o'clock or 0 degrees; as the angle increases, the read range gradually decreases until it reaches its minimum at 6 o'clock, or 180 degrees. Therefore, the angular dependence of this tag type's radiation strength is clear, as a longer read range results from a stronger signal transmission.

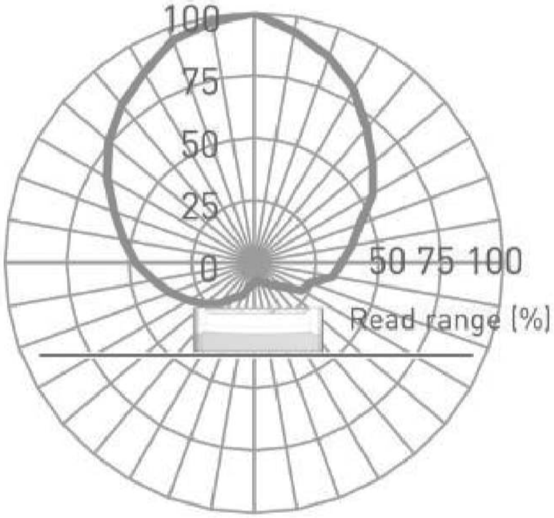


Figure 6-13: Antenna radiation pattern of selected tag type, Xerafy Cargo Trak II [12]. The antenna read ranges are determined at various angles and normalized. The plot clearly shows the angular dependence of the tag's radiation strength. The longest read range is observed at 0 degrees.

However, the radiation pattern of the RFID reader antenna is not provided and is to be determined through an antenna radiation test. The test setup is shown in Figure 6-14 left. A tripod is used to hold the spectrum analyzer at 1.5 meters from the ground, the same height as the RFID reader antenna. The distance between the spectrum analyzer and the antenna is also kept at 1.5 meters. Keeping the relative distance constant, the spectrum analyzer is rotated around the antenna. Measurement of radiation strength is conducted every 5 degrees. The measurement results are shown in Figure 6-14 right.

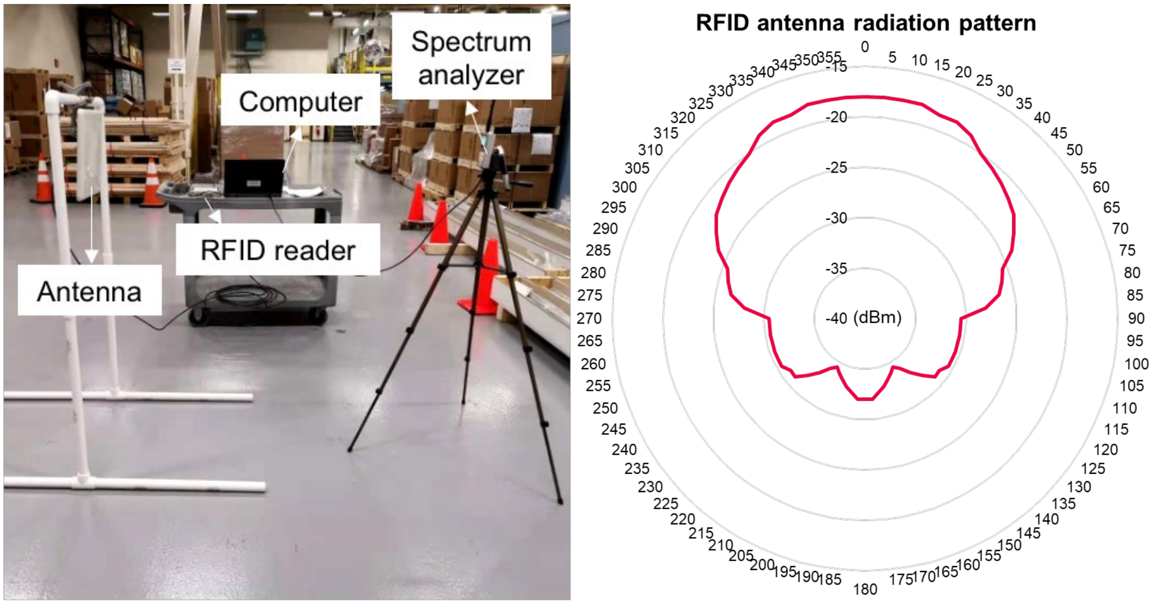


Figure 6-14: Antenna radiation pattern test setup (left) and results in absolute signal strength in decibel milliwatts (dBm) (right). A strongly direction-dependent radiation pattern is shown with the strongest signal observed at 0 degrees.

The results suggest a strongly direction-dependent radiation pattern of the RFID reader antenna. Although different from the tag antenna radiation pattern, both show the strongest signal (called the main lobe of radiation) at 0 degrees, i.e., perpendicular to the antenna face, decreasing towards the sides. This provides a good guide to the tag/antenna position design in the next step.

6.3.4 Tag/Antenna Position Design and Testing

The tag/antenna position design for rack-level implementation is discussed in this part. Based on the antenna pattern, the most promising design should ensure an antenna-tag interaction in both of their main lobes of radiation. Therefore, a face-to-face placement of the antenna and the tag is desired. Taking this into consideration, three alternatives are proposed, including side-side, top-top, and bottom-bottom placement, as shown in Figure 6-15.

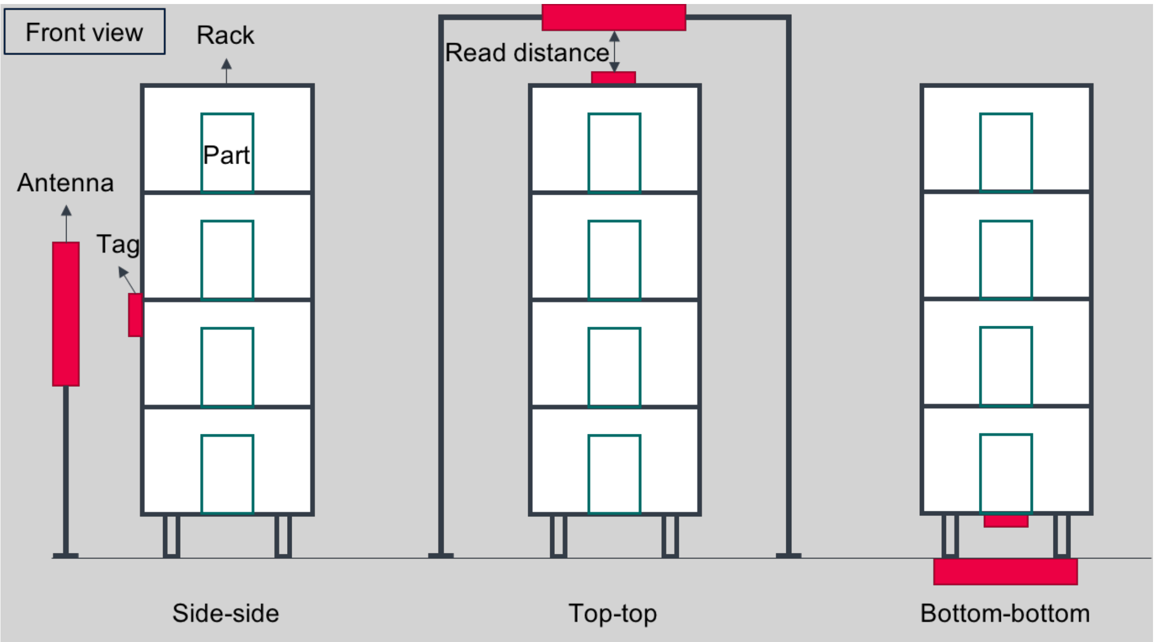


Figure 6-15: Three tag/antenna position design alternatives

After discussion with site managers, the bottom-bottom plan is eliminated, as the antenna must be placed either on or underneath the ground, leading to hindering regular personnel and material movement or destruction of the ground, respectively. Besides, the tag is not easily visible from the bottom of the rack, resulting in difficulty detecting a potential loss of the tag.

The remaining two alternatives are tested consequently.

First, the optimal read distance needs to be determined. As shown by the antenna pattern, the antenna radiation has different power outreaches in each direction, leading to a face-to-face design. However, material flow such as rack movement is a dynamic process; the tag is not always read from 0 degree or perpendicularly from the antenna. In fact, the tag always approaches the antenna from the side, enters the intersection area of the radiation pattern of both the RFID reader antenna and tag antenna (called the radiation zone), passes the perpendicular position and leaves the radiation zone. It is desirable that a tag stays in the radiation zone as long as possible to enable more read attempts and reach a higher confidence of a successful read. Therefore, a good tag/antenna position design should maximize horizontal read distance for a wider oblique read zone at optimal perpendicular read distance.

