EVALUATION OF RFID FOR INFORMATION VISIBILITY BASED JOB-SHOP SCHEDULING IN LEAN MANUFACTURING ENVIRONMENTS

By

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Submitted to the Faculty of the
Graduate College of the
Oklahoma State University
in partial fulfillment of
the requirements for
the Degree of
DOCTOR OF PHILOSOPHY
July, 2012

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CHAPTER I

INTRODUCTION

This dissertation investigates how radio-frequency identification (RFID) improves operations in manufacturing when item levels referred to as Work-In-Processes (WIPs), parts, and components become more visible in the schedule process.

Information Technology (IT) plays a vital role in all kinds of businesses, especially in facilitating routine business tasks. The old fashioned way either to manually update data into a system or to access information though printed report is costly, incomplete, prone to error, and eventually, is fading away. Many automatic identification technologies (AITs) have been developed to automate such traditional processes. Radio Frequency Identification (RFID) technology is one of the solutions to automatically capture such data. It is built around the idea that, to search for things without too much time and trouble to find out, you can just put radio transceiver tags on physical objects and then use the tags to know where those objects are (Brazeal, 2009). Literally, RFID is an information and sensor technology that collects data though reader devices and tags that are attached to or embedded inside of objects such as a document, person, animal, or container. It basically uses radio waves to transfer data from a RFID tag to a reader (Brown, 2007).

RFID has been used significantly in improving business performance in warehouse and distribution center, logistics, and inventory management across supply chain. Furthermore, the trend toward implementing RFID in other areas such as hospital or manufacturing processes is increasing (Gunther, Kletti, & Kubach, 2008; Hunt, 2007; Jones, 2008). However, considering the fact that RFID is not as mature as the existing bar-code system, certain problems of RFID implementation including the reliability of the RFID system or installation issues in the presence of liquid or metal parts can be expected (Gaukler & Hausman, 2008).

Even though widespread adoption of RFID is expected to take the place of barcodes by retailers and manufacturers, the use of RFID is still controversial, challenging, and struggling as many companies believe that return on investment (ROI) from RFID is still questionable due to the cost of technology itself, the cost of the subsequent reengineering tasks, and the considerable changes sometimes required in overall business processes and they might not get a return (Bacheldor, 2005; Brown, 2007; Gunther, et al., 2008; McCrea, 2006). According to the 2010 Google Search Volume Index (see Figure 1), the search trend for both RFID and Barcode has declined since 2004. However, when considering the news reference volume index, the number of RFID news items have increased and varied; meanwhile the number of barcode news has remained unchanged since 2004. This trend implies that even though the hype of RFID has been decreasing due to the actual adoption and diffusion of technology itself, it is still a popular area many optimistic promoters try to get into.

In manufacturing particularly, much progress in the use of RFID has been made as this technology allows us to automatically identify and track items flowing through the channel, from the production processes to subsequent lifecycle. The identification information can potentially create detailed, accurate, and complete visibility of item progress throughout the operations and consequently lead to considerable operational and strategic benefits (Gunther, et al., 2008).

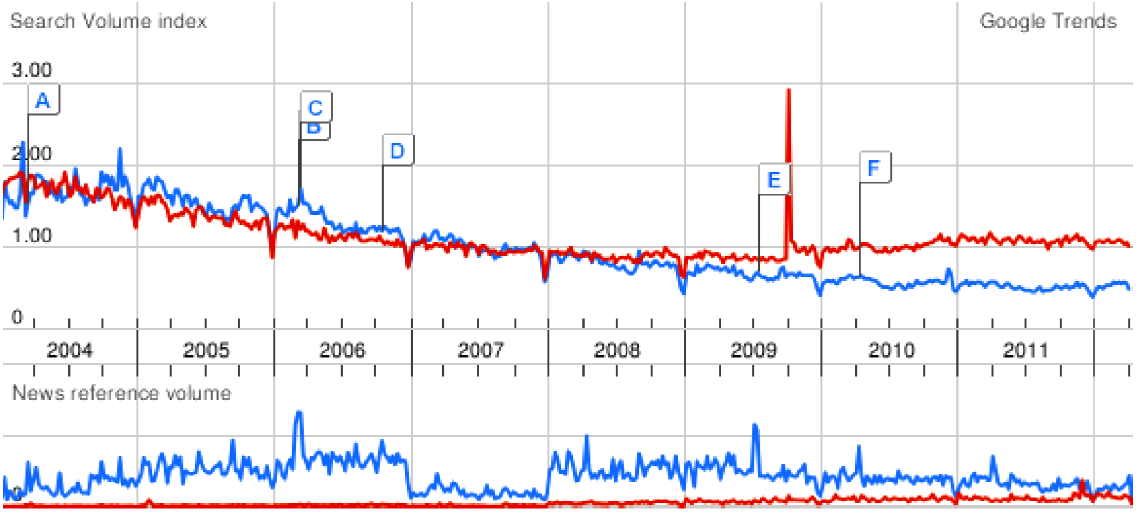


Figure 1: Google Search Volume Index: RFID vs. Barcode

1.1 Problem Statement and Background

Even though RFID has been around for a while, it recently has been brought to attention due to its use required by the U.S Department of Defense or large retailers such as Wal-Mart. Due to the increased attention in the potential use of RFID, unrealistic expectations and misinformed perceptions spawned by many articles may lead one to question the technology of what it may do and consequently delay its adoption (Hardgrave & Miller, 2006). Hardgrave and Miller (2006) try to separate these false expectations, which transform themselves into myths, from reality. They examine popular positive and negative myths of RFID by providing an exposition of reality. These myths include (1) RFID is new or RFID technology is mature and stable, (2) RFID can be used to continuously track people and objects wherever they go anywhere, (3) People can drive down the street and read RFID tags inside your home, thus knowing everything about you and your stuff, (4) RFID tags contain information about anything and everything, including sensitive personal information, (5) RFID is generating millions of terabytes of data, (6) You must have 100% reads at 100% of the read points for RFID to be useful, (7) Major retailers have mandated that all suppliers tag all products for all stores, (8) RFID is costing that average Wal-Mart vendor $23 million annually, (9) RFID is the panacea for creating the perfect supply chain, and (10) RFID is replacing the barcode (Hardgrave & Miller, 2006). Some of these myths are still considered important issues in adopting such technology in manufacturing area. Separating these myths from reality is needed in order to provide rational expectations and perceptions that can be applicable to the manufacturing environment.

In fact, there are many factors affecting RFID adoption in the manufacturing industry. Wang et al. (2010) propose a model to predict RFID adoption through the technology-organization-environment (TOE) framework. The key findings in this study indicate that complexity, compatibility, firm size, competitive pressure, trading partner pressure, and information intensity are among the significant determinants of RFID adoption (Wang, Wang, & Yang, 2010). These factors seem to be reasonable and applicable to any new technology adoption. Particularly, (1) The lack of common standards, (2) the difficulty in integrating RFID technology with its existing information systems, (3) firm size, which reflects budget-cost consideration (hardware, software, installation, consultancy support, or integration costs) in investing such technology, (4) competitive and trading partner pressures are clearly obstacles and, consequently, can impact the technological-adoption decision. Wamba et al. 2009, in their study on RFID adoption issues, find that information visibility and competitive differentiation are the key consideration for those firms who are adopting RFID, while those non-adopters of RFID technology are more concerned with the capital costs (acquisition costs, replacement costs, and ongoing costs). Regardless of whether they have adopted RFID or not, those firms are interested in the benefits RFID can bring to the organization such as data accuracy, track and trace capabilities, and improved inventory management (Wamba, Keating, Coltman, & Michael, 2009). This implies that the decision to move forward with or delay investment in RFID in manufacturing is also driven by several factors. Without a clear guidance on how RFID can be used in the manufacturing industry, it is very difficult to convince both adopters and non-adopters to believe adopting RFID is beneficial for their companies' competitive edge.

A majority of literature on RFID reports that RFID can greatly benefit manufacturing enterprise by increasing efficiency, reducing inventory, saving time, and reducing labor costs by tracking items as they move through the operations channel (Baudin & Rao, 2005; Lee & Park, 2008; Lee & Ozer, 2007; Lee, Cheng, & Leung, 2004; Niederman, Mathieu, Morley, & Kwon, 2007). According to a surveyed report from Aberdeen Group (2007), Figure 2 highlights the primary objectives of RFID in manufacturing from 150 manufacturers, who are currently adopting or planning to adopt

RFID. RFID is widely used for asset management (34%), product efficiency (20%), and supply chain visibility (19%) (Dortch, 2007, p.6).

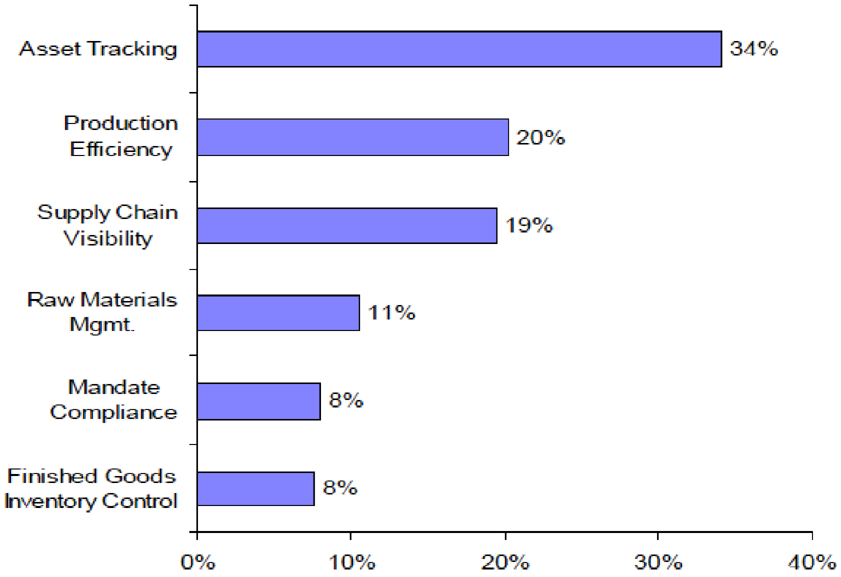


Figure 2: Top Objectives of RFID in Manufacturing (Source: Dortch, 2007, pg.6)

The values of RFID discussed in these studies are just examples of efforts to realize benefits of RFID by moving from supply chain management to manufacturing operations. Thus, such benefits reported in these literatures, whitepapers, and promotional vendor estimates are mainly focused on asset tracking, inventory management, or object location. However, only a few studies (Gunther, et al., 2008; Hozak & Collier, 2008; Huang, Zhang, & Jiang, 2008; Shibata, Tsuda, Araki, & Fukuda, 2006;Wang, 2008; Wang, et al., 2010) convert the potential of RFID into the heart of manufacturing operations such as job shop or assembly line improvement, quality inspection, or work-in-process (WIP) monitoring.

1.2 Research Questions

In order to maintain competitiveness in the global economy, many companies seek and try to adopt different business initiatives to improve their existing operations. Lean philosophy comes across as one of the prominent and common practices that have been proved successfully over a decade. Literally, the philosophy of Lean manufacturing focuses on product and its value stream (Womack & Jones, 2003), while the primary purpose of Just-in-Time (JIT) is on a smooth flow of materials to arrive as needed in manufacturing. JIT and Lean manufacturing are used interchangeably (Stevenson, 2007). The goal of lean manufacturing is to determine wastes (also called non-value added activities) in the value stream, to eliminate those wasteful activities, and to create and sustain value added activities. "Wastes" here means any human activities which absorb resources but create no value. These wastes include waiting time, overproduction, rework, motion (unnecessary movement of people or parts within a process), over-processing, inventory, transportation (unnecessary movement of people or parts between processes), and unexploited knowledge (Jugulum & Samuel, 2008; Womack & Jones, 2003a).

Of course, the benefits from the application of RFID in manufacturing and other fields have been investigated for a while. However, many organizations may not realize that the real-time updated data through RFID can also be a valuable component of lean initiatives. Some studies (Baudin & Rao, 2005; Brintrup, Ranasinghe, & McFarlane, 2010; Patti & Narsing, 2008; Zhang & Jiang, 2008) have shown that an organization can combine the RFID technology with Lean manufacturing. However, those studies are mainly focused on improving Kanban system, one of the lean strategies, but not on the heart of lean concepts which is to create values and reduce wastes (Carreira, 2005; Feld, 2000; Jugulum & Samuel, 2008). Due to this lack of case studies or analytical work related to lean manufacturing and applications of RFID, there is a need for a clear and complete guidance on how RFID can help in achieving a better lean manufacturing environment. To guide this portion of the study, the first research question is developed:

1. Can RFID and lean philosophy be complementary to improve manufacturing performance and create more value to an organization?

To answer this research question, this dissertation investigates how reduction in non-value added activities or wastes as a result of improved item-level visibility would affect the lean performance. The sub research question is "*will more accurate information from RFID-based solutions help in achieving the goals of Lean initiatives in manufacturing plant performance and, if yes, in what specific ways?*" Although our study mainly focuses on the job shop scheduling context, our analysis approaches (along with units of measure and key performance indicators), which are used to capture the process and scheduling improvement, follow the concept of lean philosophy looking at what wastes can be reduced when adopting an RFID system.

On the other hand, although there have been a lot of studies investigating the benefits and applications of RFID in manufacturing, most research papers are supply chain oriented and have not focused on how RFID can be applicable to the shop-floor operations, especially in lean manufacturing environment. Due to the lack of studies and exemplary works related to manufacturing oriented, there is a need for a clear and complete analysis of how RFID can help in achieving a better manufacturing environment. To guide this portion of the study, the first research question is developed:

2. How does manufacturing operations performance change or improve when information about item levels referred to WIPs, parts, and components become more visible through RFID?

To answer this research question, this dissertation focuses on job shop production scheduling perspectives. Scheduling tasks are very important in production management in order to meet customer demands. Due to the globalization of the current economy, the big challenge in developing a business strategy is to deliver value efficiently and effectively through either products or services to customers by optimizing time, productivity, defect level, product quality, and cost. The pressure on the production business is continually augmenting. To tackle such challenges and pressures, production scheduling plays an important role in manufacturing environments. With a wide variety of products, processes, and production levels, better scheduling can enable better coordination to increase productivity, effectively allocate limited resources, and consequently minimize operating costs. Thus, the sub research question of this dissertation is "*Under what conditions information visibility-enabled track and traceability improve manufacturing performance and how?*" The answer to this question can help business practitioners not only understand how RFID facilitates scheduling through the improved item-level visibility, but also make sound decisions when adopting RFID technology that can improve the overall manufacturing plant performance as well.

In summary, this dissertation aims to achieve two primary objectives. First, the benefits of RFID item-level information visibility based on different areas in job shop production scheduling in manufacturing are addressed. Second, our approach to analyze and evaluate those use cases follows the concept of lean philosophy looking at what wastes can be reduced when RFID technology is in place.

1.3 Simulation Studies

Two simulation studies of an organization that is considering adding RFID to integrate with its manufacturing enterprise system (MES) are presented. XYZ Company is a manufacturing services provider of complex optical and electro-mechanical components. The company considers implementing RFID on a production line of the optical receiver-transceiver, called OPT, used in telecommunication networks. Figure 3 provides an area-targeted view of how these two studies contribute to the literature. This dissertation devotes one chapter to each case study.

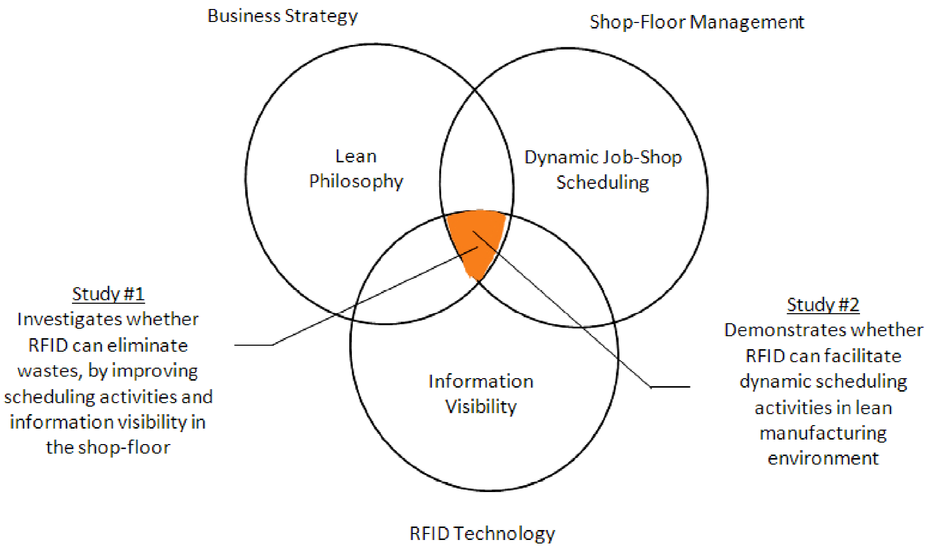


Figure 3: Research Framework

The first study (Chapter 2) aims to investigate whether addition of radio frequency identification (RFID) technologies in the manufacturing process can complement Lean manufacturing. The analysis is based on a comparison of the following three automatic identification technologies: existing 1D barcode, 2D barcode, and RFID being evaluated in a real job-shop environment where items are manufactured for meeting actual demand and also future forecast demand. We analyze the effect of information visibility in these settings by examining the various types of wastes that are typically addressed in Lean initiatives. The results of a discrete-event simulation suggest that employing RFID in Lean manufacturing initiatives can reduce some wastes but not necessarily all types of waste. We observe an increase in overproduction waste in our setting, although other wastes are reduced with improved information visibility. Overall, our results indicate that manufacturing organizations should explore information visibility through RFID to enhance their Lean initiatives.

The second study (Chapter 3) extends the benefits of RFID in a shop-floor operation by focusing on the multi-step dynamic job-shop scheduling in lean manufacturing environment. This study presents an RFID-based traceability approach to improve production scheduling. An in-depth study for a manufacturer is conducted to explore the characteristics of an RFID-based traceability system. We propose a novel information visibility-based scheduling (VBS) rule that utilizes information generated from the real-time traceability systems for tracking work in processes (WIPs), parts and components, and raw materials to adjust production schedules. We then evaluate the performance of this information visibility-based schedule against the classical scheduling rules. The results of the simulation suggest that RFID-based scheduling rule generates better performance compared to traditional scheduling rules with regard to cycle time, machine utilizations, backlogs, and penalty costs. We also note that the value of this information visibility is more relevant when the demand varies widely and/or operational disruptions occur.

In both case studies, the main goal is not to change the physical flow of parts and components in the manufacturing processes but, rather, to examine whether or not more accurate information visibility at the item level can help in achieving a manufacturing environment.

CHAPTER II

STUDY #1: ACHIEVING LEAN OBJECTIVES THROUGH RFID - A SIMULATION BASED ASSESSMENT

1. Introduction

The philosophy of Lean manufacturing focuses on a product and its value stream (Womack & Jones, 2003). While the primary purpose of Just-in-Time (JIT) is a smooth flow of materials to arrive as needed in manufacturing, JIT and Lean concepts are used interchangeably (Stevenson, 2007). The goal of Lean manufacturing is to determine waste (also called non-value-added activities) in the value stream, to eliminate those wasteful activities, and to create and sustain value-added activities. “Waste” here can be defined as any human activities which absorb resources but create little or no value. There are eight basic types of waste in manufacturing processes including waiting time, overproduction, rework, motion (unnecessary movement of people or parts within a process), over-processing, inventory, transportation (unnecessary movement of people or parts between processes), and unexploited knowledge (Jugulum & Samuel, 2008; Womack & Jones, 2003). Lean initiatives aim to deliver products or services by optimizing time, productivity, defect level, product quality, and cost by minimizing these wastes.

Even though Lean manufacturing has proved successful for more than a decade in reducing non-value-added activities, the issues of ineffective production planning, scheduling, and control; inefficient workflow or process flow; missing items; or high inventory still exist (Djassemi & Olsen, 2010; Singh, Garg, Sharma, & Grewal, 2010; Sun, 2011). One of the major causes of such failures and inefficiency in managing operations may be a lack of accurate and comprehensive, time-sensitive data and information. Over the last decade, we have witnessed that wireless technologies such as RFID offer a great opportunity to address and solve such issues.

RFID and barcodes are similar: both technologies use labels (RFID tags vs. printed barcodes) and devices to read the labels (RFID readers vs. scanners), and both rely on the back-end IT infrastructure for cross-referencing the ID number with a database system. However, RFID is an improvement over barcode systems. First, no line of sight is required for RFID whereas a clear line of sight is required to read a barcode. Second, with RFID, multiple parallel reads are possible once RFID tags come in range of the reader. In contrast, a barcode can be read only when the item is physically moved across the scanner, which adds to the time and cost of reading. Third, RFID can capture a wide range of data with minimal human intervention (contactless and remote interrogation). This means that RFID tags and readers do not have to be oriented to or close to each other in order to transmit and receive the radio signals. Finally, a barcode is unchangeable, relatively easy to forge, and cannot carry much data. RFID, on the other hand, offers a wide range of data storage capacities with secure information transfer, especially if the information is encrypted from the product to the product database (Brazeal, 2009; Brown, 2007; Hunt, 2007). With these advantages over barcodes, RFID has been used in improving business performance in warehouse and distribution centers, logistics, and inventory management across supply chains. Furthermore, the trend toward implementing RFID in other areas such as a hospital or manufacturing processes is increasing (e.g. Gunther, Kletti, & Kubach, 2008; Hunt, 2007; Jones, 2008). Disadvantages include the fact that RFID implementation is more expensive (Brown, 2007) and the accuracy of RFID tag readers is not always 100 percent (Bottani, 2008; White, Gardiner, Prabhakar, & Razak, 2007).

The benefits from the application of RFID in manufacturing and other fields have been investigated during the past decades. However, many adopters of Lean initiatives do not realize how RFID and Lean manufacturing are interrelated and how real-time updated data through RFID can also be a valuable component of Lean initiatives. Can RFID and Lean philosophy be complementary in improving manufacturing performance? Some studies (e.g. Baudin & Rao, 2005; Brintrup, Ranasinghe, & McFarlane, 2010; Patti & Narsing, 2008; Zhang & Jiang, 2008) have shown that an organization can combine RFID technology with Lean manufacturing. However, these studies have mainly focused on improving the Kanban system, which is one of the Lean strategies, and do not address key Lean concepts such as creating values or reducing wastes (Carreira, 2005; Feld, 2000; Jugulum & Samuel, 2008). Thus, the focus of this study is on the following research question: “will more accurate information from RFID-based solutions help in achieving the goals of Lean initiatives in manufacturing plant performance and in what specific ways?” Although one could argue that the answer to this question is an obvious yes, our goal is to study the detailed mechanisms of this waste reduction. We identify which wastes can be reduced by adopting an RFID system and investigate how improved item-level visibility, with its corresponding decrease in waste, affects the operational performance. This study takes place in the context of an actual company's manufacturing operations. The comprehensive simulation model we develop investigates the effects of employing Lean concepts enabled by different automatic identification technologies (AITs): 1D barcode, 2D barcode, and RFID. Our study examines the differences in operational performance due to information visibility offered by these identification technologies. The case study presented in this paper augments and strengthens the supposition that RFID can complement Lean implementations. This study helps both Lean practitioners and RFID adopters identify opportunities where RFID can add value in manufacturing operations. It adds to the literature by identifying the specific wastes that can be reduced through RFID.

After describing the related literature in the next section, we present our hypotheses for waste reduction and operational performance in a job-shop setting. Then, we develop a simulation model based upon an actual organization. Next, the results are reported and analyzed. The analysis of traditional Lean practices is also investigated. We conclude the paper with a discussion on how RFID and Lean philosophy can be complementary in improving manufacturing performance.

2. Literature Review

RFID is an information and sensor technology that collects data though reader devices and tags that are attached to or embedded inside of objects such as a document, person, animal, or container (Brown, 2007). Even though the barcode is the most common type of automatic identification technology (AIT) in use today due to its notably low cost, many studies (e.g. Garcia, Chang, & Valverde, 2006; Hozak & Collier, 2008) have noted issues about the reliability of bar code systems. For instance, the barcode reliability in many distribution centers in Spain and Korea is below 80% (Garcia et al., 2006).

RFID technologies have gained significant interest in many areas including supply chain and manufacturing. For instance, Delen et al.'s (2007) case study explores the potential benefits of RFID in supply chain management. Using actual RFID data from a major retailer, this study finds that RFID can enhance information visibility and improve the performance of the supply chain. Delen et al. (2007) also indicate that it is not just the RFID technology itself that creates value but rather the creative use of the data obtained by this technology that enables better business decisions. However, RFID is not perfect. Several data-related issues such as missing reads, multiple reads, or the magnitude of data are also reported in their study. Garcia et al. (2006) study the impact of RFID on a distribution center and analyze the real behavior of the modified facility through simulation modeling. Hozak and Collier (2008) develop a simulation model to analyze how RFID can improve manufacturing performance in different operating scenarios. Specifically, they focus on the effect of both RFID and barcode tracking mechanisms on the use of lot splitting in a job shop environment.

Proponents of RFID in manufacturing operations argue that it can benefit companies by (i) tracking materials, parts, devices, or containers to improve shipment, inventory, and asset management, (ii) improving traceability of flawed WIP, faulty and already shipped products, or recalled products to increase warranty savings, (iii) increasing efficiency in labeling, (iv) improving metadata management and reducing mistakes due to human errors by reducing a mix-up between written documents and manual data recording and maintenance, and (v) reducing misplacement, shrinkage, and transaction errors (Baudin & Rao, 2005; Gunther et al., 2008; Lee & Ozer, 2007). Some authors have also noted the labor cost savings resulting from RFID. Traditional barcode systems require a line of sight for item identification and require an operator to individually scan and position the items. RFID can automatically and continuously capture data with minimal human intervention. Also, multiple RFID tags can be read instantaneously and simultaneously instead of one at a time, compared to barcodes, for which several seconds are required to scan the individual items. Thus, RFID can result in labor cost savings (Dutta, Lee, & Seungjin, 2007; Lee & Ozer, 2007; McFarlane & Sheffi, 2003). We note that some of these benefits, in fact, support Lean manufacturing practices both directly and indirectly.

Some studies have demonstrated that an organization can combine RFID technology with Lean strategies. For instance, Baudin (2005) describes how an RFID system can improve an eKanban system. An RFID reader can detect the arrival of containers attached with an RFID tag within its proximity range. This pull signal can electronically notify the systems that the containers have reached a specific location. With sensor networks and RFID systems, the current eKanban system is reportedly more up-to-date with real time information flow, compared to the traditional eKanban system. Patti and Narsing (2008) explore the relationship between Lean manufacturing and RFID through a case study in the automotive industry. Their study describes how RFID can shorten the replenishment cycle in an electronic Kanban system and improve an item's location tracking in real time. Zhang and Jiang (2008) propose an RFID-based Kanban system for JIT manufacturing environments. A case study of a shop-floor assembly line is used to demonstrate the value of combining the systems. Su et al. (2009) describe how RFID can improve JIT operations by reducing bottlenecks through capturing real-time field information. The study is based on an RFID-based Kanban management information system where the card files used in the traditional Kanban system are replaced by RFID electronic tags. A framework of RFID-based production management is proposed to improve the circulation velocity and reduce mistakes occurring in the traditional Kanban system. Brintrup et al. (2010) present a set of tools with several case examples using the seven Toyota Production System wastes as a template to guide and analyze the RFID opportunity for Lean manufacturing.

Even though several of these studies illustrate potential benefits of RFID in Lean manufacturing environments, there has been no study focused on understanding the impact of RFID visibility on specific wastes in the shop-floor operations. Process wastes are common in job-shop situations when information is incomplete. RFID could potentially help alleviate this issue. Using a simulation approach, our study explores how Lean philosophy and RFID can be complementary and investigates whether visibility offered through RFID can reduce specific wastes and non-value-added activities, which would improve operational performance in shop-floor operations.

3. Shop-Floor Operations Environment

We consider a job-shop environment that is seeking to enhance Lean objectives. Although this simulation study has originated from the context of a specific shop-floor operation, the situation depicted in this operation is quite typical of what is observed in most job-shop manufacturing environments where some orders are built to stock, others are built to order, and the returns for repair are worked on in the same system. Another common characteristic is that the equipment may be used for processing different product families and each product (family) requires different customized setup of the equipment. Recent studies from Krajewski and Wei (2001), Zhao et al. (2002), and Hozak and Collier (2008) have shown that case studies driven by single-firm situations can provide fruitful avenues for exploration, contributing to both knowledge and practice.

Figure 4 presents a logical flow of a general job-shop operation process. Details of the specific manufacturing process are included in Chongwatpol et al. (2011). Operating on a quarterly timeframe, the company receives weekly forecasts from its customer-supplier development program at the beginning of the quarter. A total of 87 unique products are processed in this production line. Actual purchase orders are issued approximately two weeks prior to the due date. With the zero-inventory strategy, all released work orders are scheduled to be processed and shipped within 10 business days. To maximize the usage of its capacity and to avoid excessive workload at the end of the quarter, orders are released at the beginning of the week based on actual purchase orders and demand forecasts. Priority is given to satisfy the actual purchase orders from customers.

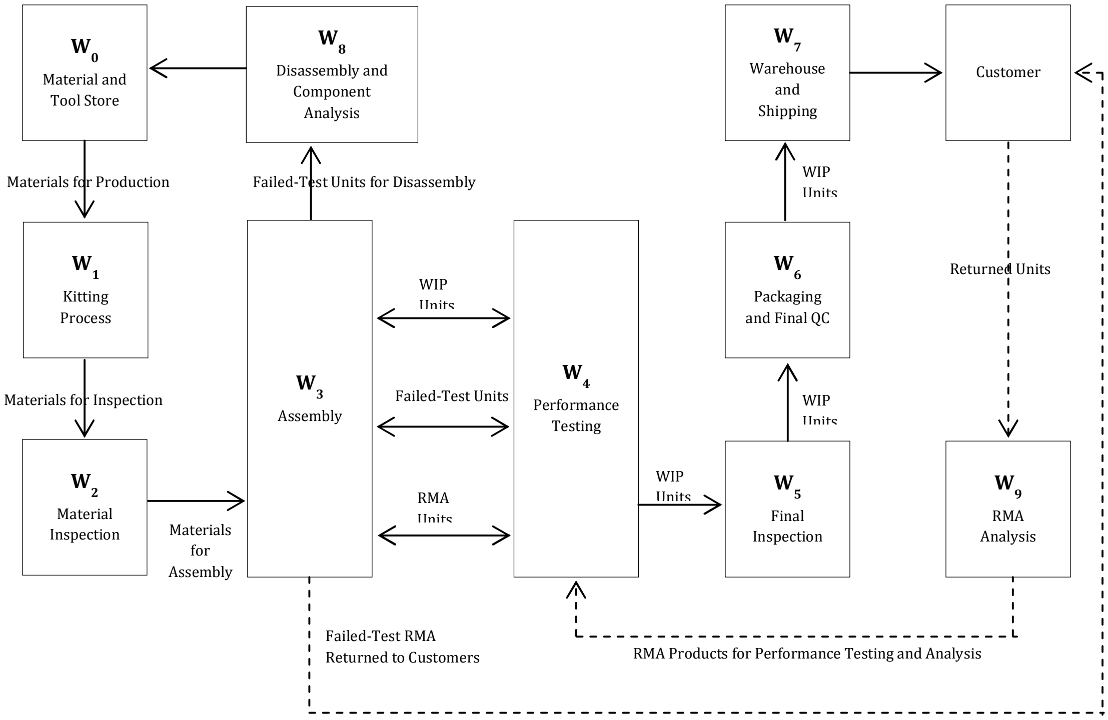


Figure 4: A Logical Flow of Job-Shop Operation Process

After receiving the weekly work orders, an operator starts kitting all parts and components into a tote at Workstation #1 (W_1). All materials are inspected at W_2 before being placed in the mechanical assembly line (W_3). At this stage, an operator manually assembles the units, also called Work in Process (WIP), based on the instructions provided either on the screen or in the tote. An operator works on one unit (or one tote) at a time. Afterward, the WIP is transferred to the next workstation (W_4) for software uploading and performance testing with various types of software packages. Because the same testing system is used for different software tests for different products, this step may entail some setup time to switch to the correct software for testing for a specific product family. If the performance testing is satisfactory, the WIP is moved back to the mechanical assembly station (W_3) for final assembly. If not, the WIP, now called the failed-test-unit, is returned to the mechanical assembly (W_3) for the problematic parts and components to be changed. After the final assembly (W_3), the WIP is tested at W_4 again with different software packages to ensure its functionality and quality. If the unit does not pass the tests, the WIP is sent back to the mechanical assembly line (W_3) and later to the performance testing station again (W_4). If the performance testing result is satisfactory, the WIP goes through the final inspection (W_5), packaging, and then the final quality control (QC) at W_6. The finished products are then moved to the warehouse and shipping section (W_7) before being shipped to the customers within one to five days. For the returned items, also called Return Merchandise Authorization (RMA) units, an operator first verifies whether the units are under warranty and checks for any physical damage at W_9. The units are then moved to the performance testing station for updating the firmware and further root cause analysis. If parts or components are required for repair, the RMA units are repaired at the mechanical assembly station and then follow the same WIP process.

Additionally, the existing job-shop operation in this study currently employs several key tenets of Lean philosophy including promoting a pull production system and minimizing the level of production through zero inventory strategies, implementing inspection systems to ensure quality at the source with statistical process control and error-proofing “Poka-Yoke”, and promoting a robust visual control or 5S system (Dennis, 2007).

Identification of Wastes

As is common in many operational environments, the facility faces the challenge of having backlogs or a high cost of overtime to catch up on the demand. We review these problems and identify the causes as different types of waste associated with Lean manufacturing. The following details represent the current production planning issues for both upstream and shop-floor levels. Without appropriate production planning, scheduling, and controlling, such non-value-added activities can be observed throughout the facility.