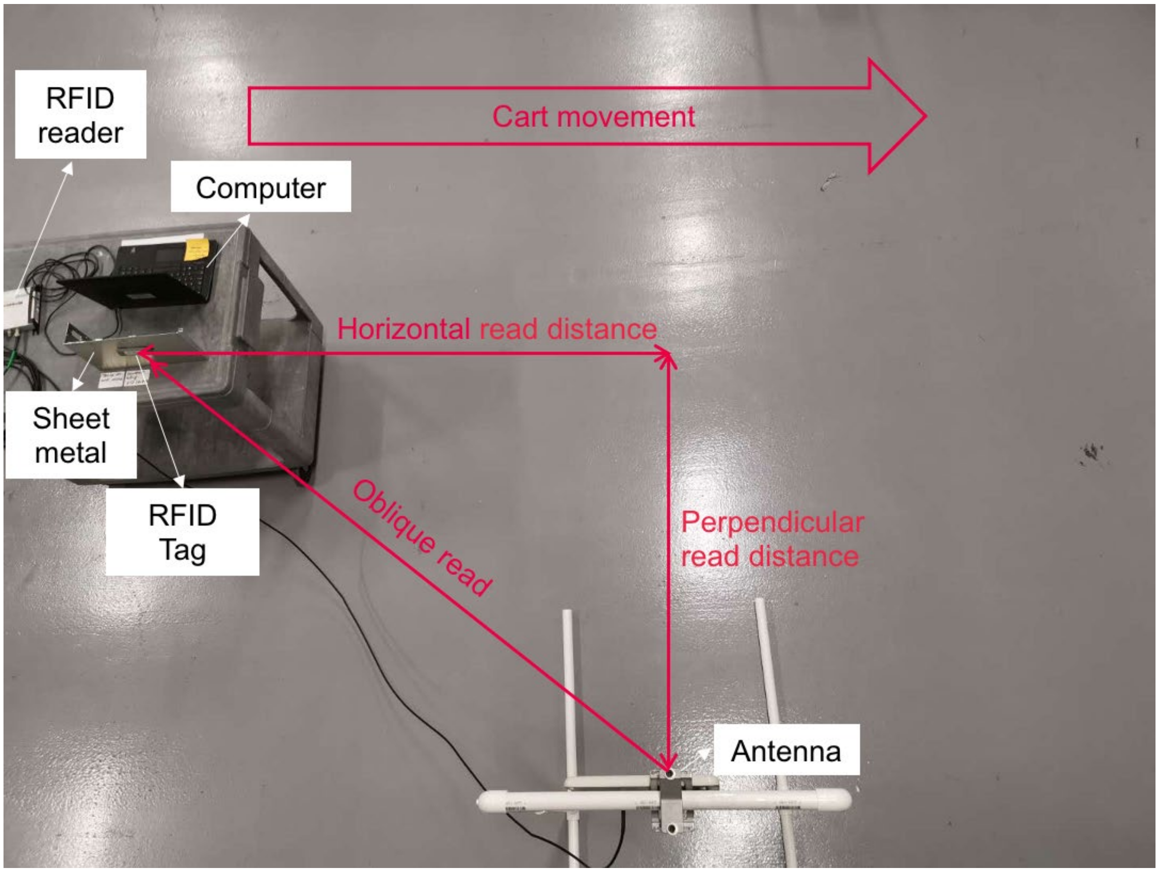


Figure 6-16: Optimal read distance test setup

To conduct the optimal read distance test, an RFID tag is attached to a sheet metal chassis on a plastic cart, as shown by the test setup in Figure 6-16. The cart is moved along a straight line and as soon as the first read of the tag is recorded, the corresponding distance of the tag from the antenna is noted. The horizontal read distance is recorded at different levels of perpendicular distances between the antenna face and the tag plane. Figure 6-17 shows the results of the optimal read distance test.

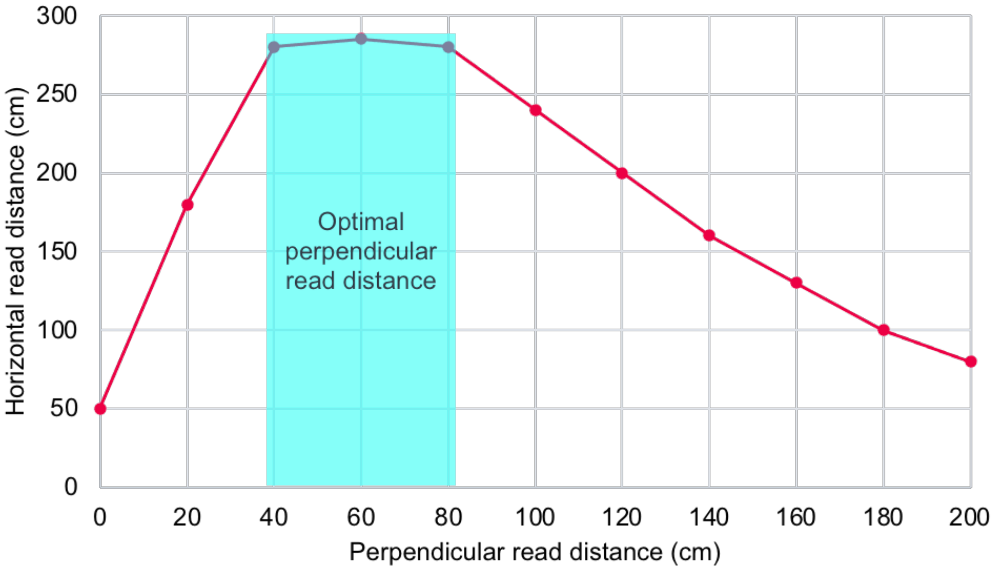


Figure 6-17: Optimal perpendicular read distance test results. The maximum horizontal read distances are reached when the perpendicular read distance is between 40 to 80 cm, allowing the longest oblique read time.

The test results show the optimal perpendicular distance between the antenna and the tag should be between 40 to 80 cm, as this is the interval that allows the maximum horizontal travel distance of the tag within the radiation zone, and thus, the longest oblique read time. Figure 6-18 compares the tag/antenna radiation zone and optimal tag movement zone in absolute meter values as a result of the test.

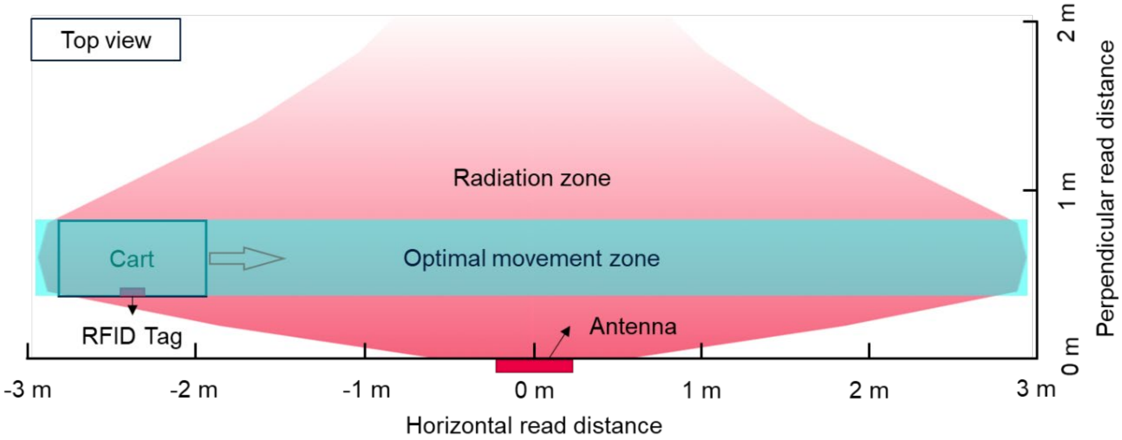


Figure 6-18: Radiation zone vs. optimal movement zone, derived from the optimal read distance test results. The radiation zone is the intersection of the radiation

patterns of the reader antenna and the tag antenna. This figure only includes the radiation zone within 2 meters of the perpendicular read distance.

Knowing the optimal read distance interval, the next step is to determine which design alternative delivers better read performance. Similar to the test for tag selection, the read rate is measured and compared between the proposed two alternative position design plans, side-side and top-top, as shown in Figure 6-19.

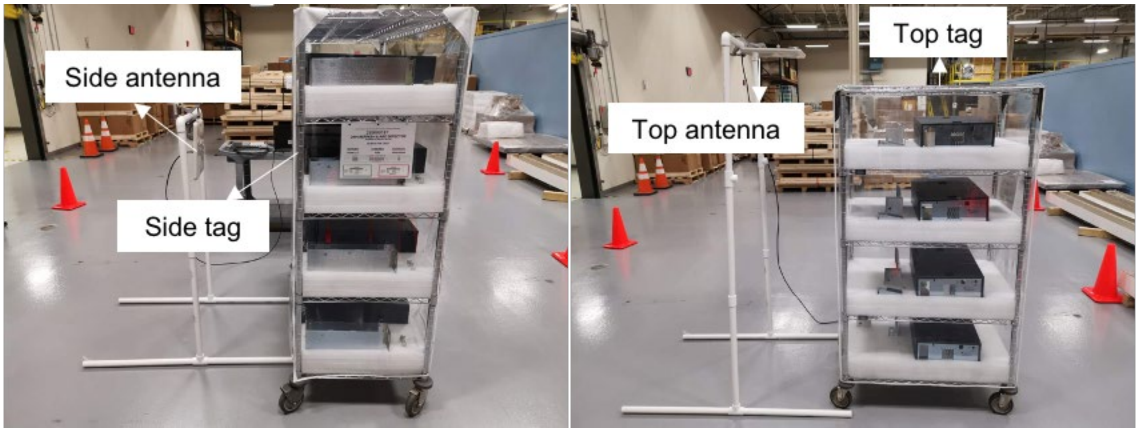


Figure 6-19: Side-side (left) and top-top (right) position designs

Three test series were conducted for each tag/antenna position combination with various antenna-tag distances within the optimal perpendicular read range including 40 cm, 60 cm, and 80 cm, to see if there is any unexpected interaction effect. Each test series consists of 10 individual tests, and each test is carried out by pushing the rack with an approximately constant walking speed of 5 km/h or 1.4 m/s. The average read rate and standard deviation (expressed as a percentage to ensure comparability) are calculated and compared, as shown in Figure 6-20.

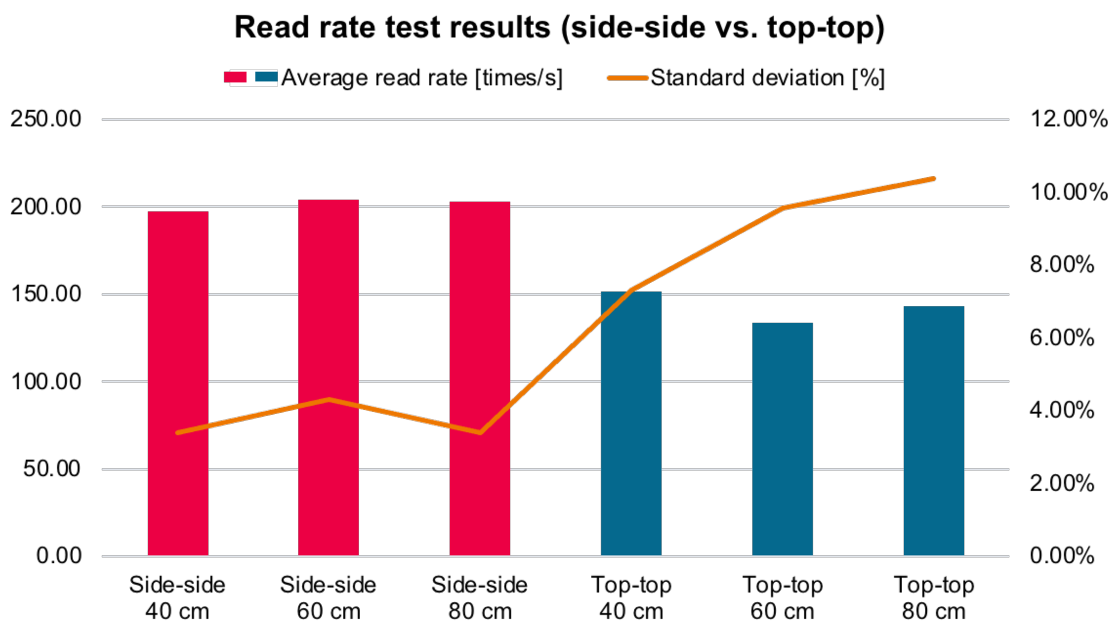


Figure 6-20: Read rate test results (side-side vs. top-top). The average read rate (in times/second) and standard deviation (in percentage) are compared. The side-side position design performed better with higher read rate and lower read rate variation. No significant difference between different read distances is observed in the given range.

The results reveal a superior performance of side-side position design for each distance tested regarding average read rate and its standard deviation, indicating the side-side paired location is a stronger and more robust design. The difference could result from the denser metal grid on the top of the rack that interferes more with the RF communication between the antenna and the tag. Besides, the results also confirm no significant difference between different read distances from the optimal read range.

However, risks exist for side-side location design as the tag could be attached to the rack on the opposite side, resulting in a back-to-face radiation intersection. To clarify the effect of this risk source, the same read rate test for this scenario was also conducted and compared to the face-to-face design. Figure 6-21 shows the test results.

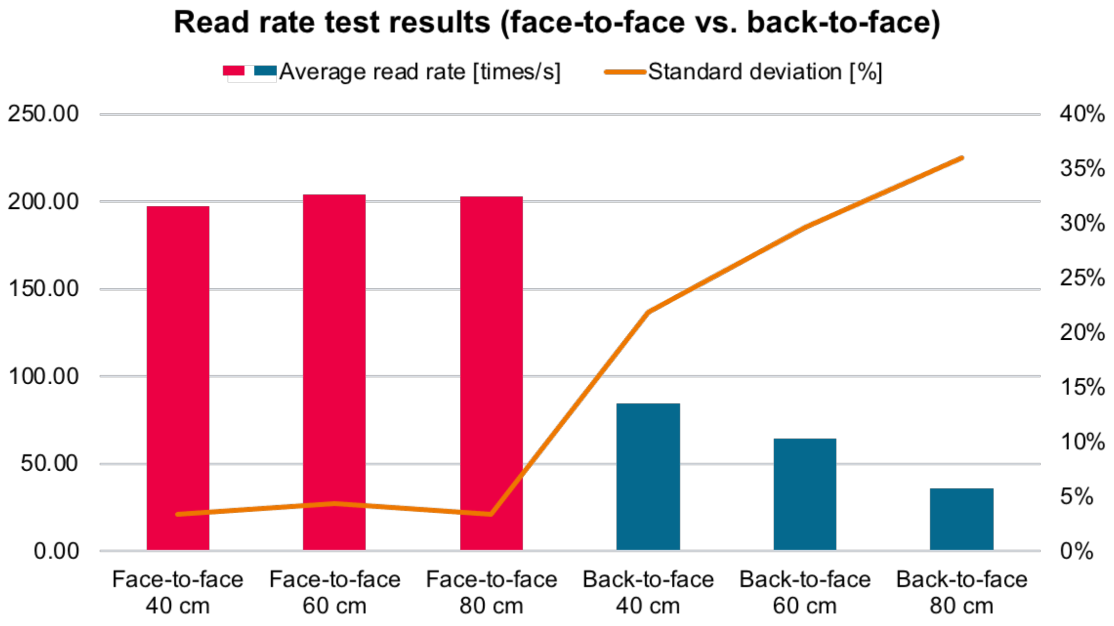


Figure 6-21: Read rate test results (face-to-face vs. back-to-face). The average read rate (in times/second) and standard deviation (in percentage) are compared. Having a higher read rate and lower read rate variation, the face-face position design performed much better than the back-back design. No significant difference between different read distances is observed in the given range. The test results suggest an RFID network with two face-to-face side antennas.

The results show a significantly inferior read performance for the back-to-face scenario of the side-side position design, as the back-to-face design has a lower read rate and higher read rate variation. This is a foreseeable outcome as the antenna radiation patterns have minimal intersection area in the back-to-face scenario. Therefore, two antennas are needed for a robust system design with one on each side.

In conclusion, the side-side position design with two antennas on each side of the entrance is shown to be most appropriate. Given the width of the rack of about 60 cm, the two antennas can be mounted 140 to 220 cm away from each other, ensuring the optimal read distance of 40 to 80 cm on each side.

6.3.5 Pilot Implementation

The pilot implementation for the rack-level RFID system is demonstrated at a selected supplier interface location (see Figure 6-22). According to the test results and the determined system design, the pilot RFID network installed at the supplier interface entrance consists of an RFID reader, two face-to-face antennas connected to the reader, and a number of *Xerafy Cargo Trak II* tags attached on the side of the eKanban racks. Several belt barriers are used to enclose the supplier interface area.

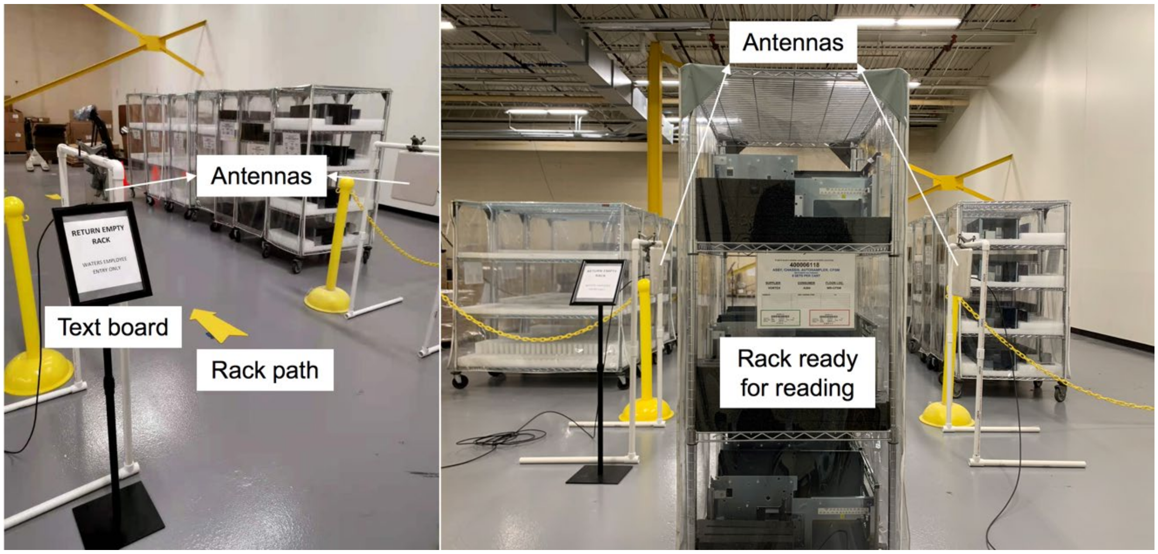


Figure 6-22: An RFID network at the supplier interface. Two face-to-face antennas are connected to a central RFID reader and are placed at the entrance as a gate.

For the rack-level implementation, the supplier interface area has two gateways, one for Waters employees to return empty racks and the other for other material movement actions such as material replenishment by suppliers. A text board is placed at the Waters employee's entrance, indicating this is the entrance for Waters employees to return the empty racks. Upon entry, the RFID tag on the empty rack will be read and updated to the information system automatically, requesting material replenishment. A temporary arrow sign is placed at the Waters employees' entrance to guide the one-way-only material movement direction. Very soon, a one-way swing gate with an infrared sensor will be mounted to make this process more reliable and mistake-proof (see Figure 6-23).

Figure 6-23: A one-way swing gate [13]

It is also worth mentioning that the supplier interface area implements 5S, a workplace organizational and housekeeping methodology that keeps the workplace clean and safe, improves workplace efficiency, and eliminates waste.

- Sort: Unnecessary items such as non-eKanban inventory or toolboxes are removed from the supplier interface area to keep the area free of obstacles.
- Straighten: All racks are placed in designated positions using aisle markings according to a numbering sequence like a library system to ensure fast positioning.
- Scrub: The supplier interface is cleaned regularly to remove grease and oil stains.
- Standardize: 5S is incorporated in standard operating procedures (SOP).
- Sustain: Regular cleaning and maintenance work is scheduled using SOP to ensure everything is clean and in place.