- Without an item level identification, the current Manufacturing Enterprise System (MES) may not differentiate between the models an operator is working on. Thus the production planners do not have visibility into the current status of the work in process. It is then difficult for the planners (upstream activities) to plan for the materials and equipment. This leads not only to ineffective production scheduling and capacity planning (resulting in *Overproduction, Unnecessary Inventory, and Inappropriate Processing Waste*), but also to a lower throughput and increased cycle time (resulting in *Waiting Waste*).
- For the performance testing station, software packages are uploaded to test a specific model before the final assembly. After the final assembly, other software packages must be uploaded for retests. Each model requires different testing structures, different types of software packages, or the same software packages with different testing values. This workstation is clearly a bottleneck: an ineffective testing schedule can delay the overall process due to software setup time and number of WIP and consequently delay the production schedule and shipment date (*Waiting Waste)*.
- Occasionally, the failed-test units may be transferred directly to the final inspection workstation rather than the mechanical assembly station. These

situations happen when an operator puts the WIP in the wrong place and the existing system does not detect the problem immediately (*Transportation and Waiting Waste*). As a result, there may be additional costs associated with having a high rework rate or high return rate from customers (*Defects*).

- After the performance testing, any failed-test units are normally returned to the mechanical assembly station. Sometimes this transfer is delayed and a testing engineer accidentally picks up the failed test units and retests those units again without proper corrective action (*Inappropriate Processing)*.
- The following incidents represent movements of operators that do not add value (*Unnecessary Motion)*. (1) Operators manually scan WIP, failed-test, and RMA units when they are transferred from one workstation to another. (2) Operators spend time searching for misplaced units.

We describe how the wastes and their impacts are measured in Section 5.1.

4. Lean Concepts and Research Hypotheses

As noted by several authors, RFID is an advanced information technology that can be used to facilitate Lean operations (Maurno & Sirico, 2010). Enabled by RFID, real time location systems (RTLS) to track all WIPs in the facility can be developed. However, some Lean theorists have different views of information technology and prefer the traditional Lean practices to technology tools. Maurno and Sirico (2010, pg. 4) explain the dichotomy between Lean concepts and such wireless technology as follows:

> *“Lean consultants accept that technology makes some improvements possible, but as a whole, do not believe that a lack of technology constrains improvement. Still, the Lean and Wireless camps have more in common than they recognize. They use different terms – Lean refers to the gemba, where value is created, whereas Wireless refers to “the edge,” where work is performed – but these are just semantics.”*

Several studies have addressed this issue. For instance, Ward and Zhou (2006) study the impact of information technology (IT) integration and Lean/Just-in-Time practices on lead time performance. The results not only confirm that implementing Lean practices significantly reduces lead time and improves firm performance, but also suggest that the extent of Lean practices is enhanced by improved IT integration. In other words, IT integration can improve the quality of information and consequently facilitate the adoption of Lean practices. Mo (2009) studies the role of Lean philosophy in the application of information technology (IT) in the manufacturing context. The key finding is that applying Lean practices such as a pull system, visualization, and an improved production planning and scheduling system and transforming the business practices to adopt the latest advanced information technology make productivity improvements sustainable.

If such traditional Lean practices can lead to significant reduction in waste, it is surmised that RFID can further enhance such reduction. Table 1 presents the potential reduction in waste through RFID. Specifically, we investigate how wastes in non-RFID environments can be ameliorated in the RFID environment.

Table 1: Summary of Wastes in the Non-RFID Environment and the Potential Reduction in Wastes through RFID

Wastes	Non-RFID Environment	Potential Reduction in Wastes Through RFID
Inventory	More WIP on hand than the customer needs right now	RFID readers immediately update the systems on how many units are WIP, failed-test, and RMA at each workstation; better ordering decision
Overproduction	Producing more than work orders released due to a discrepancy between Manufacturing Enterprise System (MES) and shop-floor activity	RFID readers immediately update the systems on how many units are WIP, failed-test, and RMA at each workstation; better production plans
Transportation	WIP are moved to the wrong place at the wrong time	Systems immediately detect the problem and notify where WIP should be moved
Motion	Non-value-added movement of operators such as for barcode scanning or to search for misplaced units	RFID readers automatically capture the information from the RFID tags and immediately update the systems
Waiting	Waiting for WIP from the previous workstation. Delayed production scheduling	Better item-level visibility helps improve scheduling issue. Waiting time due to the bottleneck issues can be minimized
Processing	WIP are wrongly processed at the wrong workstation at the wrong time	Systems immediately notify an operator whether WIP are suitable for processing at the current workstation.
Defect	High rework or return rate when an operator puts the WIP in the wrong place at the wrong time and they are wrongly processed	Real time update information can improve WIP traceability from one workstation to another. Corrective action is taken before transferring WIP to the warehouse and shipping section.

Thus, to study the potential benefits of RFID technology through a Lean lens, the following research hypotheses are proposed based on existing literature:

H_1: Information visibility through RFID reduces *inventory waste* (producing more WIP than actually needed) compared to that in the non-RFID environment.

H_2: Information visibility through RFID reduces *overproduction waste* (producing more WIP than the work orders released) compared to that in the non-RFID environment.

$H_{3.1}$: Information visibility through RFID reduces waiting time (*waiting waste*) compared to that in the non-RFID environment.

$H_{3.2}$: Information visibility through RFID reduces setup time (*waiting waste*) compared to that in the non-RFID environment.

$H_{4.1}$: Information visibility through RFID reduces assembly time (*processing waste*) compared to that in the non-RFID environment.

$H_{4.2}$: Information visibility through RFID reduces testing time (*processing waste*) compared to that in the non-RFID environment.

Research studies conducted by (Brintrup et al., 2010; Chae et al., 2010; Hozak & Collier, 2008; Maurno & Sirico, 2010; Rahman et al., 2010; Rekik et al., 2008; Su et al., 2009) lead support to these hypotheses regarding the impact of RFID technology utilization on operational performances. These four hypotheses (H_1 to H_4) focus on identifying common forms of manufacturing waste - overproduction, excess inventory, processing, and waiting wastes - to help uncover opportunities for improvement. No hypotheses on *transportation*, *motion*, and *defect* wastes are proposed because in our problem situation, these are taken as given and thus are treated as input parameters. We use real manufacturing data as a baseline case scenario and perform a simulation study on the impacts of item-level information visibility. Input parameters such as the incidents of WIP being moved to the wrong place at the wrong time (*transportation*), time to search for misplaced units (*Motion*), or high rework rate (*defect*) are captured based on the observed historical data. However, we can see the effect of these waste variations on the cycle time and backlog orders in the following hypotheses H_5 and H_6:

H_5: Information visibility through RFID reduces cycle time compared to that in the non-RFID environment.

H_6: Information visibility through RFID reduces the number of backlog orders compared to that in the non-RFID environment.

Support for these hypotheses can be found from Thiesse and Fleisch (2008), Rahman et al. (2010), Hozak & Collier (2008), and Zelbst et al. (2010). H_5 focuses on overall cycle time reduction. Cycle time is measured as the time required to complete one cycle of an operation from released work orders to finished production. H_6 focuses on the backlog orders or delayed shipment, defined as the difference between work orders released and the finished products at the end of the quarter. Both cycle time and backlog orders are considered performance measures directly related to organization's internal operations. Thus, we seek to determine if using RFID technology to enhance information visibility in shop-floor operations will result in improved operational performance, particularly in cycle time and backlog reduction. The details of the experiments are described in the next section.

5. Scenario under Study

The main purpose of this study is to examine whether or not more accurate information visibility at the item level can improve shop-floor performance in the context of Lean initiatives. We do not intend to study any changes in physical flow of parts and components. Our analysis is based on a comparison of the following four scenarios.

- *Scenario #1 (S_1)*: The production line is operated using the existing 1D barcode system.
- Scenario #2 *(S_2)*: A 2D barcode system is deployed to eliminate the drawback of the 1D barcode system and operations.

- *Scenario #3 (S_3)*: RFID is deployed to eliminate the drawbacks of 1D and 2D barcodes and operations (Assuming a 95% read rate).
- *Scenario #4 (S_4)*: RFID is deployed to eliminate the drawbacks of 1D and 2D barcodes and operations (Assuming a 100% read rate).

For the first scenario, we assume that operators follow the established operating procedures. Operators scan all WIP before and after activities at each workstation or when WIP are transferred from one workstation to another. At each workstation, an operator manually records the status of each unit with a signature on a piece of paper/instruction attached inside the tote. This scenario serves as the baseline model representing the current situation on the production line.

One of the problems of 1D barcodes is that they are limited to manufacturer and product type identification, such as a UPC code, and thus cannot differentiate an individual item in that product code family. Scenario #2 employs two-dimensional barcodes or 2D barcodes that can store the manufacturing and product code at the entity level and can uniquely identify a specific item. With a 1D barcode, an operator cannot clearly identify whether the unit being worked on is a WIP, failed-test, or RMA unit. Such information could be available through a database match using a 2D barcode, although barcodes do require a line of sight for data identification and thus take a bit of extra time in information lookup.

Passive RFID tags overcome the drawbacks of the barcode system. However, implementing new technologies may lower the reliability and efficiency of the system through their initial “break-in” and learning phases. Several studies have reported that RFID is still not perfect and data accuracy issues from missing reads or multiple reads do exist (Delen et al., 2007). White et al. (2007) report that RFID is prone to errors during the scanning process due to RFID tag equipment, user errors, misread tags, or RFID tag positioning on the physical objects. Their study finds a 45% error level - 93 errors within the 200 readings taken. The error rate seems extremely high, probably because RFID technology was developing during that period. More recently, Bottani (2008) reports that RFID reading accuracy ranges from 90% to 98% based upon several technology tests at an RFID lab. Scenario #3 (S_3), which addresses this issue, considers the case of 5% reading or scanning errors. Scenario #4 (S_4) is based on 100% read accuracy in RFID readers. In all scenarios, we assume that no errors are caused by (1) raw material issues, (2) the skill of the operators in performing tasks at each workstation, or (3) any machine downtime.

5.1 Parameter Estimates

A regular manufacturing tier consists of several sub-processes starting from managing raw materials to creating a final product. Figure 5 presents the physical and operations flow of items from a production line that can be applicable to any manufacturing tiers in general. For model simplicity, we assume that there are a total of seven workstations (W_1 to W_7) with six waiting areas (I_1 to I_6). Our simulation model is based on the logical flow presented in Figures 4 and 5. The actual data observed in the job-shop assembly line is used as the baseline scenario.

Three different types of totes are tracked using one of the identification techniques: 1D barcode, 2D barcode, and passive RFID tags. These totes include WIP totes, Failed-Test Unit totes, and RMA totes. The 87 unique products can be grouped into

16 product families (F_i when “i” = 1 to 16) according to the similarity in performance testing software packages. For simplicity, this simulation is modeled on a product family basis. Table 2 presents an example of the weekly work orders released (O_i) for all 16 product families with an individual inter-arrival distribution “Triangular (Min, Mode, Max).” This includes both the net firm orders as well as forecast demands for the near future. We use real-world data from the historical 5-quarter timeframe and fit appropriate distributions to those observed data.

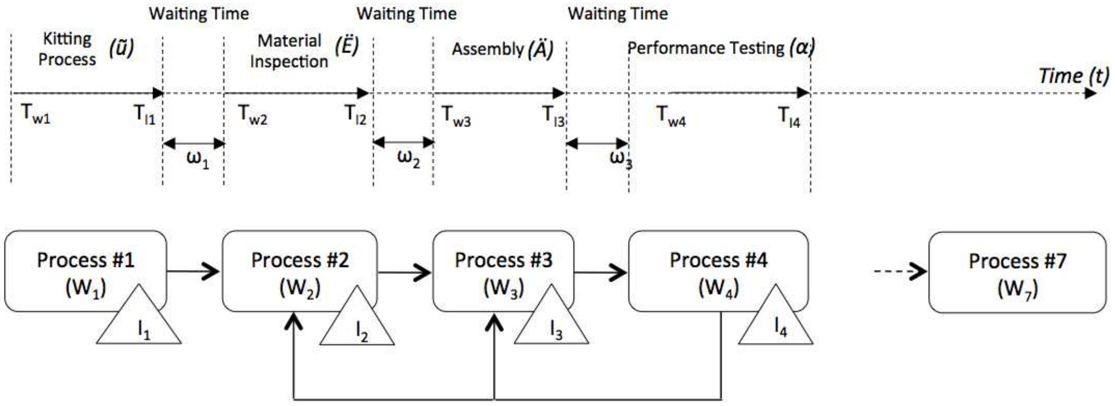


Figure 5: A Typical Production Process

The total time required to process the work orders for each product family at each workstation such as kitting time ($\tilde{u}$), material inspection time ($\ddot{E}$), assembly time ($\ddot{A}$), testing time (α), final inspection time ($\ddot{y}$), and packaging time (ρ) are captured with an individual time distribution for each parameter, either uniform (Min, Max) or triangular (Min, Mode, Max). Table 2 also presents an example of the partial parameter estimates used in this simulation model. Barcode tagging time (B_T), barcode scanning time (B_{ST}), RFID tagging time (R_T), information retrieving time (I_{RT}), or system updating time are also considered. Even though this study is based on real manufacturing process data, a limited amount of data for the RFID scenarios (such as time to code the RFID tags and the time to update the system) comes from a pilot study test on an RFID reader model ALR-9800 (Alien Technology).

Table 2: Parameter Estimates

Global Parameter Estimates

	Parameter Description	Function (Minutes/Unit)
B_T	Barcode tagging time	Random.Uniform (0.167, 0.25)
B_{ST}	Barcode scanning time	Random.Uniform (0.167, 0.2)
I_{RT}	Information retrieving time	Random.Normal (2,0.25)
R_T	RFID tagging time	Random.Uniform (0.25, 0.33)

Parameter Estimates for Product Family #1 (F_1)

	Parameters	Function (Minutes/Unit)
W_1	Kitting time ($\tilde{u}$)	Random.Uniform (4,7)
W_2	Material inspection time ($\ddot{E}$)	Random.Uniform (1,2)
W_3	Assembly time ($\ddot{A}$) – WIP unit	Random.Triangular (95,120,140)
	Assembly time ($\ddot{A}$) – failed test unit	Random.Triangular (30,60,90)
	Assembly time ($\ddot{A}$) – RMA unit	Random.Triangular (30,60,90)
	Quality checking time (CQ)	Random.Uniform (5,10)
W_4	Performance Testing time (α)	Random.Triangular (90,120,150)
W_5	Final inspection time ($\ddot{y}$)	Random.Uniform (1,2)
W_6	Packaging time (ρ)	Random.Uniform (5,7)
I_2	Assigning and training task time	Random.Triangular (1,2,4)
I_3	Time to rearrange the incoming unit	Random.Uniform (1,3)

Work Order Released

PF	The Inter-arrival distribution (Units/week)
O_1	Random.Triangular (0,11,54)
O_2	Random.Triangular (0,37,68)
….	………………….
O_7	Random.Triangular (37,118,382)
O_8	Random.Triangular (15,50,163)
…	………………….
O_{16}	Random.Triangular (0,9,42)

5.2 Scheduling Rules

In this shop-floor operation; two locations (assembly workstation-W_3 and performance testing workstation- W_4) require scheduling decisions. Ineffective decision-making in one location can greatly impact the overall scheduling performance.

5.2.1 Scheduling Rules at Assembly Workstation (W_3)

For W_3, with a 1D barcode, WIP totes are assigned to the workstation based on the traditional Earliest Due Date (EDD) scheduling rule. After improving item-level visibility in 2D barcode scanning (S_2) scenarios, the EDD scheduling rule with priority in assigning tasks can be set based on the purchase order due date or availability of both assembly workstations and performance testing workstations. For instance, in S_2, the operating engineer might set the priority on product family “3” first because the system indicates that the majority of product family “3” are being processed in both assembly (W_3) and performance testing (W_4) workstations. This strategy can improve the flow of operations. All units of product family “3” flow smoothly from W_3 to W_4 without any interruption. As a result, the setup time on the software packages at the performance testing workstation (W_4) can be reduced. However, one of the drawbacks of the existing barcode system is that the engineer cannot differentiate whether the units are regular WIP, failed-test, or RMA units without carefully inspecting the unit or the attached instructions. With RFID technology (S_3 and S_4), the system could accurately update the quantity of WIP, failed-test, and RMA units at each workstation. This information can be used to improve scheduling and assignments.

5.2.2 Scheduling Rules at Performance Testing Workstation (W_4)

Due to limited resources, the performance testing workstation (W_4) can test only one product family at a time. Priority in selecting a particular product family for performance testing is set on the basis of the order due dates, availability of both assembly workstations and performance testing workstations, or special circumstances as follows.

- S_1: a testing engineer selects a tote to test based on the purchase order due date (traditional EDD scheduling rule). In this case, it is possible that software setup time could increase due to frequent changes of models across different totes.
- S_2: the testing engineer knows the exact quantity of units in each product family in this area (ω_2). A priority is set to the product family with the highest quantity. However, without carefully visualizing the unit, the attached instructions, or scanning each tote with a 2D barcode, she cannot differentiate whether the stacks of totes in the waiting area (ω_2) are regular WIP, failed-test unit, or RMA units.
- S_3 and S_4: real time and correct information on each tote is available for the testing engineer to make the right decision. For instance, the system may indicate that 50% of all units in this waiting area (ω_2) are of product family #10 (F_{10}). In a normal case as in S_1 and S_2, she should set the priority to this model (F_{10}). However, with RFID, she may notice anomalies. For example, she may notice that about 40% of all F_{10} models are failed-test units and immediately realize that there might be something wrong with this model. As a result, she postpones processing of this product family and selects the next available set of WIPs whose product family matches the majority of the units being assembled at W_3 to test instead to smooth the operations flow.