With the rack-level implementation, human errors emerging from the flawed manual scanning process are eliminated and the information flow of the eKanban system is improved. Not only does it greatly improve the material availability and reduce the inventory level at Waters Milford facility, but it also provides a more automated and reliable eKanban process that vendors are more willing to be involved in. Besides, the newly designed supplier interface achieved a three-fold expansion of the eKanban storage capacity, allowing many more vendors and SKUs to be incorporated in the eKanban system.

Chapter 7

Looking into the Future: Item-Level System Design and Implementation

7.1 Rack-Level versus Item-Level

Material flow optimization cannot be performed without accurate data from information flow. With the rack-level implementation, the issue of information flow delay generated by human errors is well addressed. However, information delay still exists from a systematic perspective caused by a lack of transparency in the company's primary in-house operations.

Systematic delay of information in SAP has been an issue at Waters for a long time. Manufacturing companies usually use SAP to keep track of the flow of materials such as inventory and WIP, but this only works if the comprehensive information of the material is captured, uploaded to SAP, and updated throughout its flow path. The current practice at Waters, however, is that the material flow information only gets updated in SAP at the first and final stages of material movement when they are scanned; anything in-between is a black box. Also, material information is only updated at the rack-level; individual part movement or consumption data within a rack is not available. Although the rack-level RFID eliminates human errors along the process, the low visibility of the current material flow is causing difficulties in supply chain coordination and production planning.

Therefore, comprehensive material flow tracking across all major operational stages is desirable as it would allow upstream traceability and data analysis of critical processes, further streamlining material flow, planning, and controlling.

Tracking and visualizing material flow across the whole process only makes sense when we break rack-level observation into item-level, as the change between the full and empty states of the rack does not accurately and comprehensively represent individual part movement or consumption. Therefore, in order to increase the visibility of material flow information to a broader extent, an item-level RFID solution is proposed in this chapter and can be adopted in the future.

To realize an item-level RFID deployment, an RFID tag will be attached on each part and readers will be installed at designated locations where material flows from one operation to another in Waters Milford facility. In this way, material movement information at each operational step from receiving dock over warehouse and assembly line down to packaging and outbound shipment can be automatically captured, uploaded to SAP and made visible to various engineers, planners, and management across the organization.

Although the previously discussed challenges still exist for item-level RFID implementation, this chapter aims to present a technical study and guide for future adoption.

7.2 System Design

The system design process of an item-level RFID network is similar to the rack-level approach documented in Chapter 6. and some of the rack-level test results can also be insightful for the item-level design. First, locations of interest where RFID networks will be installed are selected and evaluated; second, the most meaningful RFID tag type for item-level implementation is selected; third, various tag/antenna position combinations are tested and the most appropriate one is selected

7.2.1 Location Selection

Selecting the right locations to install RFID networks is critical for an efficient material flow tracking. A good RFID system should give management and engineers correct and prompt information on inventory level and WIP to identify and correct process bottlenecks and inefficiency. Therefore, three key locations are selected to install RFID network at Waters Milford facility:

1) **Supplier interface**: Materials flow through the supplier interface as raw materials. An RFID network mounted here can be used to inventory the incoming material into SAP and conduct eKanban inventory screening or shrinkage checking;
2) **Corridor to assembly**: Materials flow through the corridor to assembly as WIP. With information of number and kinds of WIP continuously updated to SAP, production and procurement planning can be completed in a more accurate and agile manner;
3) **Conveyor belt**: Materials flow through the conveyor belt as finished products. As the assembly process is completed, the final products are transported to the kitting and shipping area via the conveyor belt. The material information read from the RFID labels can allow the SAP system to prepare outgoing shipments and keep track of product lead time.

Figure 7-1 shows the pictures of these locations. Site assessment was performed at the corridor to assembly and conveyor belt following the same procedures for the supplier interface at the rack-level design. No abnormal RF activity or notable interference was identified, as there is no machine operation at these locations.

Figure 7-1: Selected locations. From left to right: supplier interface, corridor to assembly, and conveyor belt.

7.2.1 Tag Selection

The item-level RFID implementation has more challenging requirements on tag selection than rack level. In addition to the two critical criteria, read rate and read sensitivity in metal environments, the main difference lies in the fact that the item-level design must meet the demands of fast, high-volume applications since the tags are placed on individual parts rather than on racks, and the number of tags consumed will reach a higher order of magnitude compared to the rack-level design. This poses significant challenges in terms of unit price and encoding speed of the tag.

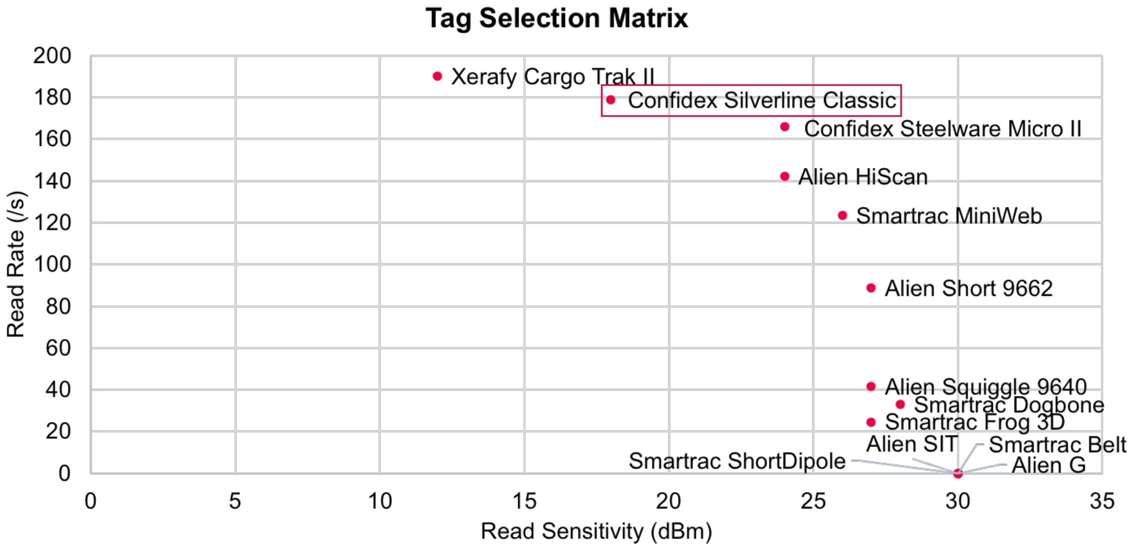


Figure 7-2: Tag selection matrix. The second best-performing tag type is selected as it is printable and more affordable for the high-volume item-level use.

Using the same tag selection matrix presented in Chapter 6, the *Confidex Silverline Classic* is chosen over the *Xerafy Cargo Trak II* for the item-level design, see Figure 7-2. This tag delivers excellent (second best) metal-compatible performance in both tests, and it is also

1) printable and encodable with compact equipment, i.e., the RFID "printer";
2) less expensive than the *Xerafy Cargo Trak II*, making it more affordable for the high-volume item-level use.

Therefore, the *Confidex Silverline Classic* fulfills all challenging criteria and is considered the most appropriate tag type for the item-level RFID implementation.

7.2.2 Tag/Antenna Position Design and Testing

Based on the experience of the successful rack-level tag/antenna position design, the following alternatives are proposed and tested sequentially for the item-level tag/antenna position design:

1) Tag position (on each individual item, as shown in Figure 7-3)
   a) Top
   b) Front/back
   c) Side
2) Antenna position (relative to individual items)
   a) Top, one antenna
   b) Side, one antenna
   c) Side, two face-to-face antennas

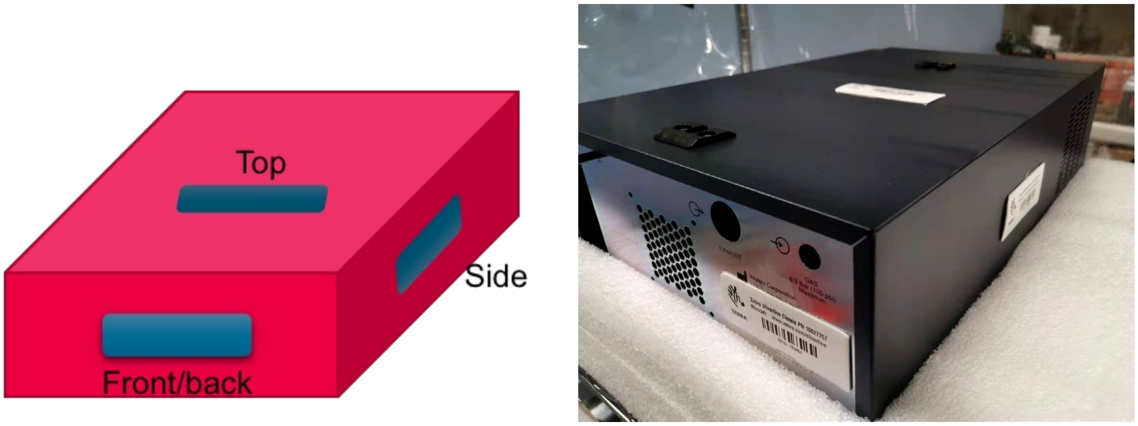


Figure 7-3: Tag position alternatives (top, front/back, and side)

Unlike the rack-level design where the read rate of a single tag is measured, read completion time is used as the performance metric for the item-level design because multiple items are read simultaneously. The best item-level position design should give the shortest read completion time and allow a smooth, uninterrupted material movement.

Each tag/antenna position combination is tested, resulting in nine test series in total (three antenna positions times three tag positions). Each test series consists of 10 individual tests, and each test is carried out by pushing the rack with an approximately constant walking speed of 5 km/h or 1.4 m/s. For all tests, perpendicular read distance is kept at 80 cm and the antenna power output is set to 30 dBm, equivalent to 1 Watt. Considering the number of eKanban parts in one rack varies for different kit types and ranges from 4 to 12 parts, all tests are performed with a maximum number of 12 tagged parts representing the most challenging case scenario. The read mode “AutoSet Dense Reader Deep Scan” is selected as recommended by the reader manufacturer as it can optimize the reader's configuration automatically and dynamically. (The hypothesis that using this read mode would result in the best read performance will be tested in the next section.) The average read completion time for each test series is provided in Table 7-1, illustrated and compared in Figure 7-4.

Table 7-1: Read completion time (s) test results

Tag location / Antenna location	Top	Front/back	Side
Top, one antenna	>5	>5	>5
Side, one antenna	4.5	2.3	1.3
Side, two face-to-face antennas	3.6	1.8	0.5

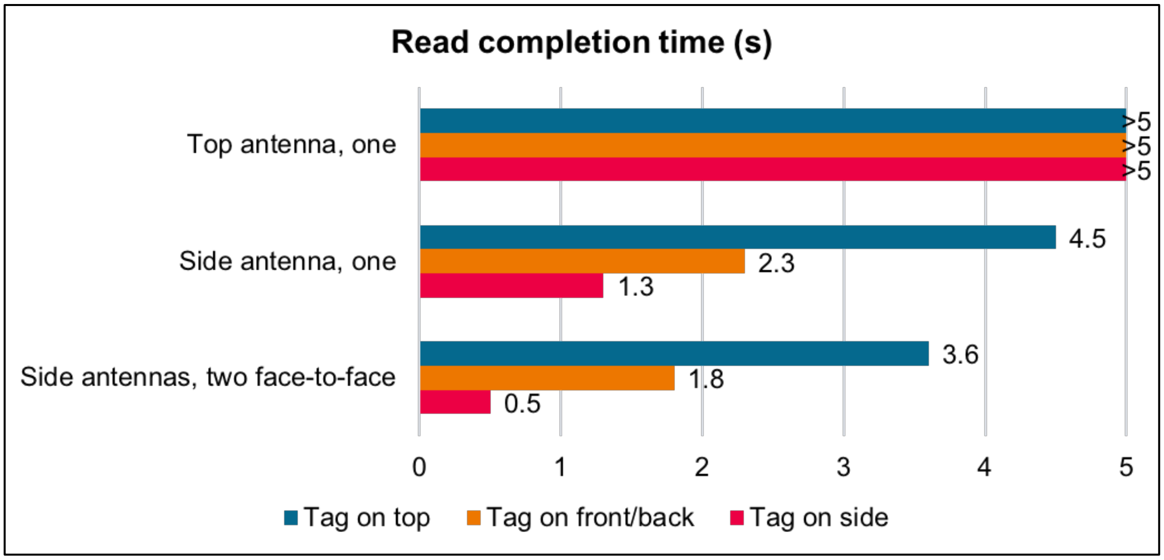


Figure 7-4: Read completion time for various tag/antenna position combinations. The side-side design performed the best with the shortest read completion time.

The side-side combination, again, shows superior performance as it takes the least time to complete the reading of all tags in the rack. This result can be interpreted in two steps:

A first look at the chart shows two face-to-face antennas on the sides deliver the best performance in terms of read completion time, regardless of the tag position. Compared to one antenna on the side, two antennas provide larger radiation zones and therefore tags on different places of the rack can be captured by either of the antennas quickly.

On the other hand, it is clear that placing the antenna above the rack is not a good idea. During the test, when the antenna was placed from the top of the rack, it was impossible to complete the reading of all the tags in most replicates, and when it was done it took a very long time. Further study revealed that the few tags on the bottom level of the rack were often difficult to read because they were away from the antenna by many layers of metal parts and metal mesh, which greatly hindered signal transmission of radio waves, as shown in Figure 7-5 left.

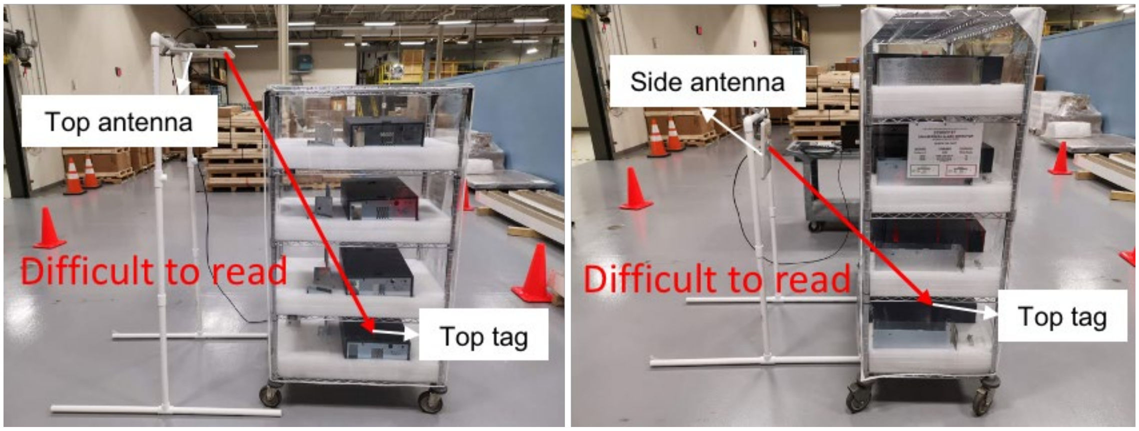


Figure 7-5: Difficulty in reading tags at the bottom level of a rack as the metal parts and metal mesh of the rack hinder signal transmission of radio waves

Secondly, placing a tag on the side of each item performs the best across all tested scenarios, especially with two side antennas: an average read completion time of 0.5 seconds is excellent. This makes sense as it allows the antenna-tag communication to stay in the intersection area of their radiation patterns for the longest time. On the other hand, placing a tag on the top of each item performs the worst even with two side antennas, as the antennas take longer to read the tags at the bottom level of the rack from an angle where communication is hindered by metal above, as shown in Figure 7-5 right. Figure 7-6 also illustrates the longer read completion time of the tag-on-top design because of the longer read time of a few particular tags at the bottom.

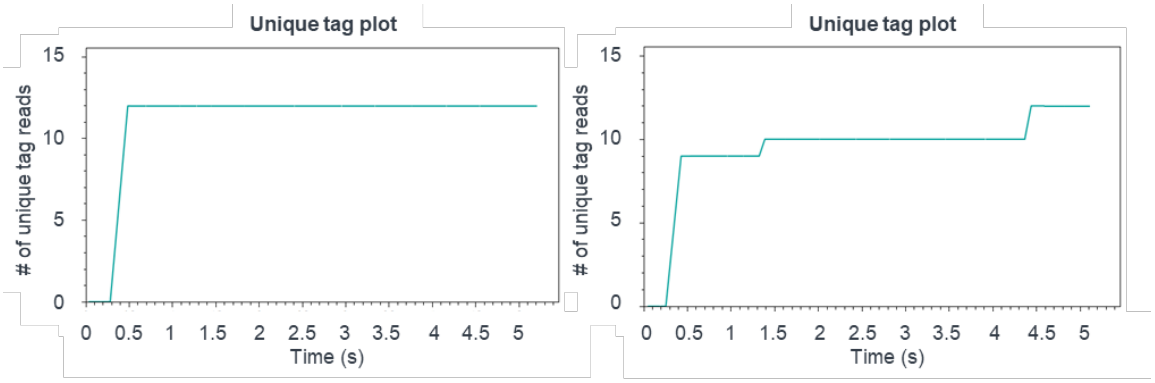


Figure 7-6: Unique tag plot: side antenna with tag-on-side (left)/tag-on-top (right). The longer read completion time of the tag-on-top design indicates the difficulty in reading the few tags at the bottom level of the rack

In conclusion, the position combination with two antennas on the sides and tag attached on the side is proven to be the most satisfactory design, completing reading of all tags within 0.5 seconds. As we plotted in Chapter 6, the width of the radiation zone is about 6 meters. At a movement speed of 1.4m/s (normal human walking speed), the materials and the tags should stay within the radiation zone for more than 4 seconds. With the selected position design, therefore, a complete reading of all tags in a rack is guaranteed.

7.2.3 Read mode test

Unlike the rack-level design, read mode at item-level can significantly affect the read completion time, as multiple tags are being read simultaneously, posing more challenges to the reader configuration.

The RFID reader manufacturer provides various read modes for the reader used in this thesis. Different read modes are optimized for different application scenarios where factors such as the number of readers used in the environment, tags dynamics, etc. vary. During the previous test, the read mode “AutoSet Dense Reader Deep Scan” is selected as recommended by the manufacturer, given this mode’s ability to cycle between a subset of reader modes, continuously optimizing the reader's configuration and selecting the most appropriate configuration settings for various application scenarios. To prove the hypothesis that for the item-level design this read mode delivers the best performance among the eight read modes provided, a read mode test is conducted based on previous test setup and methodology used by tag/antenna position test with the best performing side-side design. Read completion time for each tested read mode is shown in Figure 7-7.