5.2.3 Corrective Actions for Misplaced WIPs

In addition to the regular operations, following are examples of two incidents frequently observed in this facility. We note that without RFID technology, such incidents can happen in any scenario without real-time, proper corrective action. As a result, product cycle time increases, fewer throughputs and a bigger production backlog can be expected, and eventually customer satisfaction decreases.

- In final inspection (W_5) and packaging and QC (W_6), only the finished products are allowed. If any WIP or failed-test units are accidentally transferred to this workstation, an automated ID system can immediately notify an operator in those workstations. Such would not be the case in a 1D or 2D barcode setting where the barcode must be expressly scanned to learn of a pending issue.
- Periodically, without carefully looking at the instruction placed in the tote, a testing engineer may accidentally retest the units, which have already been tested and marked as failed-test units. This incident occurs when the tested units are misplaced or have not yet been transferred to the proper location. RFID can quickly help reduce such incidents. For example, assume a test engineer tests a regular WIP unit coded “800 xxx 00” at W_4 with an unsatisfactory result. The unit becomes a failed-test unit and is updated with a new RFID ID coded as “800 xxx 09”. The system may be set up such that it only allows the units with the code ending with number “00” to be tested in this performance testing workstation (W_4). While the test engineer is setting up the workstation to test the incoming WIPs, an automated ID system can immediately notify that there is a unit coded ending with “09” in the testing area. Thus, the chance of retesting the same unit is dramatically reduced.

5.3 Performance Measures

As presented earlier, we develop six research hypotheses to evaluate the effect of information visibility through RFID on eliminating wastes, including overproduction, inventory, processing time, waiting time, cycle time, and backlog (see Table 3). Overproduction measures items that are not part of the current demand and eventually are not required by customers. Meanwhile, excess inventory refers to any WIP inventory that is produced in excess of customer need based on the current or actual demands but can be used once the future demands are released. Waiting time is captured in the form of periods of inactivity or time lost when WIPs are waiting to be processed at each workstation. Processing time is the amount of time required to complete a particular procedure in work area. Cycle time is measured as the time required to complete one cycle of an operation from released work orders to finished production. Backlog or delayed shipment refers to unfinished work that cannot be delivered based on the actual purchased orders. Table 3 presents these performance measures in analytic form.

5.4 Development, Verification, and Validation of the Simulation Model

SIMIO^{TM}, version 2.38, was used to develop the model for our environment. SIMIO is a 3D simulation modeling software. SIMIO employs an object-oriented approach to modeling and has recently been used in many areas such as factories, supply chains, healthcare, airports, and service systems (Pegden, 2007). In order to verify that the model replicates real world operations and performs as intended, random demand variables for all product families generated in this simulation were plotted and compared to the actual data observed in the production line from the last 5-quarter timeframe. For the base case scenario in this simulation model, the number of WIPs, which is the difference between work orders released and the finished products at the end of the quarter for all product families, were examined and compared to the actual data to confirm that the simulation of existing operations produced valid results.

Table 3: Lean Performance Measures

Improvement Measure	Units of Measure
1. Inventory	Inventory occurs when the number of units being produced at the end of the week (N_f) is greater than the actual demands (weekly work order released, O_f), and there are additional work orders released for the following period. $I_{f.t} = N_{f.t} - O_{f.t}$
2. Overproduction	Overproduction occurs when the number of units being produced at the end of the week (N_f) is greater than the actual demands (weekly work order released, O_f), and there is no demand until the end of the planning horizon. $I_{f.13} = N_{f.13} - O_{f.13}$
3. Waiting Time	The average waiting time (ω) (hour/unit/product family), see Figure 5 $\overline{\omega_f} = \frac{\sum_{L=1}^{N_f}(\sum_{k=1}^{K}(\omega_{1,k}+\omega_{2,k}+\omega_{3,k}+ \ldots. +\omega_{6,k})_L}{N}$
4. Processing Time	The average assembly ($\ddot{A}$) and testing time (α) at w_3 and w_4 (hours/unit/product family) $\overline{\ddot{A}_f} = \frac{\sum_{L=1}^{N_f}(\sum_{k=1}^{K}(t_{I3}-t_{w3})_k)_L}{N}$ $\overline{\alpha_f} = \frac{\sum_{L=1}^{N_f}(\sum_{k=1}^{K}(t_{I4}-t_{w4})_k)_L}{N}$
5. Cycle Time	The average time required to complete one cycle of an operation (hours/unit/product family) $\overline{\hat{C}_f} = \frac{\sum_{L=1}^{N_f}(\sum_{k=1}^{K}(\tilde{u}_k+\omega_{1,k}+\ddot{E}_k+\omega_{2,k}+\ddot{A}_k+\omega_{3,k}+\alpha_k+\omega_{4,k}+\ddot{y}_k+\omega_{5,k}+\rho_k+\omega_{6,k})_L}{N}$
6. Backlog	Delayed shipment (units/quarter) The difference between work order released (O_f) and the finished products at the end of the quarter (N_f) $B_f = \sum_{t=1}^{13} O_{f.t} - \sum_{t=1}^{13} N_{f.t}$
Note: “n” is denoted as a subset of N_f (n Є N_f) and N_f is a number of items in each product family “f” “k” is the number of repeated paths a unit passes through during the entire production process “L” is a unique identification number for product family “f” (F_f) and unit # n within the product family “t” indicates number of the week	

The simulation was collected for a quarter (thirteen weeks, assuming a regular working period of 40 hours per week) excluding the warm-up period. Only data in the steady-state condition is considered in order to remove the potential effects of a typical initial system condition. Kelton et al. (2010) explain that too short a warm-up period can lead to start-up bias and too long a warm-up period can increase the sampling error. A warm-up period of 2,000 hours (approximately 7,000 work orders released for all product families) was used to eliminate any effects of initialization bias. Additionally, to address the issue of random variations of the results obtained from the simulation model, we also run the simulation for 15, 30, and 100 replications and compare the parameter estimates such as demand pattern, total time spent at each workstation, or number of backlog orders. To obtain a precise estimate of the true mean, we increase the number of replications, making the confidence interval on the mean of the random variable arbitrarily small (Banks, 1998; Kelton, Smith, Sturrock, & Verbraeck, 2010). Thus, we choose to conduct 100 replications for each simulation run. Lastly, common random numbers are employed for all scenarios to reduce the variability of our simulation results. We follow the guidelines of Sari (2010) and Banks (1998), which contain a detailed discussion of the model development, variance reduction techniques, experimental design, and validation of the simulation model.

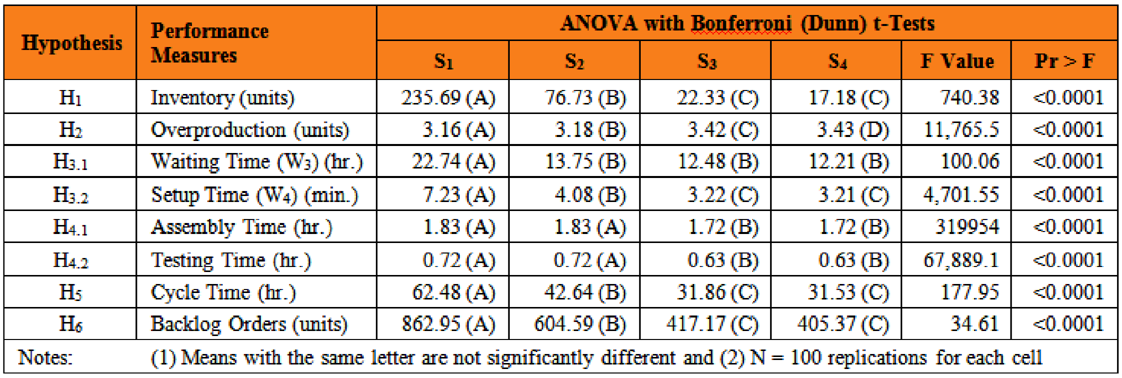
6. Simulation Output Analysis

Both multivariate analysis of variance (MANOVA) and analysis of variance (ANOVA) are run to test each hypothesis using SAS Enterprise. In this study, barcodes and RFID (all four scenarios) are considered the levels of the factor (independent variables). Performance measures such as the various wastes of time, cycle time, or backlog orders are treated as dependent variables. With an appropriate warm-up period (2,000 hours) and 100 replication runs of the simulation model, we assume that randomization produces the factor groups (independent variables) that are roughly equal on all measured characteristics. Although the results of Levene's test for homogeneity indicate that not all performance measures have equal variances across all scenarios, a plot of the data shows that the sample distributions of performance measures across all scenarios have roughly the same shape without extreme scores or skew and the sample sizes are equal (n=100) for each scenario.

6.1 MANOVA Analysis

We are first interested in observing how improved information visibility though barcodes and RFID (independent variables) can explain the variability in a set of dependent variables (overproduction, inventory, processing time, waiting time, cycle time, and backlog orders) simultaneously instead of one dependent variable at a time because we want to control for correlations among dependent variables in the experimental design. According to the MANOVA analysis, all p-values for Wilks' Lambda (F value of 2568.23), Pillai's Trace (F value of 102.26), Hotelling-Lawley Trace (F value of 47,384.4), and Roy's Greatest Root (F value of 141,491) are less than 0.0001. Wilks' Lambda measures the ratio of the generalized error variance to the generalized total variance. Pillai's Trace measures the proportion of variance explained by the model. Hotelling-Lawley Trace measures mean differences among dependent variables. Roy's Maximum Root measures the maximum variance accounted for in a linear combination of the variables. (For more detailed information about MANOVA, see Hair, Black, Babin, Anderson, & Tatham, 1998). These test statistics measures are commonly used to test the hypothesis of no overall scenario effect among all dependent variables in MANOVA. Thus, we can conclude that increasing information visibility at the item level through 2D and RFID technology has a significant effect at the multivariate level on different types of waste, overall cycle time, and backlog orders considered together. Given the significance of MANOVA tests, we conduct ANOVA analysis as presented in Table 4.

Table 4: ANOVA Results



Hypothesis	**Performance Measures**	**ANOVA with Bonferroni (Dunn) t-Tests**					
		S_1	**S_2**	**S_3**	**S_4**	**F Value**	**Pr > F**
H_1	Inventory (units)	235.69 (A)	76.73 (B)	22.33 (C)	17.18 (C)	740.38	<0.0001
H_2	Overproduction (units)	3.16 (A)	3.18 (B)	3.42 (C)	3.43 (D)	11,765.5	<0.0001
$H_{3.1}$	Waiting Time (W_3) (hr.)	22.74 (A)	13.75 (B)	12.48 (B)	12.21 (B)	100.06	<0.0001
$H_{3.2}$	Setup Time (W_4) (min.)	7.23 (A)	4.08 (B)	3.22 (C)	3.21 (C)	4,701.55	<0.0001
$H_{4.1}$	Assembly Time (hr.)	1.83 (A)	1.83 (A)	1.72 (B)	1.72 (B)	319954	<0.0001
$H_{4.2}$	Testing Time (hr.)	0.72 (A)	0.72 (A)	0.63 (B)	0.63 (B)	67,889.1	<0.0001
H_5	Cycle Time (hr.)	62.48 (A)	42.64 (B)	31.86 (C)	31.53 (C)	177.95	<0.0001
H_6	Backlog Orders (units)	862.95 (A)	604.59 (B)	417.17 (C)	405.37 (C)	34.61	<0.0001
Notes:	(1) Means with the same letter are not significantly different and (2) N = 100 replications for each cell						

6.2 *Comparison of Inventory*

The ANOVA results in Table 4 indicate that information visibility through 2D barcodes and RFID has a significant effect on inventory level at the 5% significance level (F = 740.38 and p-value = <0.0001). Further analysis shows that the use of 2D barcodes (S_2) and RFID (S_3, S_4) can reduce the inventory level from approximately 236 units to 77, 23, and 18 units, respectively, compared to the baseline scenario (S_1). The post hoc Bonferroni (Dunn) t-Tests show that increasing information visibility at the item level results in a lower inventory level; there is clearly a considerable difference between the inventory level with 2D barcodes or RFID. The results are reasonable. Work orders are released based on purchase orders and demand forecasts to utilize the workstation capacity and avoid additional workload at the end of the quarter. Although the priority is always set to first produce items from actual purchase orders, without information visibility as in S_1, shop-floor operators may continue working on particular models without realizing that the weekly shipment requirement of those models has been met. As a result, shop-floor resources (labors, machines, and materials) may be allocated inappropriately and inventory level of those models can increase unnecessarily. With 2D barcodes and RFID, once systems know exactly how many units for each product family are at each workstation, the priority is changed to product families that have not yet met the actual purchase order requirements. Consequently, the inventory level declines significantly and the capacity at W_3 and W_4 are utilized more efficiently for other unfinished WIPs. Thus, we can conclude that the results obtained in this section support Hypothesis 1.

6.3 Comparison of Overproduction

Producing more than what customers require (*overproduction waste*) usually results from a discrepancy between the MES system and actual shop-floor activity. The ANOVA results in Table 4 indicate that the information visibility through 2D barcodes and RFID has a significant effect on overproduction levels at the 5% significance level (F = 2,024.83 and p-value = <0.0001). Interestingly, the Bonferroni (Dunn) t-Tests show that increasing item-level information visibility results in increasing the overproduction level and there is a considerable difference among all scenarios. In this study, we are tracking the variation of overproduction within the thirteen week periods of the simulation run. Since increasing information visibility results in more effective use of capacity (due to the reduction in waiting time, setup time, and processing time), there may be available capacity left to work on the lower priority items recommended for production due to forecast demands in addition to the actual purchase orders. When actual purchase orders are not received for the following week, the forecast demand production is considered overproduction in this situation.

For example, in this case, without any information visibility in S_1, the limited resource capacities at W_3 and W_4 are allocated to work on the WIPs with actual purchase orders. There is less additional capacity that can then be utilized for the WIPs released based on demand forecasts. On the other hand, better resource management through information visibility as in the case of 2D barcode and RFID could allow more work orders to be processed to utilize the available capacity. As a result, the chance of overproduction increases somewhat. Although the overproduction issue in this context arises because of possibly incorrect forecast demands, overproduction in a particular model can impact the cycle time and backlog orders for other models. Thus, based on the findings in this section, Hypothesis 2 is not supported.

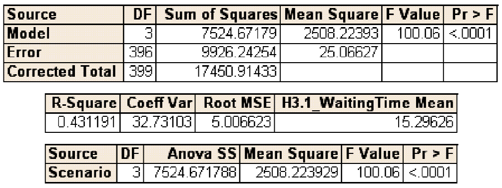
6.4 Comparison of Waiting and Processing Times

With the existing operations, W_3 and W_4 are bottlenecks that can delay the entire production. In other words, the capacity of these two workstations limits the overall production process, resulting in delays in the production schedule and shipment dates. Waiting time ($H_{3.1}$), setup time ($H_{3.2}$), assembly time ($H_{4.1}$), and processing time ($H_{4.2}$) are compared.

The current average time waiting is estimated at 22.74 hours per unit. However, as presented in Figure 6, the average time in waiting declines in the case of 2D barcode (13.75 hours, 39.53% improvement), RFID-95% (12.48 hours, 45.11%), and RFID-100% (12.21 hours, 46.30%). ANOVA results in Table 4 indicate that the information visibility through 2D barcodes and RFID significantly affects waiting time at the 5% significance level (F = 100.06 and p-value = <0.0001). However, the post hoc Bonferroni (Dunn) t-Tests show that there is no difference between the waiting time in S_2 (2D barcodes) and S_3 and S_4. This result implies that 2D barcodes perform almost as well as the RFID scenario.

Setup time ($H_{3.2}$) is another performance measure indicating that increasing information visibility results in decreasing the average time to prepare software packages at W_4. The ANOVA results indicate that 2D barcodes and RFID significantly affect the setup time at the 5% significance level (F = 4,701.55 and p-value = <0.0001). The Bonferroni (Dunn) t-Tests show that there is a considerable difference in setup time between non-RFID and RFID scenarios. The effect of information visibility through 2D barcodes and RFID on assembly time ($H_{4.1}$) and testing time ($H_{4.2}$) at the 5% significance level ($F_{H4.1}$ = 319,954 with p-value = <0.0001 and $F_{H4.2}$ = 67,889.1 with p-value = <0.0001) is also significant. The Bonferroni (Dunn) t-Tests show that there is also a considerable difference between the non-RFID and RFID environments and both assembly and testing times decline significantly with RFID (approximately 10% improvement).

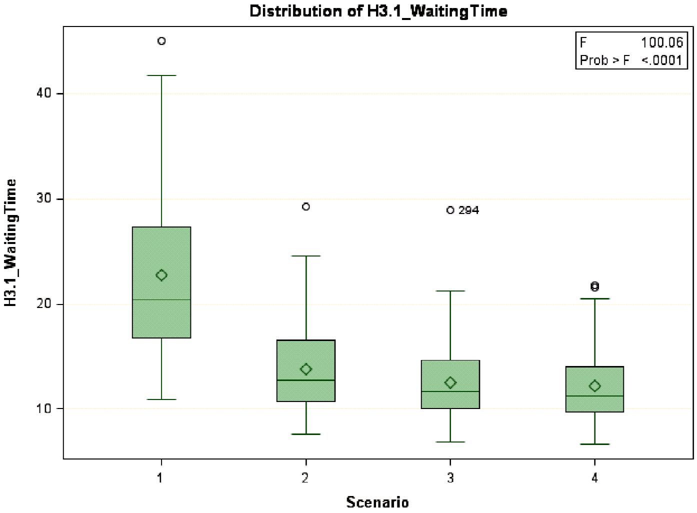
Overall, the appropriate priority setting for working and testing units made possible with RFID helps smooth the operations flow, decreases the software setup time, and reduces the bottleneck at assembly and performance testing workstations compared to the non-RFID environment. Thus, the findings in this section support Hypotheses 3 and 4.

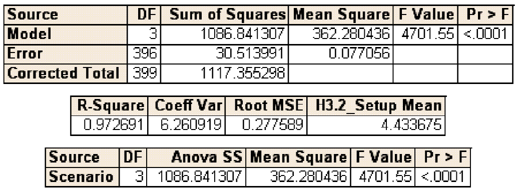


Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	3	7524.67179	2508.22393	100.06	<.0001
Error	396	9926.24254	25.06627		
Corrected Total	399	17450.91433			

R-Square	Coeff Var	Root MSE	H3.1_WaitingTime Mean
0.431191	32.73103	5.006623	15.29626

Source	DF	Anova SS	Mean Square	F Value	Pr > F
Scenario	3	7524.671788	2508.223929	100.06	<.0001





Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	3	1086.841307	362.280436	4701.55	<.0001
Error	396	30.513991	0.077056		
Corrected Total	399	1117.355298			

R-Square	Coeff Var	Root MSE	H3.2_Setup Mean
0.972691	6.260919	0.277589	4.433675

Source	DF	Anova SS	Mean Square	F Value	Pr > F
Scenario	3	1086.841307	362.280436	4701.55	<.0001

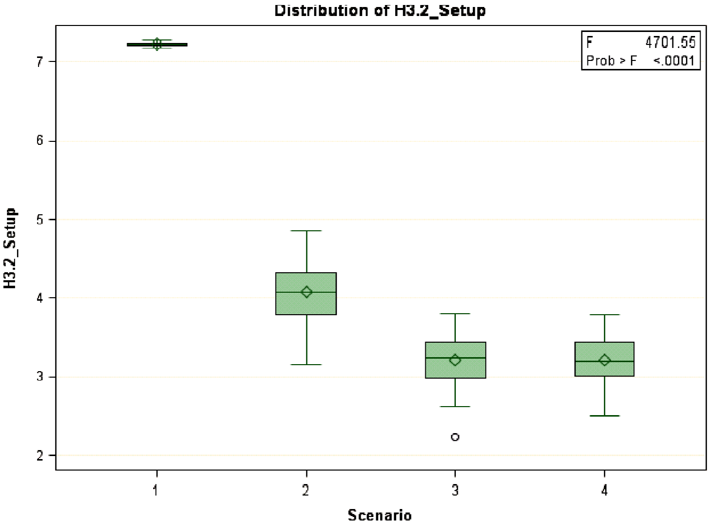
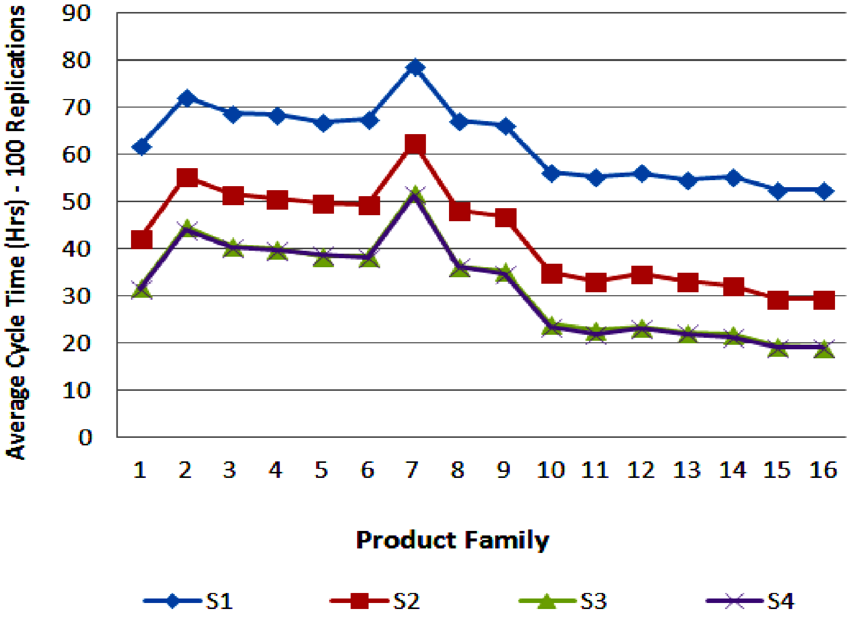


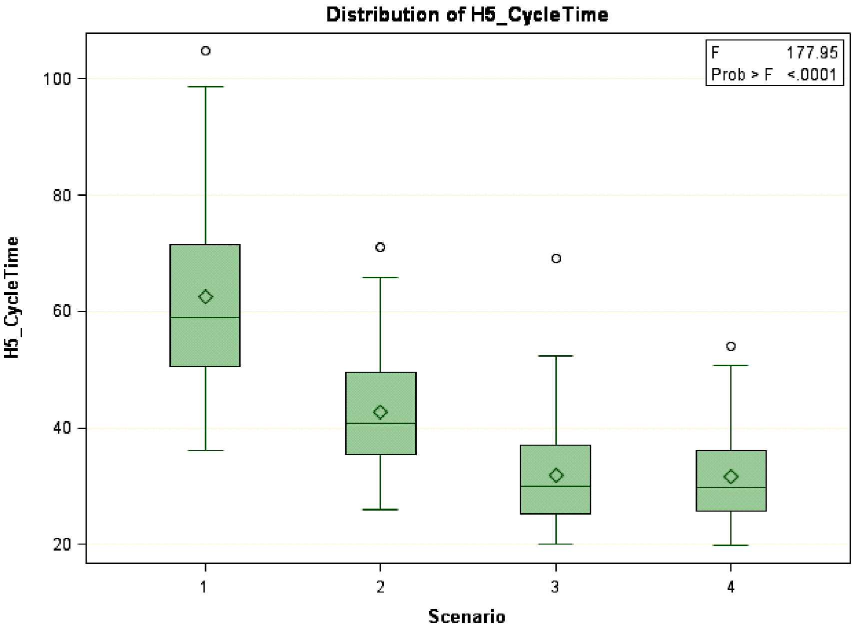
Figure 6: Waiting and Setup Time Comparison

6.5 Comparison of Cycle Times

We next analyze the cycle time for different product families for S_1, S_2, S_3, and S_4 (see Figure 4\7a). For instance, the average quarterly demand for product family #7 (F_7) is 1,421 units. With the baseline scenario (S_1), the cycle time per unit is estimated at 84.96 hours. Cycle time performance improves with 2D barcodes (60 hours, 12%), RFID-95% (52 hours, 43%), and RFID-100% (51 hours, 43%). Similar improved cycle time performances can be seen for other product families. As presented in Table 4 and Figure 7b, ANOVA results indicate that the effect of information visibility through 2D barcodes and RFID has a significant impact on cycle time performance at the 5% significance level (F = 177.95 and p-value = <0.0001). The cycle time for all product families is estimated at 62.48 hours for S_1, 42.64 hours for S_2, 31.86 hours for S_3, and 31.53 hours for S_4. Clearly, 2D barcode and RFID show significant cycle time improvement at approximately 32% and 49%, respectively, compared to the baseline scenario. The Bonferroni (Dunn) t-Tests show no difference between the average cycle time in S_3 (RFID-95%) and S_4 (RFID-100%) and there is a considerable difference between non-RFID and RFID scenarios. When RFID is in use, an operator can keep track of the flow of each item, and make better scheduling decisions using the scheduling approach described earlier. Accordingly, the waiting time at the assembly workstation (W_3) decreases significantly. Similarly, the bottlenecks at the performance testing workstation (W_4) decrease dramatically. However, the time to perform the barcode scanning and tracking activities somewhat offsets the performance gained from item level visibility in S_2 (2D barcode). Thus, we can conclude that the results obtained in this section support Hypothesis 5.



(a)

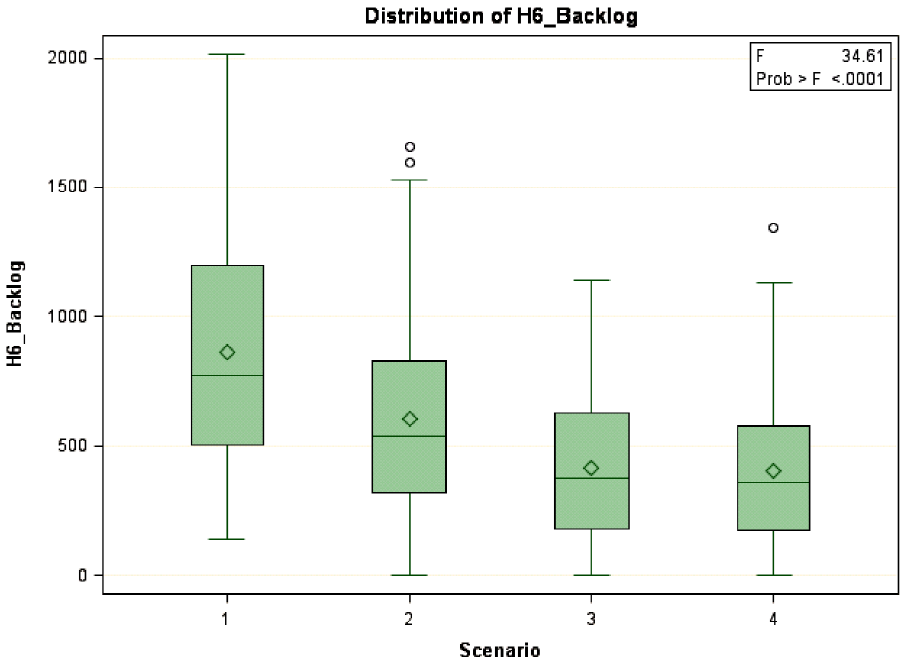


(b)

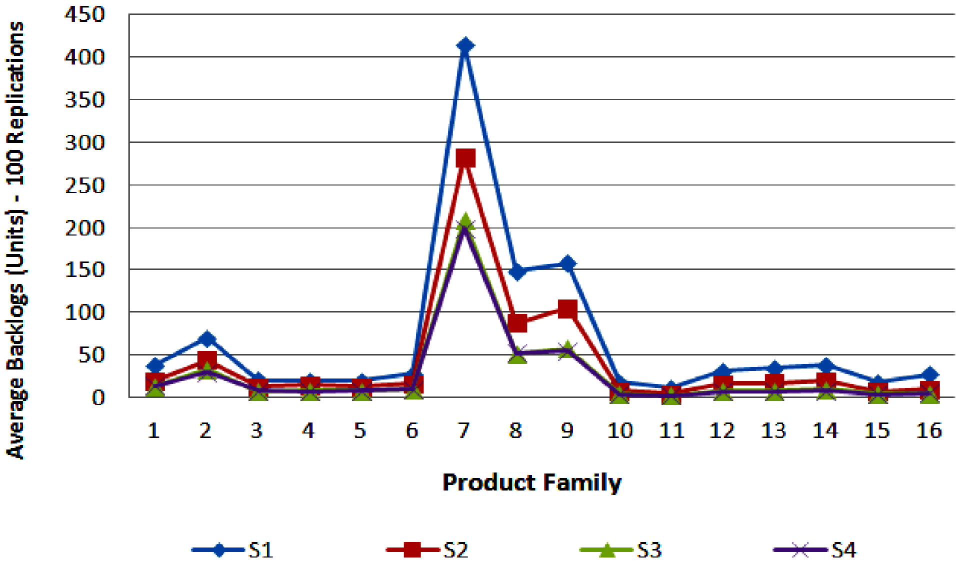
Figure 7: Simulation Results for Cycle Time

6.6 Comparison of Backlog Orders

As presented in Figure 8, the average backlogs decreases when RFID is used. With an average quarterly demand of 7,478 units for all product families, the average backlogs for S_1, S_2, S_3, and S_4 are approximately 863, 605, 418, and 406 units respectively. The ANOVA results in Table 4 and Figure 8a indicate that information visibility through 2D barcodes and RFID significantly affects the backlog orders at the 5% significance level (F = 34.61 and p-value = <0.0001). F_7 in Figure 8b presents a good example of how RFID can facilitate production scheduling and significantly reduce the backlog. The backlog orders drop from approximately 420 units in S_1 to 370 units in S_2 and to 200 units in S_3/S_4. With RFID, the setup times at W_4 and the waiting times to assemble and test the units at W_3 and W_4 are less than those in the baseline scenario. Although S_2 shows improvement, the total time to scan the items and to update the system lessens the benefit gained from information visibility. Both cycle time and backlogs are somewhat correlated and the observed results are correct. As in the case of product family #7, a decrease in average cycle time (in S_2, S_3, and S_4) results in backlogs. Thus, we determine that the findings in this section support Hypothesis 6.



(a)



(b)

Figure 8: Simulation Results for Backlog Orders

6.7 Discussion of Results and Implications

Our results described above show that RFID-enabled approaches to Lean initiatives hold much promise. The six hypotheses proposed in this study capture both discrete and aggregate levels of information visibility assessment. At the aggregate level, we analyze the impact of RFID on inventory level (H_1), overproduction (H_2), cycle time (H_5), and backlog orders (H_6), which are performance measures directly associated with an organization's internal operations. At the discrete level, we focus on the comparative assessment of barcodes and RFID on waiting time ($H_{3.1}$), setup time ($H_{3.2}$), assembly time ($H_{4.1}$), and testing time ($H_{4.2}$) to provide better understanding of performance characteristics. We also separately investigated cycle time at each product family level to ensure that product specification does not affect the performance measures. We ran an ANOVA analysis for each product family individually, and found the hypotheses H_1-H_6 holding in the same manner as at the overall plant level. The simulation results show that the percent reductions in cycle time for 2D barcodes and RFID over baseline scenario across all product families are similar. We use Earliest Due Date (EDD) scheduling rule as a common scheduling rule across all scenarios. The operational lead times at each workstation have also been adjusted, using the same processing-time distributions for all product families. Therefore, we can assume that the influence of product family and process specification on the performance measures (dependent variables) is minimal.

The key findings are summarized in Table 5. As can be seen from simulation results, the ability to capture the status of WIPs in real time can provide valuable information to aid in Lean objectives. When RFID is applied, the model exhibits a superior performance in almost all Lean aspects. The simulation analysis presented in this study first demonstrates the power of employing a Lean lens in understanding the value of information visibility affected by recent automatic identification technologies such as 2D barcodes and RFID. The efficiency in production process arises from better visibility of products. This leads to reduced setup time, assembly time, testing time, and waiting time. The biggest reduction is in waiting time, which results from a smoother and timely flow of WIP from one step to another. Of course, these reductions then lead to a shorter cycle time as well.

However, our results show that although increasing information visibility reduces inventory waste, we observe an increase in overproduction waste in our setting. In a production setting where products are both made to order and WIPs are made to stock in order to improve delivery times for customer orders, increased information visibility surprisingly increases the overproduction wastes. This is because of the practice of preparing WIPs in anticipation of future orders and the capacity becoming available due to more efficient production enabled by RFID. When setup time, waiting time, and processing time decrease through the use of RFID, additional available capacity is then utilized to meet both purchase orders and forecast demands.

Our results are somewhat contradictory to other studies (Brintrup et al., 2010 and Maurno & Sirico, 2010) in the situation when RFID is only used to keep track of the finished products. In our case, real-time tracking information of WIP through RFID is utilized to facilitate production scheduling in the shop-floor operations. Thus, overproduction waste is possible.

Table 5: Summary of Key Findings

#	Performance Measures	Key Findings	Remarks
1	**Inventory level**	The use of 2D barcodes and RFID significantly reduce the inventory level approximately 70% and 90%. There is a considerable difference between non-RFID and RFID scenarios.	RFID > 2D barcodes > 1D barcodes
2	**Overproduction**	Increasing information visibility at the item level results in increasing overproduction level! When RFID is used, the average overproduction increases at approximately 8%.	1D barcodes > 2D barcodes > RFID
3	**Waiting time**	Appropriate priority setting for working and testing units made possible with 2D barcodes and RFID helps decrease average waiting time at W_3 at approximately 39% and 45%, respectively. However, 2D barcodes performs almost as well as RFID scenario	2D/RFID > 1D barcodes
4	**Processing time**	The average assembly time (W3) and testing time (W4) decreases when RFID is used. Although there is no difference between 1D and 2D barcodes, RFID shows a reduction in processing time at approximately 12%.	RFID > 1D/2D barcodes
5	**Cycle time**	The average cycle time significantly decreases in the case of 2D barcodes (32%) and RFID (49%). There is a considerable difference between non-RFID and RFID scenarios.	RFID > 1D/2D barcodes
6	**Backlogs**	The average backlogs decrease when RFID is used (approximately 50%) and there is a considerable difference between non-RFID and RFID scenarios.	RFID > 2D barcodes > 1D barcodes

7. Conclusion

Our investigation of the effect of RFID implementation on the Lean manufacturing perspective focuses on which types of waste can be reduced and how this reduction impacts the operations performance. Using discrete-event simulation, we assess the value of RFID deployment in the context of an actual company’s manufacturing operations.