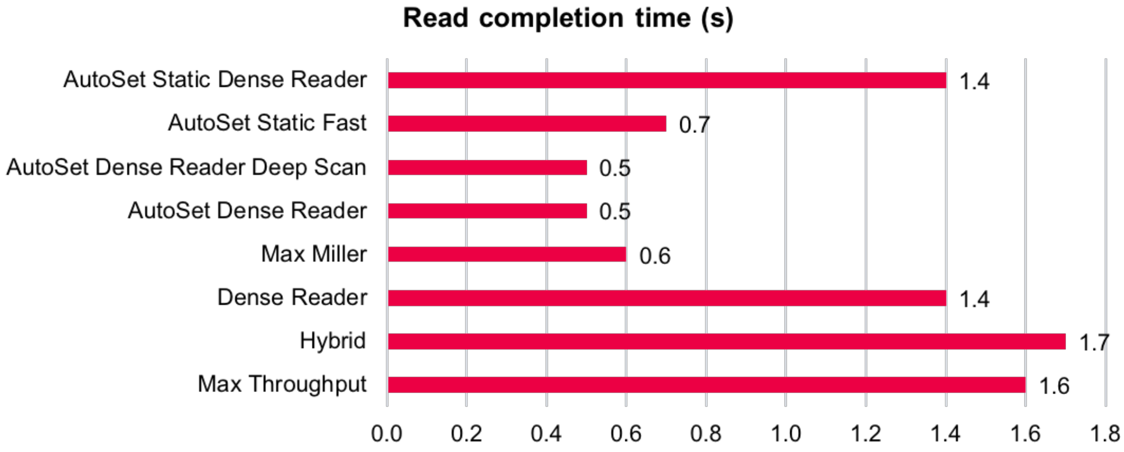


Figure 7-7: Read mode test results. Read completion times for eight different read modes are recorded in seconds. The read mode “AutoSet Dense Reader Deep Scan” and “AutoSet Dense Reader” deliver the best performance, i.e., the shortest read completion time of 0.5 seconds

As can be seen from the comparison, the read mode “AutoSet Dense Reader Deep Scan” and “AutoSet Dense Reader” deliver the best performance, validating the proposed hypothesis. This should result from their ability of automatic and dynamic optimization and selection of the reader's configuration, while other read modes are configured towards specific application scenarios that do not apply to the designed eKanban process.

7.2.4 Pilot Implementation

The pilot implementation is demonstrated at the selected locations critical to material flow at Waters Milford facility, including the supplier interface, the corridor to assembly, and the conveyor belt. Figure 7-8 shows three RFID networks installed at those locations. According to the test results and the determined system design, each of the RFID networks consists of a reader, two face-to-face antennas, and a number of *Confidex Silverline Classic* tags attached on the side of the individual eKanban parts.

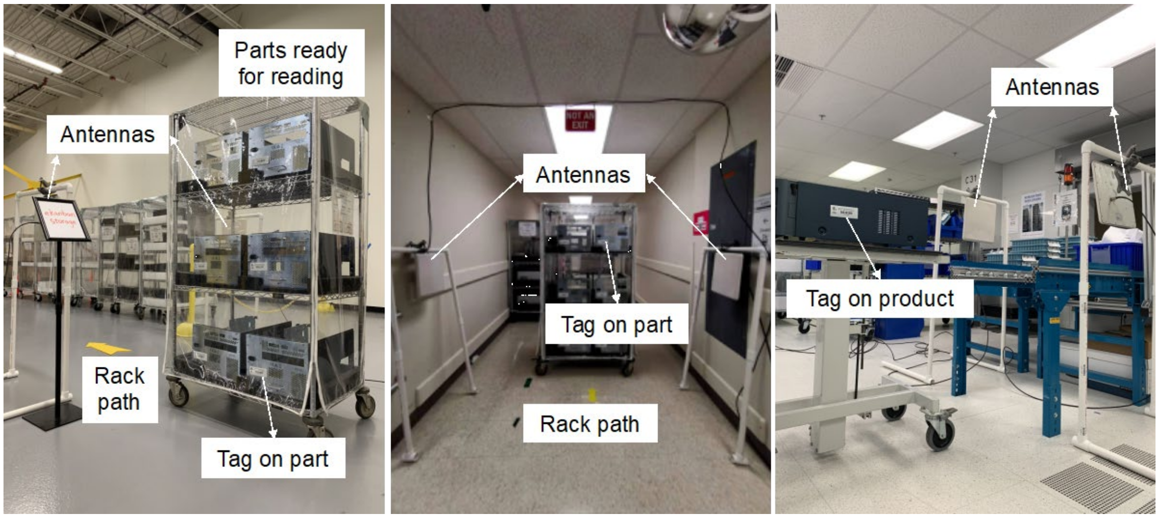


Figure 7-8: Implementation at selected locations. From left to right: supplier interface, corridor to assembly and conveyor belt

Unlike the rack-level implementation, the item-level supplier interface area has only one gateway entrance. Upon entry in the supplier interface area, refilled racks with RFID tagged parts are read into inventory automatically, updating the current inventory level continuously. When the racks are moved to the assembly area passing the RFID network installed at the corridor, individual part information is identified and the quantity of WIP is updated in the information system, ensuring accurate and agile production scheduling and capacity planning. As the assembly process is completed, the final products transported via the conveyor belt are read by the RFID network there for outgoing shipment tracking. Thus, a facility-wide material tracking is achieved, and the material flow visibility is improved throughout the supply chain.

Chapter 8

Data Integration and Interpretation

In a dynamic manufacturing environment, data is the most valuable asset. With the proposed and implemented RFID systems, a large volume of material flow data is collected and stored continuously throughout the production processes. Many manufacturing companies have invested in various technologies for operational improvement, yet have not realized the importance of interpreting and understanding the data emerging from the daily activities in their factories. This chapter presents how material flow data can be integrated and interpreted in an efficient way that helps in operational decision making.

8.1 Data in Manufacturing: Why Data Integration & Interpretation?

The application of data has been a growing trend in manufacturing. Industry 4.0, Internet of Things (IoT), Smart Factory, etc., all emphasize the importance of data. In order for manufacturing data to be used for operational improvement, companies must be ready to collect and interpret the data emerging from their daily operations. With the material flow tracking technologies discussed in this thesis, data generated by the material flow process can be collected. The collected material flow data from various manufacturing stages can then be integrated to a central user interface shared over the internet, interpreted for the end users in the manufacturing facility, and used in various operational improvement activities. This thesis, in particular, focuses on 1) process transparency improvement and 2) system fail-safe improvement to address the problems at the studied manufacturing facility.

First, one system issue identified and discussed in Chapter 4 is the lack of transparency of the information flow along the physical material flow process, which causes difficulties in internal production management and external supply chain coordination. Achieving a transparent information flow requires not only data collection along the whole manufacturing process, but also appropriate analysis and presentation of the real-time collected data. The collected data must be integrated into a centralized, user-facing system and interpreted through data visualization. This will make the material flow process transparent and readable, empowering facility managers, planners, and executives to see the invisible, identify process gaps and bottlenecks, clarify resource distribution, and make informed and timely decisions.

In addition to improving the transparency of the material flow process, proper use of the collected data can also contribute to making the material flow tracking process more robust. As we discussed in Chapter 5, a barcode system is often fail-safe through instant feedback such as a beep sound after each successful scan, while it is hard for an RFID system to detect one or more RFID tags that have not been successfully read when reading multiple tags. Instead of a sound indicator that cannot be applied to this case, given the number of parts being read simultaneously, a potential fail-safe solution for RFID systems is visual feedback. Real-time data visualizations of data collected by the RFID networks can provide a simple fail-safe measure by giving the operator immediate visual feedback indicating the quantity of tagged parts that have been successfully read. For example, a display can be mounted at each RFID-equipped location to show the status of real-time tag reading, if the tag information read by the RFID reader can be collected, transmitted, and shared over the network and visualized in a display.

8.2 Data Management at Waters Corporation: Current State

Material flow data captured via material tracking systems such as barcode or RFID networks can be analyzed and interpreted in different ways. A common practice is sending the data to SAP through commercial middleware, a layer of connective software that collects, manipulates, and disseminates data from one end (hardware components like an RFID reader) to another (enterprise applications like SAP). Often, companies need to use specific Application Programming Interfaces (API) to access and configure specific services or functions from the middleware. Waters Corporation is using such a set of tools to process the data collected from the current barcode scanning process.

The current state of data management at Waters was investigated. As a typical manufacturing company, Waters' daily operations generate a massive amount of data, and the company has invested in a barcode material tracking system that, although it makes use of the data, only provides very limited material flow visibility and unreliable data through the imperfect manual scanning. The problem that Waters is facing now is that the company's current middleware system, Catamaran, has been in use for seven years without an update and can only be used for the barcode system. Waters is assessing its options to perform a complete update of this middleware system or investigate other industrial solutions in 2021. However, it is still undecided whether to purchase the RFID module in addition to the current middleware infrastructure in order to realize a full-scale RFID data integration and, in turn, full transparency of the material flow. Besides, a complete RFID integration at Waters may take a long time since any changes to the current SAP process are subject to the Food and Drug Administration's (FDA) approval and validation owing to the nature of the company's products, which are widely used in the pharmaceutical industry.

Therefore, it makes sense to develop a pilot RFID data integration solution that can

1) demonstrate the new, effective, and transparent RFID process since this is critical to management's decision making on whether to purchase the RFID middleware module;
2) serve as a useful tool during the transition period and pave the way for future full-scale RFID implementation;
3) provide a fail-safe measure to render the RFID tag reading process more reliable.

8.3 Development of the Data Integration System

8.3.1 Current Information Flow Analysis and New Solution Proposal

The current information flow system at Waters comprises five critical steps, as shown in Figure 8-1. First, material flow data collected through a barcode scan is sent to the middleware system, Catamaran, for first processing. Next, a specific business API is used to access the barcode module of the middleware and identify and retrieve material data before sending the data to SAP. Lastly, the user retrieves and downloads the data of interest. In this way, however, the data is presented in a raw form with unfiltered information. Individuals must spend time processing the data, for example, creating various unstandardized sheets, forms, and diagrams via Excel, PowerPoint, or other commercial software to interpret the data for decision-making. This is not only time-consuming but also requires a significant coordination effort given the inconsistent data interpretation quality.