In the shop-floor operations, it is essential that production planners not only know where WIPs are and when they are transferred from one workstation to another, but more importantly, that they can utilize this granular level of information to facilitate production scheduling activities such as rescheduling production tasks or prioritizing particular WIPs. An important observation can be made with respect to the comprehensive simulation experiments and statistical analysis of the simulation outputs. It appears that both 2D barcodes and RFID offer a great opportunity to reduce variation in operations (inventory, overproduction, processing time, waiting time, cycle time, and backlog orders) compared to the current 1D barcodes. However, the total time to perform the 2D barcode scanning and tracking activities somewhat reduces the performance gained from item level visibility. Additionally, 2D barcodes still require a line of sight for data identification, while these issues can be easily overcome by using RFID. The results show that the benefits gained from RFID implementation are greater than those from 2D barcodes in all aspects.

Our study contributes to both theoretical and managerial bodies of knowledge. This is the first study to have studied specific wastes associated with Lean manufacturing in an RFID setting. For managers who seek to improve their shop-floor/job-shop operations, this study serves as a case example on how RFID can be applied in manufacturing settings with the goals of reducing cycle time or backlogs to increase customer satisfaction. For any Lean adopters who are responsible for continuous improvement, this study shows that RFID can complement Lean manufacturing. Specifically, this study outlines how more accurate information from RFID helps in eliminating wastes in the operations. In either case, this study also raises awareness that RFID is not an absolute solution even with the perfect RFID implementation. RFID shows significant improvement over almost all aspects of Lean manufacturing operations. However, excess inventory and waiting time still exist, as well as a significant backlog given the current capacity and production planning process. More importantly, this study shows that RFID can increase the chance of overproduction as a result of improved information visibility. Overall, backlogs decrease significantly and the benefits gained from RFID (reducing cycle time, avoiding penalties due to late shipment, or reducing overtime costs to catch up all backlogs) far exceed the overproduction issue.

This work has implications for further research. Although this study validates the view that information visibility can improve manufacturing operations by specifically reducing various wastes commonly encountered in such settings, this result should be validated in other manufacturing environments such as assembly lines. Obviously, results of all simulation studies need to be validated in actual field situations.

Innovative wireless technologies such as RFID have not been convincing to many Lean practitioners, especially those who have historically relied on traditional Lean principles such as standardized work, process stability, pull level production, or quality at the sources. These practitioners are making limited efforts to adopt RFID technology. Thus, it would be interesting to analyze the shop-floor performance when traditional Lean practices are established with and without the presence of RFID. This would provide a better view of the connection between Lean manufacturing and information technology.

Another possible extension of this study is to test the performance of RFID implementation against traditional production scheduling strategies. In order to determine what WIPs to process next at each workstation, scheduling rules such as First-In-First-out (FIFO), Earliest Release Date First (ERD), Earliest Due Date (EDD), or Shortest Processing Time (SPT) can often be found in practice. It would be interesting to learn how RFID can facilitate job-shop production scheduling activities and compare the results with the classical scheduling techniques (FIFO, ERD, EDD, or SPT) that do not utilize any real-time location information. Additionally, the decision to move forward with RFID or delay RFID investment depends on the return on Investment (ROI). Thus, there is a continuing need to evaluate the economic impacts of implementing RFID.

In conclusion, the ability to track WIPs in real time through wireless technologies such as RFID and 2D barcodes and utilize such information to stave off bottlenecks in assembly and testing workstations is an example of how these technologies can be used as a driving tool to improve internal processes and operations, which complements Lean objectives. With a complete analysis of how RFID can help achieve Lean objectives by reducing waste in shop-floor operations, both RFID and non-RFID adopters can make better-informed decisions to move forward with RFID or choose other familiar and less expensive alternatives.

ACKNOWLEDGEMENTS

The authors thank the associate editor and two anonymous referees for their constructive comments on earlier versions of the paper. They also thank Bill Hardgrave for jointly exploring potential applications of RFID in manufacturing.

CHAPTER III

STUDY #2: RFID-ENABLED TRACK AND TRACEABILITY IN JOB-SHOP SCHEDULING ENVIRONMENT

1. Introduction

In most manufacturing situations, physical and information flow of products from the raw materials, parts, components, and work-in-processes (WIPs) to the end products can become quite complex. Without full information on any delays or interruptions in the production processes, companies face the issues of ineffective production planning, scheduling, and control, missing items, low product quality, or high defect level. Many automatic identification technologies (AITs) such as Radio Frequency Identification (RFID) offer the track and trace capabilities. RFID is built around the idea that, to search for things without too much time and trouble, one can simply put radio transceiver tags on physical objects; the tags can then be used to find those objects (Brazeal, 2009; Brown, 2007). RFID has been used extensively in improving business performance in warehouse and distribution centers, logistics, and inventory management across the supply chain. Furthermore, the trend toward implementing RFID in other areas such as a hospital or manufacturing processes is increasing (Gunther, Kletti, & Kubach, 2008; Hunt, 2007; Jones, 2008).

A majority of literature on RFID is supply chain oriented, focusing on tracking items as they move through the operations channels. Only a few studies consider the potential of RFID-improved track and traceability in manufacturing operations such as job shop or assembly line improvement, quality inspection, or work-in-process (WIP) monitoring. In exploring this potential of RFID in manufacturing, the question arises, under what conditions information visibility-enabled track and traceability improve manufacturing performance and how? To answer this research question, this study focuses on job shop production scheduling perspectives. Scheduling tasks are very important to meet customer demands by optimizing time, productivity, defect level, product quality, and cost. Thus, the goal of this study is to examine how track and traceability through RFID can facilitate job shop production scheduling activities and under what settings such information visibility can add value to an organization. We also study the impact of RFID on capacity utilization and under the conditions of demand variation and raw material shortage. We seek to study the benefit of information visibility is even greater when the current scheduling plan is inevitably changed due to these disruptions (changes in demand pattern or jobs' due date, delays in the arrival of raw materials, or machine downtime).

After describing the related literature in the next section, we propose a dynamic tracing-based scheduling rule in Section 3. In Section 4, we take a case study of an organization that is considering adding RFID to integrate with its manufacturing enterprise system. Thus, our evaluation and justification of RFID deployment is based on real manufacturing process data. Section 5 describes the specific implementation of the scheduling rule for our case study situation. Section 6 presents the simulation model built for the evaluation. We describe the results of the simulation in Section 7, followed by conclusion in Section 8.

2. Literature Review

2.1 RFID and Traceability in the Literature

The term "traceability" has been defined variously. According to the International Standards Organizations (ISO8492: 1995), traceability is the ability to trace the history, application or location of an entity, by means of recorded identifications (ISO, 1995). Meanwhile, in the context of manufacturing perspective, Nair and Shah (2007, p.8) define traceability as "to knowing everything that happened to a product through the manufacturing process – from the initial raw material to final product, including details on operators who worked on the product (or component that was built or mixed into product), equipment and tools used in the manufacturing process, rework that was done, and the status of production process control limits among others" (Nair & Shah, 2007).

With regards to traceability improvement, RFID technology has been applied in many different areas. Delen et al. (2007) conducted a case study to explore the potential benefits of RFID on supply chain management. Based upon actual RFID data from a major retailer, the findings of this study indicate that RFID can enhance information visibility to allow a detailed view of the performance of the supply chain. They emphasize that it is not just the RFID technology itself that creates value to the business performance but rather the creative use of the data obtained by this technology that can help make better business decisions (Delen, Hardgrave, & Sharda, 2007). Sari (2010) studied the impact of RFID on supply chain performance. A simulation framework presented in the study focuses on four-echelon supply chain including a factory, a warehouse, a distributor, and a retailer. The results show that RFID can benefit a supply chain when (i) the level of collaboration among echelons increases, (ii) the level of uncertainty in customer demand decreases, and (iii) the lead times along the supply chain are longer (Sari, 2010).

Lee and Park (2008) propose a model to dynamically trace the end item and its subparts included in the Bill of Materials (BOM). Their study provides an example of a dynamic tracing model focusing on a hypothetical physical flow of items in the manufacturer tier. RFID, tagged on both end items and subcomponents, is exploited to keep track of the information on the specific location, the time spent in that location, and eventually the history of an entity throughout the manufacturing tier. This information is then transformed into path information sets with specific path connection rules that connect the linkage between the end item and its subparts to obtain the full traceability (Lee & Park, 2008). We next briefly review the use of RFID in production scheduling.

2.2 RFID and Production Scheduling in the Literature

Scheduling has been defined in different ways. Stevenson (2007, p.721) defines scheduling as “establishing the timing of the use of equipment, facilities, and human activities in an organization (Stevenson, 2007).” Heizer and Render (2006, p. 518) refer to aggregate scheduling as “determining the quantity and timing of production for the intermediate future … with the objective of minimizing cost over the planning period (Heizer & Render, 2006).” In the job shop environment, scheduling refers to a set of activities in the shop that transform inputs, a set of requirements, to outputs, products to meet those requirements (Nahmias, 2004, p. 403). In a manufacturing facility, Hermann (2006) defines production scheduling systems as a dynamic network of persons who share information about the manufacturing facility and collaborate to make decisions about which jobs should be done when. The information shared includes the status of jobs (also known as work orders), manufacturing resources (people, equipment, and production lines), inventory (raw materials and work-in-process), tooling, and many other concerns (Herrmann, 2006, pg. 94).

Even though some scheduling problems can be formulated as linear programs, there are many problems that quickly become large and complex. This is known as NP-hard, a class of combination optimization problems that optimal solutions are limited by the amount of computer time (Pinedo, 2009). Many books such as Herrmann, 2006 and Pinedo, 2009 provide a more detailed review the literature in the area of scheduling algorithms or schedule generation methods, which are beyond the scope of this study. In practice, instead of trying to solve scheduling problems optimally, dispatching rules have been introduced as they produce acceptable feasible solutions within some acceptable computational time. Dispatching rules are used to prioritize the jobs that are waiting for processing in the machine queue (Pinedo, 2009). Dispatching rules can be classified in various ways. Although many techniques (Shortest Processing Time – SPT, Longest Processing Time First – LPT, Most Work Remaining – MWKR, Fist In First Out – FIFO, Last In First Out – LIFO, The Shortest Setup Time First – SST, or The Shortest Queue at the Next Operation – SQNQ) do exist in literature, we describe only a few representative ones that are relevant to our case study (Dominic, Kaliyamoorthy, & Kumar, 2004; Pinedo, 2009):

- *The Service in Random Order (SIRO):* No priority is given to the waiting jobs. The next job is selected randomly.
- *First In First Out (FIFO):* the priority is given to the waiting jobs that arrive at the queue first. This rule is equivalent to the Earliest Release Date First (ERD). The objective is to minimize the variation in the waiting times of the operation.
- *The Earliest Due Date First (EDD):* the priority is given to the jobs with the earliest due date with the objective of minimizing the maximum lateness among the jobs waiting to be processed.

Several studies have explored the use of RFID to facilitate and improve production scheduling. Shibata et al. (2006) introduce RFID technology at production sites through “the Production Process Monitoring Solution” in order to visualize the production process in the production line in real time and to support the efficient operational improvement and the utilization of data collected by RFID (Shibata, Tsuda, Araki, & Fukuda, 2006). Huang et al (2007) propose the RFID-based approach to improve the real time shop-floor information visibility and traceability at a walking-worker fixed-position flexible assembly line. This type of shop floor environment normally has limited spaces at work centers with high dynamics of material and worker flows and is suitable for a modest variety of products and production volumes. Their study demonstrates how RFID can facilitate and smoothen the production flow in such environments (Huang, Zhang, & Jiang, 2007). Zhou et al (2007) develop the RFID-based remote monitoring system for internal production management. Accordingly, the flow of raw materials, work in processes, finished products, and information is transparent through the central monitoring system (Zhou, Ling, & Peng, 2007). Huang et al (2008) present RFID-based wireless manufacturing approach to improve shop-floor performance. They describe how RFID can manage work in process (WIP) inventories in job shop environment, which normally suffers from a bottleneck of capturing and collection of real-time information. Liu and Chen (2009) apply RFID technology to improve production efficiency at an IC packaging house. The study indicates that RFID can reduce the operating time, eliminate data processing errors, eliminate clients' complaints and penalties, reduce operator's workload, and increase productivity.

Another important issue in dynamic scheduling decisions is to cope with unexpected events or disruptions that occur in the operations. These disruption scenarios include (1) the arrival of new urgent work orders released, (2) changes to a job's due date, (3) delays in the arrival of raw materials, and (4) limited resource capacity. Although many studies (Duwayri, Mollaghasemi, Nazzal, & Rabadi, 2006; Li, Shaw, & Martin-Vega, 1996; Vieira, Herrmann, & Lin, 2003) propose different scheduling heuristics to tackle the challenges of changes or disruptions in dynamic rescheduling environments, these studies have not utilized information visibility through RFID to improve the existing rescheduling policy. In fact, they merely focus on finding optimal schedules or improving scheduling decisions in dynamic manufacturing environment through the mathematical analysis of production scheduling problems by assuming that all data is known with certainty. Real-time monitoring of those deterministic assumptions is required in order to enhance or adjust the existing production schedules appropriately. Thus, to our knowledge, no study has focused on how track and traceability through RFID can help in achieving better job shop scheduling, especially in facilitating dynamic scheduling activities in shop-floor operations. Although these studies point out the importance of tracking WIPs or finished products in real time in the operations and illustrate the value of location information to facilitate scheduling activities, they have not proposed and evaluated how RFID can facilitate rescheduling tasks or update an existing plan when disruption situations or unexpected events occur in the shop-floor operations. Thus, our study aims to partly address this gap by proposing a traceability-based information visibility model and investigating how an RFID-based scheduling rule can facilitate job-shop scheduling activities.

3. Proposed Visibility-Based Scheduling (VBS) Rule

Job-shop scheduling activities are viewed as a decision making process, involving and requiring interaction with many functions in an enterprise. Most of the scheduling input data such as production plans, master schedules, capacity planning, or resource allocation are prepared at a higher planning level (e.g. ERP system) before the detailed scheduling tasks begin. Orders released to the shop floor are determined based on inventory levels, demand forecasts, and resource requirements. Accordingly, production planners prepare an operational schedule and release it to the shop floor. The most important scheduling task is to determine which jobs should be done and when these jobs should begin and end. The information is used (i) to prioritize jobs for production, (ii) to sequence production tasks, and (iii) to assign and reassign manufacturing resources such as people, equipment, raw materials, work-in-process, tooling, or production lines (Herrmann, 2006; Pinedo, 2009).

Figure 9 presents a real time track and traceability-based scheduling rule that utilizes improved information visibility from RFID. RFID is deployed at the shop floor level to provide a unique identification to every work-in-process (WIP) along with major parts and components throughout the production line. This means that the production planners can immediately identify, locate, and appropriately address all work orders/units in the facility. The gap between physical and information flow of the work orders is reduced and, consequently, the planners know exactly which units are being worked on. As presented in Figure 9, the visibility-based scheduling (VBS) rule begins when the planners release work orders to the shop floor operations based on actual customer demand as well as demand forecasts (A). Usually, there are multiple products or different product families processed in the shop-floor operations. The planners are also able to determine whether the raw materials are available for the production run (B) and determine both utilized and available capacity at each workstation (C). If there are rush jobs waiting at the operating workstation (D), the priority is then set to those jobs first (E). Any changes to the jobs due to material shortage or machine failures are reported in a timely manner (F). The planners can reschedule the current plan and set the highest priority to the product family that has the highest penalty cost per backlog (G). With RFID, the planners are also able to determine the total quantity of WIPs for each product family waiting and being processed at the next workstation (H and I). This information visibility leads to significantly improved operational flow, especially when each product family may require different production procedures or require significant set-up time for material and machine preparation. If the incoming WIPs at the current workstation are from the same product group that are mostly processed at the next workstation, the priority can be set to those groups to increase the flow of the production run (J). Likewise, if the incoming WIPs are from the same product group as being run on the machine currently (K), the priority is set to those groups to reduce setup time (L). Otherwise, an operator at the workstation can select the unprocessed units that have the longest waiting time (N) or select units using the traditional scheduling rules (O) such as earliest due date (EDD).