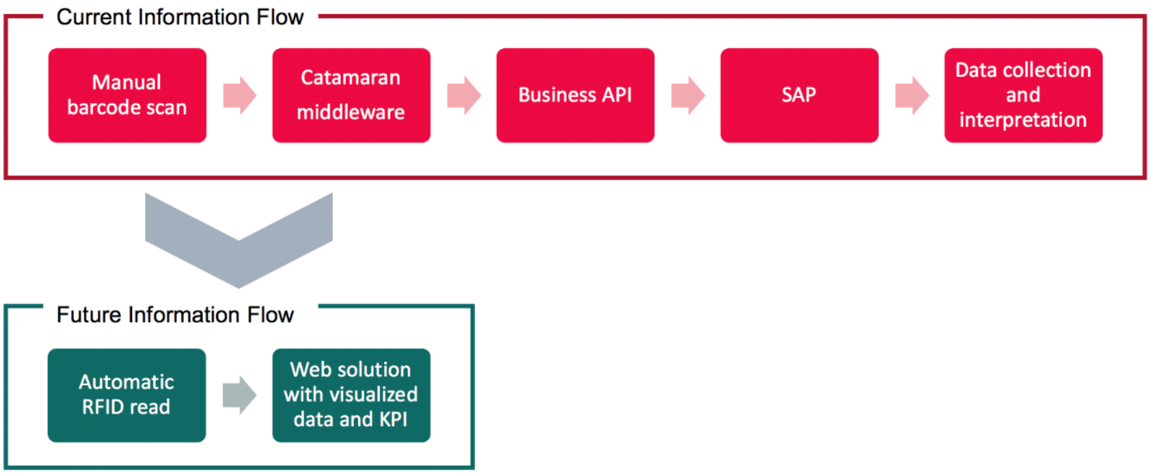


Figure 8-1: Current and proposed future information flow process

To ease the use of data by the end users (e.g., operators, facility managers, and executives), a new, integrated information flow process is proposed that simplifies the information flow to only two steps. First, data is collected along with the whole in-house material flow process automatically through the RFID reads and centralized to a local or cloud database in real time. Then, a web solution accesses the data in real time and processes and interprets the data through visualized charts and KPIs, supporting decision-making for the end users.

With the new information flow process, operators and managers would have simple access to already visualized and interpreted real-time data to make plans and decisions accordingly. For example, it would allow them to understand the dynamic of the actual material flow process, find any discrepancy between the planned and actual situation, recognize the process bottleneck or material shortage at an early stage, and carry out corrective or preventive actions. It also gives operators immediate visual feedback indicating the number of tagged parts that have been successfully read, and thus serves as a reliable fail-safe measure for the RFID system.

8.3.2 Data Integration Scheme and System Setup

To realize the proposed new information flow process, a data integration solution is developed. The integrated system comprises one or multiple RFID readers, a web server, a database, and a web interface. The server, database, and web interface are programmed and packed together, making up the proposed web solution. Figure 8-2 shows the scheme.

The data integration scheme divides the four key components into three layers, i.e., the client layer, the logic layer, and the data layer. The client layer includes the RFID reader and the web interface, which directly interact with the physical world, collecting and presenting data. The logic layer is represented by a web server that consists of "business logic," interacts with both clients, and manages their requests. The data layer, represented by the database, manages the data and listens to the server. The functionalities of each of the four components are described below:

- The reader receives tag information, decodes it to identify the tagged object, and continuously sends the information to the server along with a timestamp.
- The database is a logical framework that allows people to read, write, and organize collected data in tables. Data stored in a database can be retrieved based on user requests via database queries.

- The server is a program containing a set of logic that manages data on demand. A server listens to the requests of other entities (i.e., clients) such as the reader and the web interface, processes data with a set of logic and algorithms, and sends the data to fulfill the requests. Upon the "post" request from the reader or "get" request from the web interface, the server stores data in or accesses data from the database to complete the requests, respectively.
- The web interface is a graphical user interface (GUI) page that enables online interaction with the system users from a web browser. After receiving data from the server, it presents the data in a predefined, organized, and human-readable way to the end users.

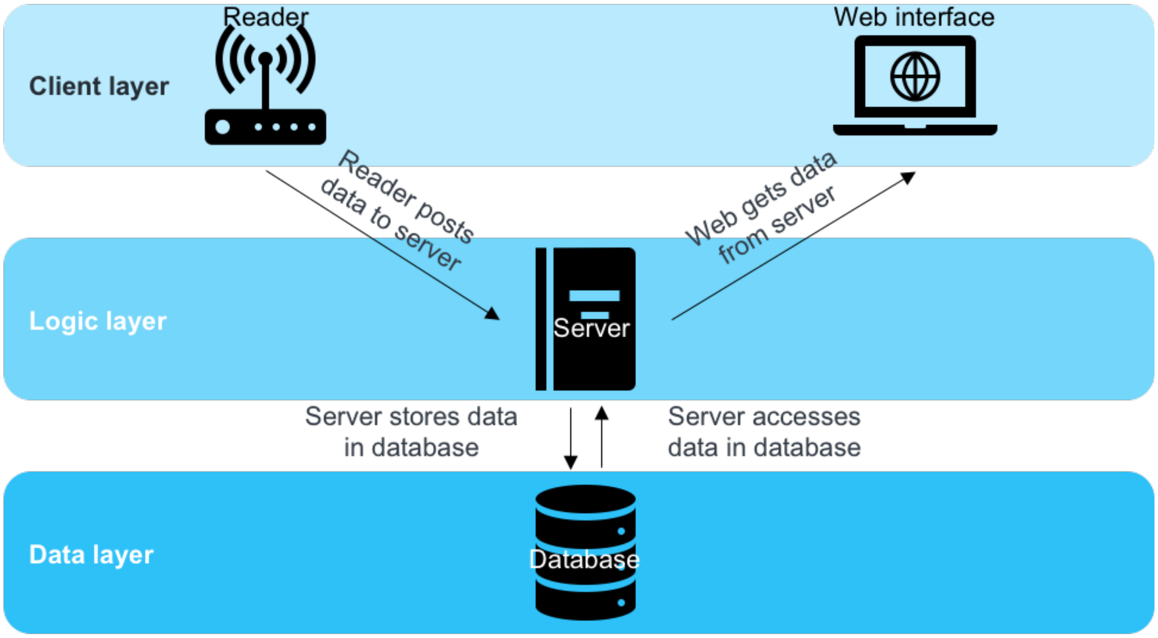
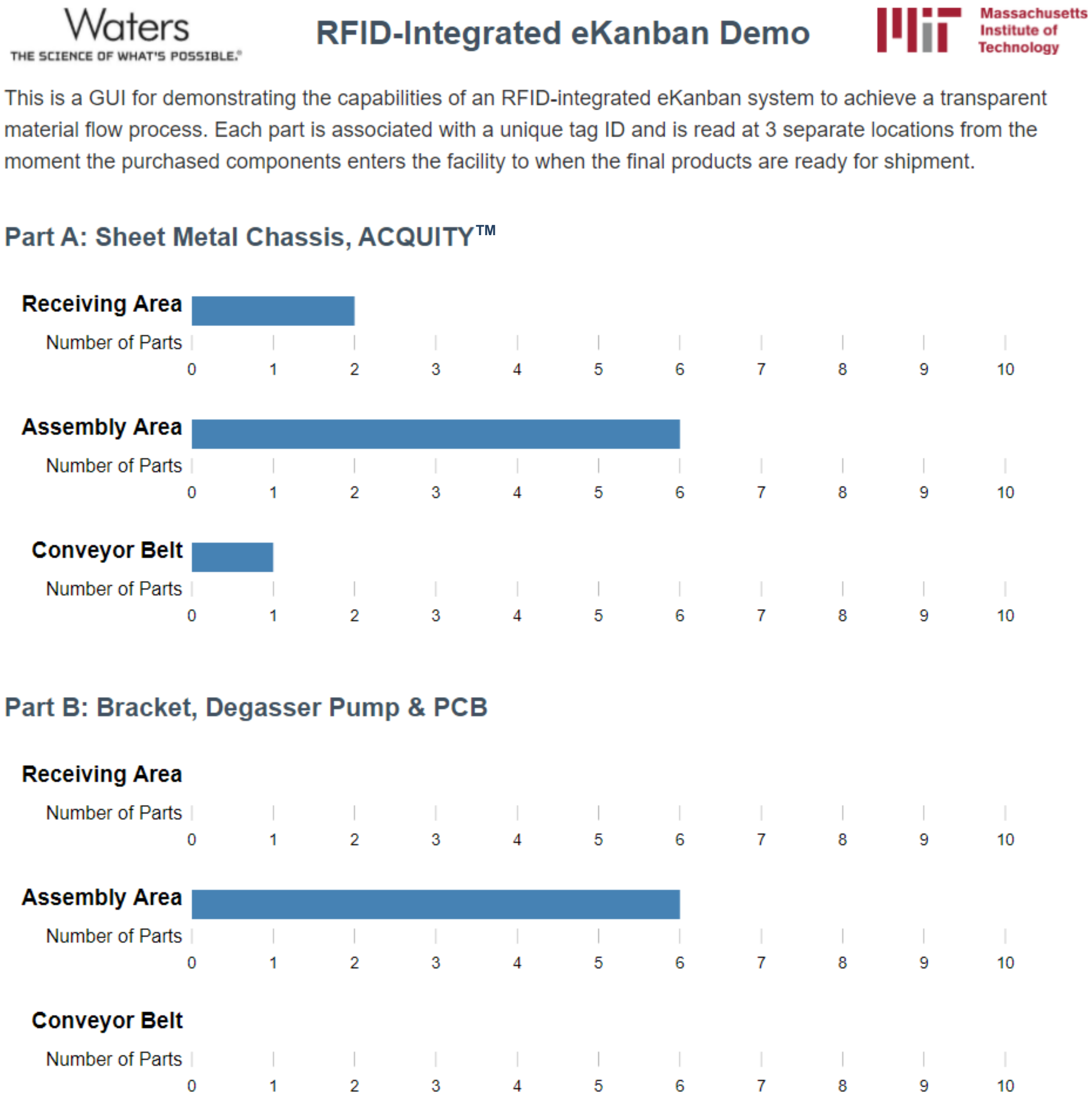


Figure 8-2: Proposed data integration scheme. After the reader receives the unique information stored in the tag attached on a part, product, or rack, it identifies the tag's ID and passes it along with other information such as location, time, etc., to the server. The server then stores the tag information in the database and looks for the specific object, such as a sheet metal chassis, that is tagged and encoded with the unique ID. When the web interface retrieves data from the server, the server finds the corresponding data from the database and sends it to the web interface.

The server and the database are set up using Python, while the web interface is written in JavaScript, Cascading Style Sheets (CSS), and Hypertext Markup Language (HTML), three mainstream languages for web development. The reader and the web interface interact with the server via Hypertext Transfer Protocol (HTTP), a protocol for encoding and transferring information between a client (such as an RFID reader or web browser) and a web server. Technical details of the system setup will not be discussed in the thesis. The web interface that interacts directly with end users will be presented next.

8.3.3 Data Visualization and Interpretation

The key part of the web solution is the web interface that enables convenient, uncomplicated online interaction with end users from a web browser. The core function of this web interface is to realize real-time visualization of material flow data, which can increase the transparency of the material flow process and provide a fail-safe measure for the RFID system. Figure 8-3 shows the web interface for demonstrating the material flow dynamics of two types of parts from the moment they enter the facility to the moment the final products are produced and ready for shipment. Part A and B represent two different types of parts, in this demonstration, the sheet metal chassis for the ACQUITY UPLC™ system and the bracket for the degasser pump and PCB, respectively. Each part is associated with a unique tag ID and is read sequentially at three locations: the receiving area, assembly area, and conveyor belt. Each bar represents the real-time number of a type of part currently located in the corresponding area. When a rack containing multiple A and B parts approaches one of these locations, the tags on the parts are read and the quantity of both types of parts in the rack is recorded and displayed. As the parts are moved to the next stage, the bar of that stage becomes longer and the bar of the previous stage becomes shorter to reflect the dynamic material movement.



RFID-Integrated eKanban Demo

This is a GUI for demonstrating the capabilities of an RFID-integrated eKanban system to achieve a transparent material flow process. Each part is associated with a unique tag ID and is read at 3 separate locations from the moment the purchased components enters the facility to when the final products are ready for shipment.

Part A: Sheet Metal Chassis, ACQUITY™

Part B: Bracket, Degasser Pump & PCB

Figure 8-3: The web interface that enables online interaction with users from a web browser. Demonstrated is the material flow of two part-types from when they enter the facility to when the final products are produced and ready for shipment. Part A and B represent two different part types. Each part is associated with a unique tag ID and is read sequentially at three locations: the receiving area, assembly area, and conveyor belt. Each bar represents the real-time quantity of a type of part currently located in the corresponding area.

In this way, the material flow system at a manufacturing facility becomes transparent and interactive:

- Transparent: The information flow along the material flow process reaches full transparency. Inventory level, the quantity of WIP parts, and process time at each operational stage are ready to access. Operational processes from procurement and storage to production planning and shipment can be adjusted and rebalanced in response to changes in sales and product quantities, ensuring a more efficient, agile, and resilient manufacturing operation to survive and thrive in today’s dynamic market.
- Interactive: The individual material flow processes are fully connected without discontinuity, and work and communicate closely with people, making a fail-safe RFID network possible. Mounting a monitor that displays the web interface at each RFID-equipped location, the status of real-time tag reading can be visualized, giving the operator immediate visual feedback with respect to whether or not the read was successful or how many tagged parts were read successfully.

This page is intentionally left blank.

Chapter 9

Conclusions and Future Work

9.1 Conclusions

The importance of monitoring and controlling material flow has been underestimated by some manufacturing companies until the recent COVID-19 pandemic. The ever-increasing market volatility pose manufacturing companies huge challenges to their material flow management along the supply chain.

This thesis studied the material flow process and related operations at a leading global manufacturing company, Waters Corporation. Leveraging lean Six Sigma manufacturing methodologies such as value stream mapping (VSM), critical problems and gaps that constrain or misdirect the material flow of the eKanban process (which is used both internally across various departments at the company's major production facility and externally with several vendors were identified.). Following the problem statement, different purchasing methodologies and material flow tracking technologies were investigated. Using inventory modeling and in-depth comparison, it was determined that using RFID technology in the eKanban process is the most effective approach to improving the company's material flow operation. Next, an advanced, RFID-based material flow tracking system was proposed to replace the current flawed barcode scanning system, tested various system setups and RFID hardware, and consequently determined the optimized system design with the most suitable types of RFID tags. Then a pilot RFID network at both rack and item levels was implemented, addressing the identified issues and outlining the future direction of a corporate-scale upgrade of the material flow process. Lastly, an integrated web solution that visualizes and interprets the data captured by the RFID networks along the material flow was developed, increasing visibility of the material flow process and providing a fail-safe measure for the RFID reading process.

Together with the newly designed supplier interface area and the web-based data integration solution, the proposed RFID system realized an expansion of eKanban storage capacity and managed to eliminate human errors emerging from the manual barcode scanning process, reduce overall inventory level and waste, and increase material availability and transparency along the company's whole material flow process.

9.2 Future Work

The first part of future work for Waters Corporation is to purchase and set up RFID tag printers for the item-level RFID implementation. An RFID encoder built inside the printer can write data to the tag through RF transmission, enabling printing and encoding information on RFID tags simultaneously. For the selected RFID tag type, *Confidex Silverline Classic*, the *Zebra ZT410 RFID Silverline Printer* (see Figure 9-1) is recommended, which is well suited for on-metal, item-level applications and is capable of printing and encoding up to 500,000 RFID tags per year.

Figure 9-1: Zebra ZT410 RFID Silverline Printer [14]

Another part of future work is to install more RFID networks at more stages along the material flow for a full-scale implementation. This thesis describes a pilot implementation at limited locations at the Waters Milford facility; however, there are other locations within and outside the Waters Milford facility where installing RFID networks makes sense, including quality inspection area, shipping area, and the company's distribution centers at other global locations such as Singapore and England. Having more RFID networks set up in these locations, monitoring and controlling material flow throughout the product's life cycle from the raw material to the customer's hand can be possible, offering full product traceability. If RFID networks are available to a broader extent along the whole supply chain from the vendors to the end customers, supply-chain-scale visibility of material flow can be achieved, lowering the information barrier between business partners (i.e., suppliers, manufacturing companies, and customers) and improving information flow efficiency.

This page is intentionally left blank.

References

[1] R. Lee, “Development of solutions to reduce variability in material flow at a factory,” Master’s Thesis, Massachusetts Institute of Technology, Cambridge, MA, 2021.

[2] Waters Corporation, “2019 Annual Report,” 2020. [Online]. Available: https://www.waters.com/waters/en_US/Annual-Reports [Accessed Nov. 16, 2020].

[3] Waters Corporation, “ACQUITY Advanced Polymer Chromatography System,” 2020. [Online]. Available: https://www.waters.com [Accessed Nov. 16, 2020].

[4] N. Vinakollu, “Evaluation of ion transfer capillary geometry on sensitivity of a desorption electrospray ionization and mass spectrometry system,” Master’s Thesis, Massachusetts Institute of Technology, Cambridge, MA, 2021.

[5] C. Hsu, “Investigation of ion transfer efficiency through multi-channel capillaries at a desorption electrospray ionization (DESI) interface,” Master’s Thesis, Massachusetts Institute of Technology, Cambridge, MA, 2021.

[6] J.P. Womack and D.T. Jones, *Lean Thinking.* New York, NY: Simon & Schuster, Inc., 1996

[7] M. Rother and J. Shook, *Learning to See.* Cambridge, MA: Lean Enterprise Institute, 1999

[8] L. Bolotnyy and G. Robins, “The case for multi-tag RFID systems,” in *IEEE International Conference on Wireless Algorithms, System and Applications (WASA)*, Chicago, IL, 2007, pp. 174–186.

[9] B. Jang and H. Yoon, “Examine the effects of phase noise on RFID range,” *Microwaves and Rf*, 2008.

[10] United States Department of Commerce, “United States radio spectrum frequency allocations,” 2016. [Online]. Available: https://www.ntia.doc.gov/files/ntia/publications/january_2016_spectrum_wall_chart.pdf [Accessed Nov. 23, 2020].

[11] L. Mo and H. Zhang, “RFID antenna near the surface of metal,” in *IEEE International Symposium on Microwave, Antenna, Propagation, and EMC Technologies For Wireless Communications,* Hangzhou, China, 2007.

[12] Xerafy Singapore, “Xerafy Outdoor Trak Series,” 2020. [Online]. Available: https://www.xerafy.com/outdoor-series [Accessed Nov. 16, 2020].

[13] Alibaba, “One-way swing gate,” 2020. [Online]. Available: https://www.aliexpress.com/item/32686377577.html [Accessed Nov. 23, 2020].

[14] Zebra, “ZT400 SERIES RFID PRINTERS,” 2020. [Online]. Available: https://www.zebra.com/us/en/products/printers/industrial/zt400-rfid.html [Accessed Dec. 6, 2020]