With RFID, the planners can keep track of when the WIPs actually arrive or leave specific workstations and can determine the exact time WIPs actually stay at each workstation. This information is very helpful to the scheduling tasks. As presented in Figure 10, if the average processing time of the selected WIPs is longer than historical data (P), the planners can stop the production on that product family, conduct a root cause analysis, and select other units instead (R). RFID also allows tracking the rework or failed WIPs for each product family in real time. If the percentage of reworked units is greater than the predetermined threshold, proper corrective action can be made to avoid unnecessarily utilizing the current shop-floor resource capacity (R).

Additionally, the RFID system can recognize whether or not WIPs are appropriate for a specific workstations. The incident of putting the WIPs in the wrong place at the wrong time is immediately identified. Thus, the ability to capture the status of those orders in real time provides valuable information to the job shop scheduling process. With the information support from RFID, the shop floor units can control the implementation of production and scheduling plans and provide feedbacks back to the system (ERP and MES) so that the production planners can periodically generate new schedules or revise the existing schedule. A detailed explanation of how RFID is applicable in shop-floor operation and how track and traceability through RFID provides valuable inputs to scheduling tasks is presented in the next section

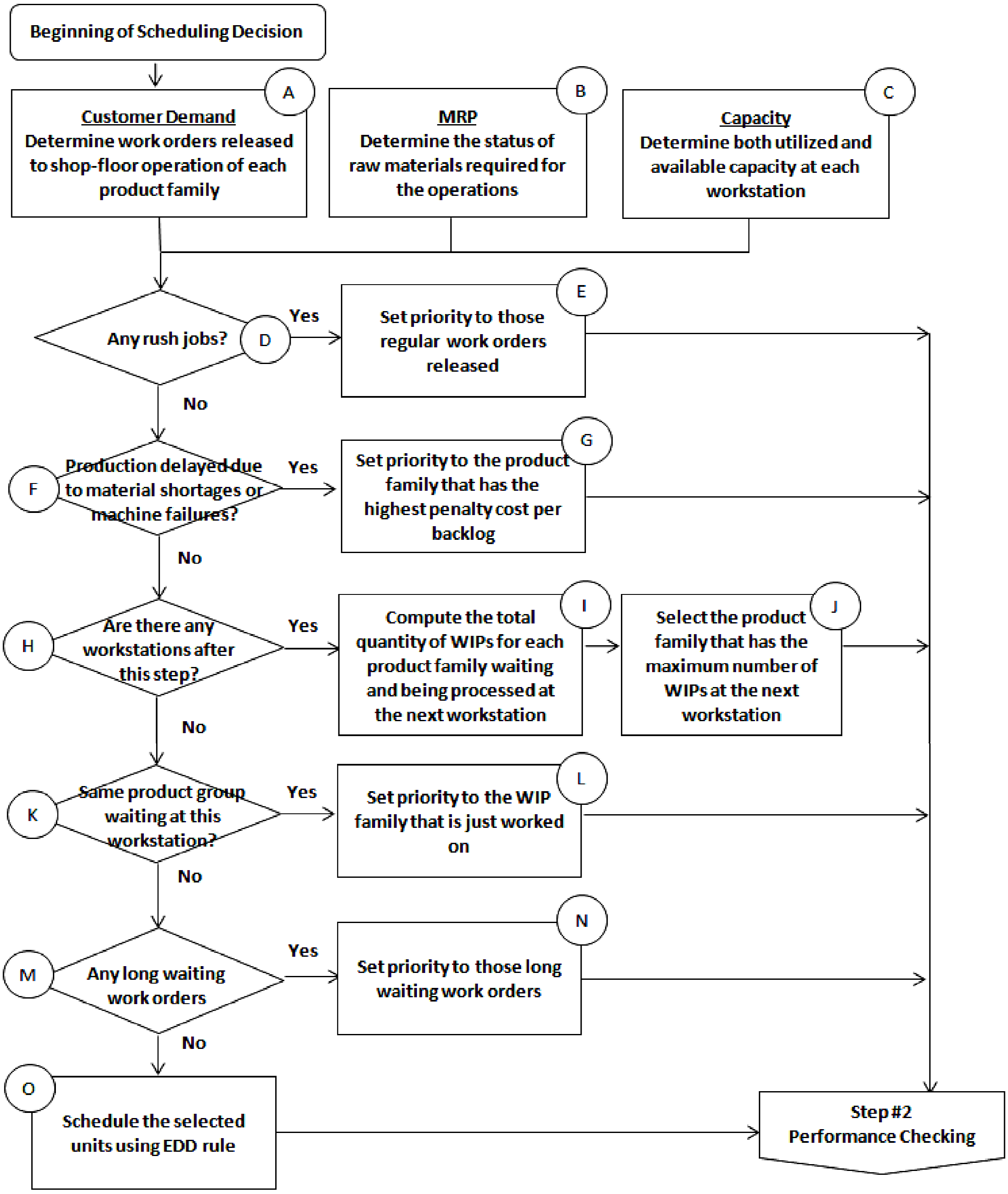


Figure 9: Visibility-Based Scheduling (VBS) Rule

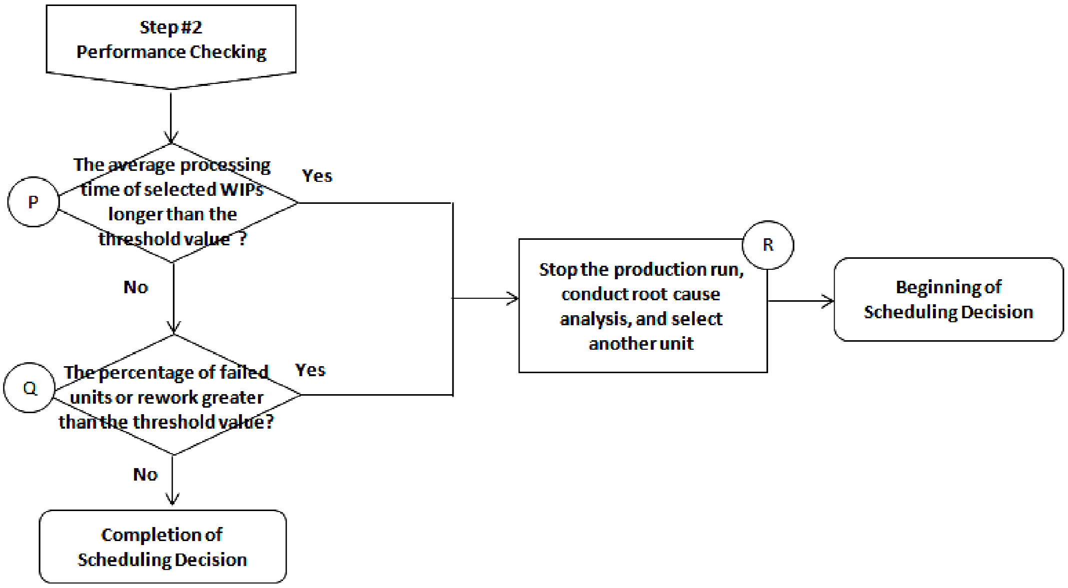


Figure 10: Visibility-Based Scheduling (VBS) Rule (Step #2)

3.1 Dynamic RFID-based Traceability Framework

In order to develop a RFID-based traceability system, first we need to determine whether the desired RFID system is a closed-loop system or an open-loop system. In any closed systems, the tracked objects are only recorded internally and the systems do not require any RFID activities (tagging and reading) outside the organization. All of the data related to the objects is maintained and reused locally with the complete history of the tracked objects. Since such systems do not require sharing information with any participants from other value chains or partners (such as suppliers, retailers, or customers), nonstandard designators can be used and the usual concerns about the absence of RFID standards do not apply. By contrast, an open-loop system is utilized when RFID tags, which are attached to the objects at the beginning of its processes, permanently remain on the tracked objects along the entire chain. Open-loop system permits utilization by two or more enterprises. Basically, the complete history of the tracked objects can be shared and accessed by these enterprises. For instance, in a supply chain, manufacturer can use such data for production control, while a dealer accesses the same data for inventory purposes. Usually, RFID standards or special agreement is necessary to share information to generate appropriate benefits among enterprises and to optimize their cost effectiveness (Bartneck, Klaas, & Schoenherr, 2009; Hansen & Gillert, 2008). This study assumes a closed-loop RFID system. All WIPs, parts, and, components are tracked using passive rewritable RFID tags.

We begin with a general job shop framework. Regular manufacturing tiers consist of several sub-processes starting from managing raw materials to creating a final product. Figure 11 presents a physical and operations flow of items in a production line, which is applicable to any number of manufacturing tiers in general.

For model simplicity, let us assume that there are a total of seven workstations (W_1 to W_7) with six waiting areas (I_1 to I_6). We use the symbol "P_{ijk}" to represent a path where a unit is transferred from one location to another.

Let i = the current location where a unit is being processed

j = the destination a unit is being transferred to

k = the number of repeated paths a unit passes through the path i-j during the entire production process

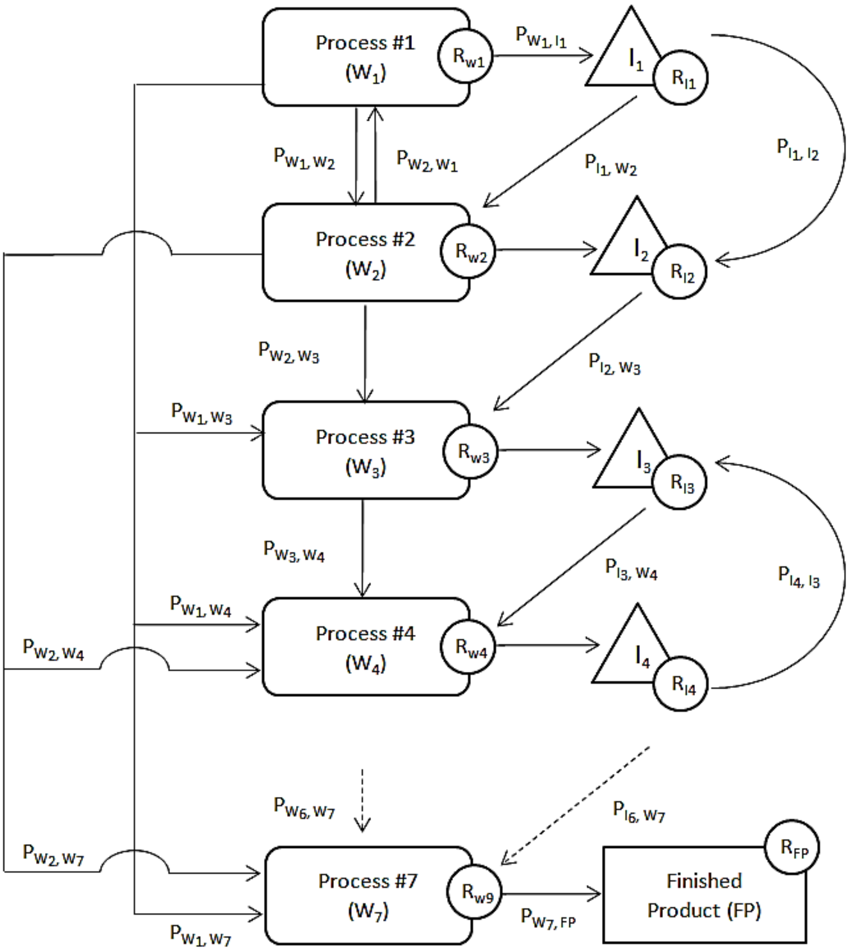


Figure 11: General Production Process

For instance, $P_{W_1, I_1, 1}$ represents a path when a unit is transferred from W_1 to I_1 for the first time or $P_{W_1, W_2, 1}$ represents a path when a unit is transferred directly from W_1 to W_2 without passing through a waiting area. If a unit travels on the same path twice from W_1 to W_2, the RFID reader at W_1 (R_{w1}) will read the tag and the system will note it as $P_{W_1, W_2, 2}$. Each workstation may have different sub-workstations or different capacities. We assume that each sub-workstation can only process one unit at a time. Different production routing for each unit can be expected throughout the production line. In fact, each unit may have to undergo multiple operations on a number of specific workstations. Different production routings including bypassing or revisiting a workstation several times can be expected throughout the production line.

Another way of looking at the flow of WIPs is via a timeline. Figure 12 illustrates the RFID reading times as WIPs flow through the production line.

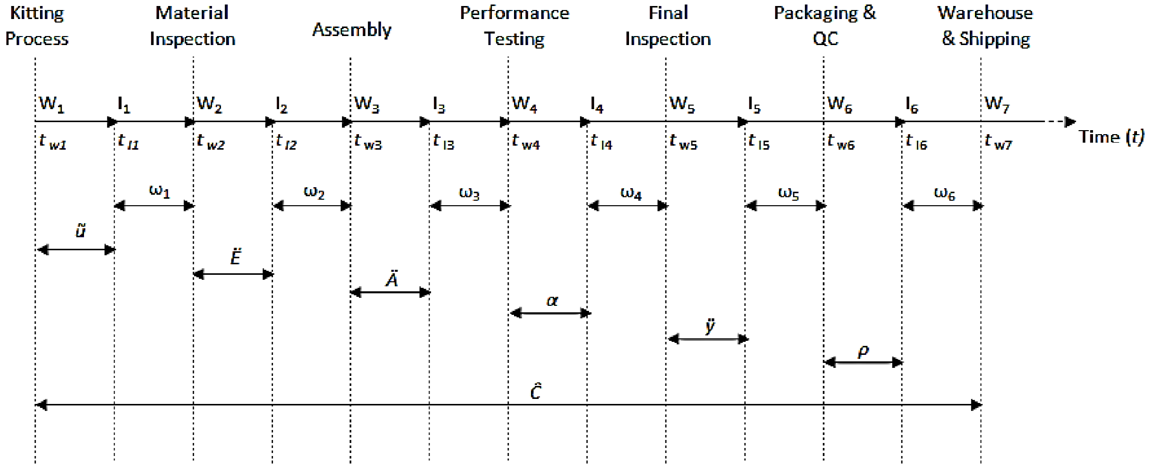


Figure 12: The Timeline for the WIPs Movement Reads in the Production Line

As presented in Figure 12, t_{w1} through t_{I7} represent RFID reads at various locations from the kitting process in W_1 to the warehouse and shipping (W_7). From the RFID data reads, we can compute waiting time (ω), kitting time ($\tilde{u}$), material inspection time ($\ddot{E}$), assembly time ($\ddot{A}$), testing time (α), final inspection time ($\ddot{y}$), packaging time (ρ), and cycle time ($\hat{C}$) as follows. Note that each reading recorded as any particular combination of production families, item # with that product family, time, and location, is tagged as observation “L”, out of N_f reading. In other words, “L” is a specific tag for product family “f” (F_f) and unit # n within the product family. Let us denote “n” as a subset of N_f ($n \in N_f$) where N_f is the number of items in each product family, “f”. However, for ease of reading, we will skip the subscripts “L” in the following.

$$
\begin{array}{llll@{\qquad}llll}
\tilde{u}_k & = & (t_{I1} - t_{w1})_k & (1) & \alpha_k & = & (t_{I4} - t_{w4})_k & (7) \\
\omega_{1,k} & - & (t_{w2} - t_{I1})_k & (2) & \omega_{4,k} & = & (t_{w5} - t_{I4})_k & (8) \\
\ddot{E}_k & = & (t_{I2} - t_{w2})_k & (3) & \ddot{y}_k & = & (t_{I5} - t_{w5})_k & (9) \\
\omega_{2,k} & = & (t_{w3} - t_{I2})_k & (4) & \omega_{5,k} & = & (t_{w6} - t_{I5})_k & (10) \\
\ddot{A}_k & = & (t_{I3} - t_{w3})_k & (5) & \rho_k & = & (t_{I6} - t_{w6})_k & (11) \\
\omega_{3,k} & = & (t_{w4} - t_{I3})_k & (6) & \omega_{6,k} & = & (t_{w7} - t_{I6})_k & (12)
\end{array}
$$

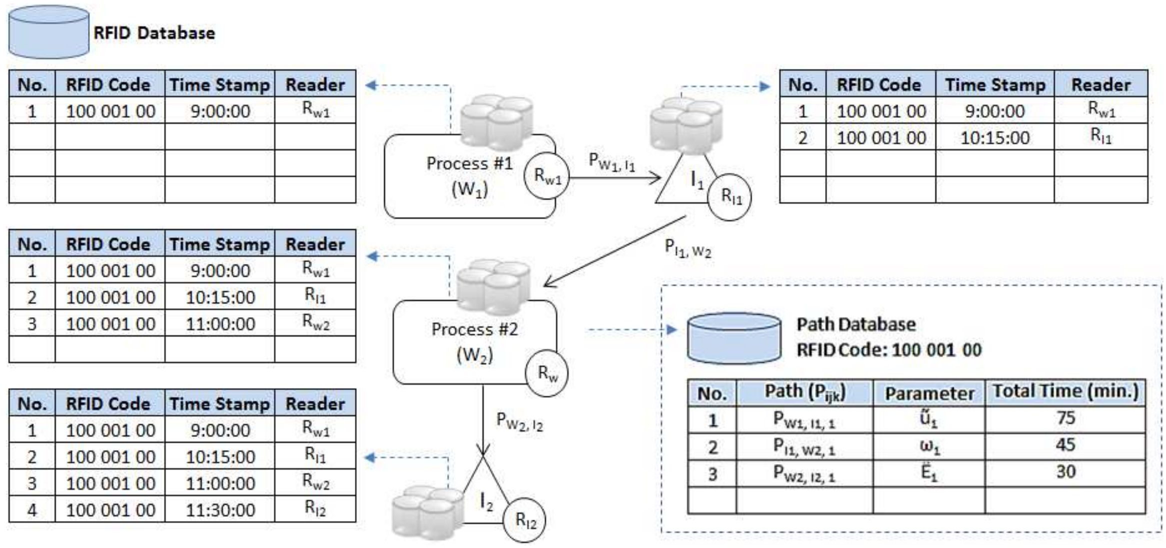
$$\hat{C} = \sum_{k=1}^{K} (\tilde{u}_k + \omega_{1,k} + \ddot{E}_k + \omega_{2,k} + \ddot{A}_k + \omega_{3,k} + \alpha_k + \omega_{4,k} + \ddot{y}_k + \omega_{5,k} + \rho_k + \omega_{6,k}) \quad (13)$$

Given that these readings are taken over N observations for Product Family “*f*” we can compute the means of all the measures proposed above. For instance, for ω_3

$$\overline{\omega_{3_f}} = \frac{\sum_{L=1}^{N_f} (\sum_{k=1}^{K} (t_{w4} - t_{I3})_k)_L}{N} \quad (14)$$

Similar computations are also completed for $\tilde{u}$, $\ddot{E}$, $\ddot{A}$, α, $\ddot{y}$, ρ, and $\hat{C}$. The means of these measures are then automatically updated to the RFID and Path database as references for job-shop scheduling tasks later on.

Performance measures $\tilde{u}$, $\ddot{E}$, $\ddot{A}$, α, $\ddot{y}$, and ρ are aimed at estimating the total operating time at each workstation, whereas performance metric ω is used to measure the time an item is waiting at the queue before operations. Similarly, $\hat{C}$ measures the complete time for an item starting from kitting process to warehouse and shipping location. Figure 13 presents an example of data flow between the readers and RFID database. In this case, we are tracking the movement of an item with RFID tag coded as 100 001 00. Each reader detects and sends information to the database once an item is transferred from one location to another. Additional information such as RFID code, time stamp, and reader ID are updated into the RFID database accordingly. In the meantime, all paths that the item passes through are recorded and all performance metrics are calculated and stored in the path database, so that we have a view of the whole path of the item throughout the production line.



No.	RFID Code	Time Stamp	Reader
1	100 001 00	9:00:00	R_{w1}

No.	RFID Code	Time Stamp	Reader
1	100 001 00	9:00:00	R_{w1}
2	100 001 00	10:15:00	R_{I1}

No.	RFID Code	Time Stamp	Reader
1	100 001 00	9:00:00	R_{w1}
2	100 001 00	10:15:00	R_{I1}
3	100 001 00	11:00:00	R_{w2}

No.	RFID Code	Time Stamp	Reader
1	100 001 00	9:00:00	R_{w1}
2	100 001 00	10:15:00	R_{I1}
3	100 001 00	11:00:00	R_{w2}
4	100 001 00	11:30:00	R_{I2}

Path Database
RFID Code: 100 001 00

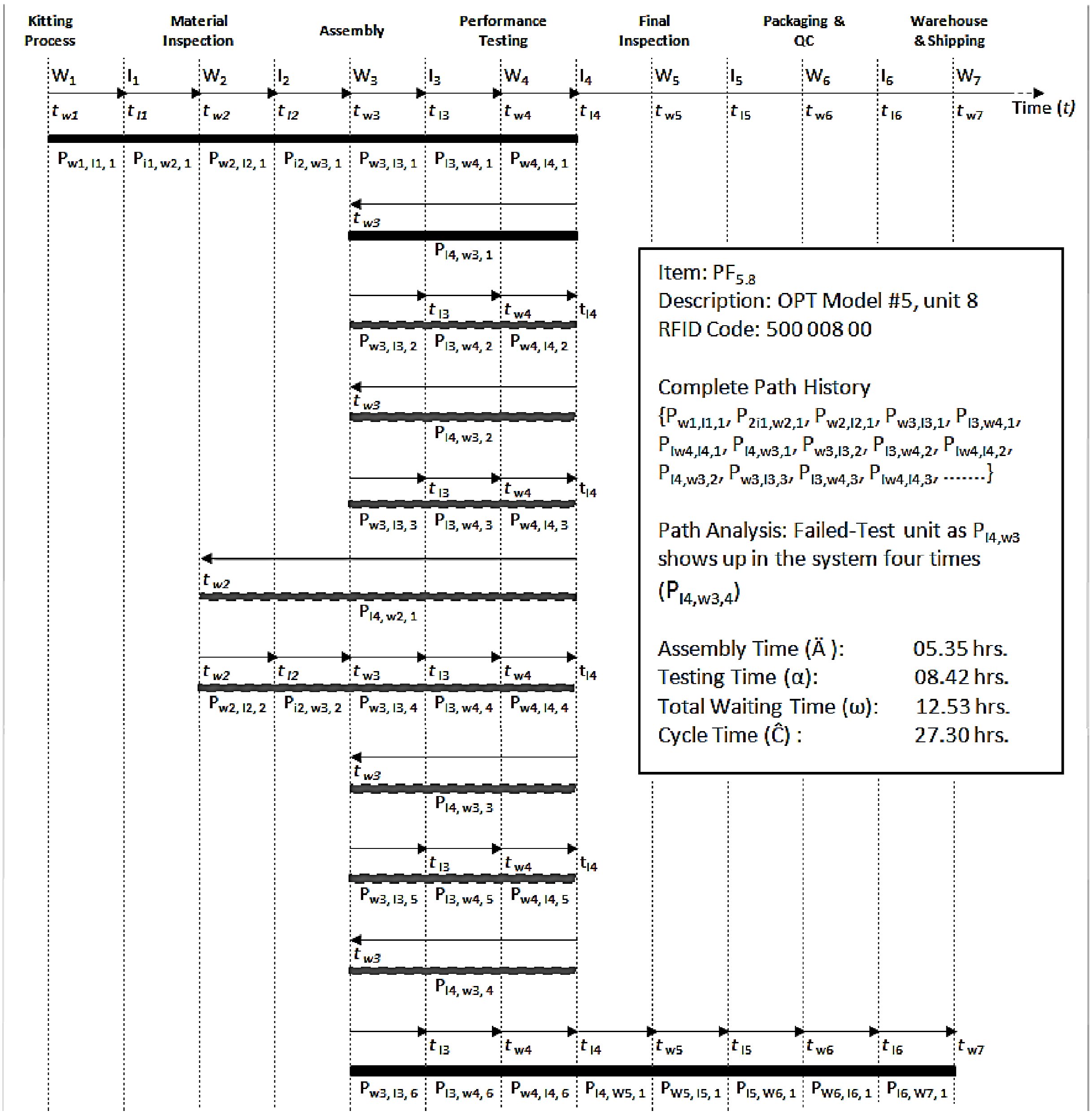
No.	Path (P_{ijk})	Parameter	Total Time (min.)
1	$P_{W1, I1, 1}$	ű$_1$	75
2	$P_{I1, W2, 1}$	ω_1	45
3	$P_{W2, I2, 1}$	$\ddot{E}_1$	30

Figure 13: RFID-based Traceability

Figure 14 presents an example of the full path of a unit. The solid black line (▬) represents the case of traditional WIP paths and the dash-gray line (- - -) for the reworked units path history when the unit fails to meet the specified criteria at the performance testing workstation. By employing the RFID-based traceability system, we are able to keep track of the movement and path history of the unit once it has been transferred from one workstation to another. Thus, we have a view of the whole path of the unit in the overall production chain. As presented in Figure 14, the system can also trigger an alarm signal. For example, for the unit #$F_{5.8}$ ($F_{5.8}$: Production Family #5, unit# 8 with RFID code of 500 008 00), when Path $P_{I4,w3}$ shows up in the path database four times ($P_{I4,w3,4}$), a predetermined rule may signal a problem in manufacturing a regular

WIP and this unit can be identified the reworked or failed unit. Assembly time ($\ddot{A}$), testing time (α), waiting time (ω) and cycle time ($\hat{C}$) are recorded and used in the production planning and scheduling activities accordingly.

An RFID-based traceability system can notify an operator immediately when any incidents or unexpected events (see Figure 15) occur in the shop-floor operations and that might be an obstacle to the production scheduling activities. The first common incident is when WIPs are moved to the wrong place at the wrong time (incidents #1 and #2 in Figure 15). For instance, after getting through the assembling process in W_3, the WIP may accidentally be transferred to final inspection (W_5) without testing the performance at W_4 as it should be. With an RFID-based traceability system, the readers systems automatically capture the information from the RFID tag, immediately detect the problem, and notify the shop-floor operator where the WIP actually belongs. Another common incident is when WIPs are wrongly processed at the wrong workstation at the wrong time (incident #3). For instance, any failed-test units after the performance testing are normally returned to the mechanical assembly station. An operator fixes the problematic parts and components and transfers those units back to the performance testing station for the retest. However, on some occasions, a testing engineer may accidentally pick up the failed test units and retest those units again without proper corrective action. With RFID technology, the system immediately notifies an operator whether or not WIPs are suitable for processing at the current workstation.



Item: $PF_{5.8}$
Description: OPT Model #5, unit 8
RFID Code: 500 008 00

Complete Path History
{$P_{w1,I1,1}$, $P_{2i1,w2,1}$, $P_{w2,I2,1}$, $P_{w3,I3,1}$, $P_{I3,w4,1}$, $P_{Iw4,I4,1}$, $P_{I4,w3,1}$, $P_{w3,I3,2}$, $P_{I3,w4,2}$, $P_{Iw4,I4,2}$, $P_{I4,w3,2}$, $P_{w3,I3,3}$, $P_{I3,w4,3}$, $P_{Iw4,I4,3}$, ...}

Path Analysis: Failed-Test unit as $P_{I4,w3}$ shows up in the system four times ($P_{I4,w3,4}$)

Assembly Time (Ä): 05.35 hrs.
Testing Time (α): 08.42 hrs.
Total Waiting Time (ω): 12.53 hrs.
Cycle Time (Ĉ) : 27.30 hrs.

Figure 14: An Example of Path Analysis

Figure 15: Unexpected Incidents and RFID-based Traceability System

4. Case Example

An in-depth study of an RFID deployment assessment at one of the production lines from XYZ Company (name disguised) is conducted to explore the benefits of an RFID-based traceability system. XYZ Company is a manufacturing services provider of complex optical and electro-mechanical components. The company is considering implementing RFID on a production line of the optical receiver-transceiver, called OPT, used in telecommunication networks. Although the case presented in this study is for a specific job shop, it does provide details of logical process flows and problem scenarios that normally occur in manufacturing operations. A logical flow of OPT manufacturing processes is presented in Figure 16.

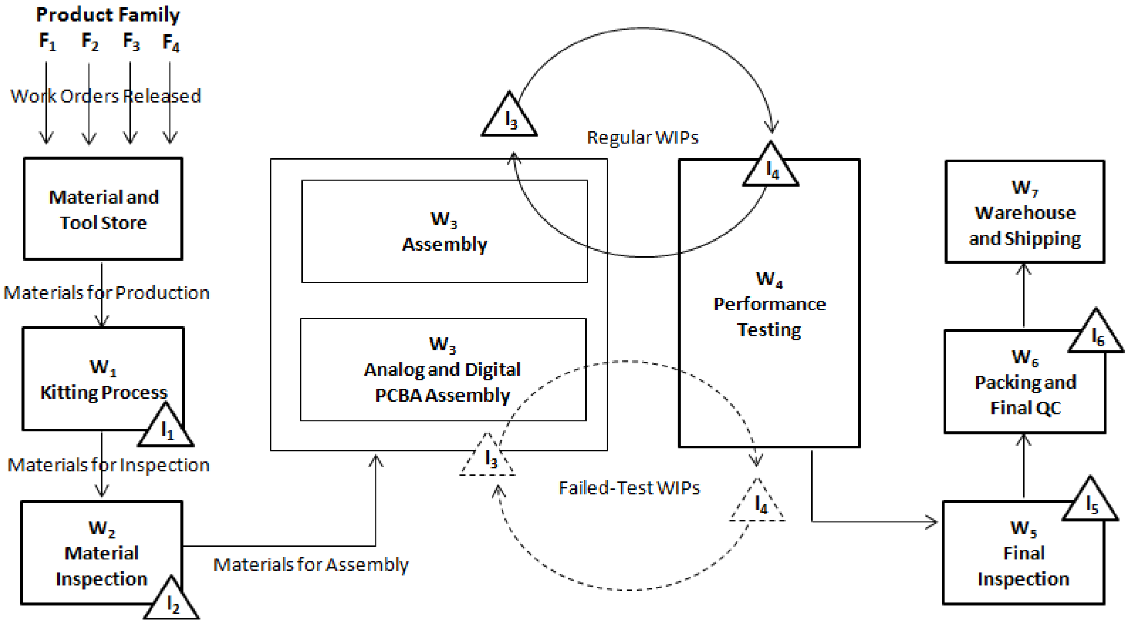


Figure 16: A Logical Flow of OPT Manufacturing Processes

This production line manufactures about 87 different products but can be grouped into four major product families (F_f =4 where "*f*" = 1 to 4) at a total volume of approximately 4,000 units/quarter. Operating on a quarterly timeframe, the facility receives weekly forecasts from its customer-supplier development program at the beginning of the quarter. The company employs a zero-inventory strategy so that all the work orders are released based on actual purchase orders and estimates of demands and are scheduled to be processed and shipped within 10 business days. To utilize its capacity and to avoid overtime at the end of the quarter, orders are released at the beginning of the week based on both confirmed purchase orders and demand forecasts. Priority is given to the released production orders that represent actual purchase orders from customers.

After receiving the weekly work orders, an operator starts kitting all parts and components into a tote at Workstation #1 (W_1). All materials are inspected at W_2 before being placed in the printed circuit board (PCBA) and mechanical assembly line (W_3). At this stage, an operator manually assembles the units, also called Work in Process (WIP), based on the instructions provided either on the screen or in the tote. An operator works on one unit (or one tote) at a time. Afterward, the WIP is transferred to the next workstation (W_4) for software uploading and performance testing with various types of software packages. Because the same testing system is used for different software tests for different products, this step may entail some setup time to switch to the correct software for testing for a specific product family. If the performance testing is satisfactory, the WIP is moved back to the mechanical assembly station (W_3) for final assembly. If not, the WIP, now called the failed-test-unit, is returned to the mechanical assembly (W_3) for the problematic parts and components to be changed. After the final assembly (W_3), the WIP is tested at W_4 again with different software packages to ensure its functionality and quality. If the unit does not pass the tests, the WIP is sent back to the mechanical assembly line (W_3) and later to the performance testing station again (W_4). If the performance testing result is satisfactory, an operator performs the final inspection (W_5), packaging, and then the final quality control (QC) at (W_6). The finished products are then moved to the warehouse and shipping section (W_7) before being shipped to the customers within one to five days.

The shop-floor currently relies on a barcode system and assumes that all operators follow the established operating procedures by scanning all WIPs before and after WIPs are transferred from one workstation to another. However, the current operations suffer from several major issues:

1. Currently, there is no system to keep track of when the WIPs actually arrive at or leave operating workstations and how long those WIPs actually stay at each workstation.

WIPs might arrive at a particular workstation and sit for a period of time before an operator at that workstation updates the manufacturing enterprise system (MES) by scanning the barcode on the paperwork that accompanies each WIP. Accordingly, the status of those WIPs in the MES system is not accurate. This can cause the estimates of an operation time for producing WIPs for each product family to be incorrect.

For the performance testing station (W_4), there are three software packages to upload and test any given model before the final assembly and three others after the final assembly. Each model/product family may require different testing structures, different types of software packages, or the same software packages with different testing values. Thus, this workstation is clearly a bottleneck. One of the most important factors that obstructs the operational flow and delays the production schedule and shipment due date is the set-up time. When the products need to be processed at performance testing workstation in batches (maximum 30 units of the same product family at a time), costly capacity is wasted on preparing the testing machine.

2. The current system cannot monitor or keep track of the movement of each WIP in the production line in real time.

Occasionally, an operator puts WIPs in the wrong place at the wrong time and the existing system does not immediately detect the problem or notify the operator regarding the incidents. For instance, there are several times when the failed-test units are transferred directly to the final inspection workstation instead of the mechanical assembly station. As a result, there may be significant time involved to search for those misplaced units and additional resources (testing machine, assembly machine, or labor) dedicated specifically to those units.

In the next section, we propose a scheduling rule by improving track and traceability of WIPs that would facilitate scheduling tasks in this shop-floor operation, improve bottlenecks at testing workstation, and solve the problems of misplaced units in real time.

5. RFID-based Traceability System in Job-Shop Scheduling Environment

The real time RFID-based track and traceability system (described in Section 3) can enable dynamic scheduling activities in shop-floor operations. Although there are multiple locations (workstations) in this production line that require scheduling decisions, W_3 and W_4 are the main focus as they represent the bottleneck operations due to their limited resource capacities. The performance testing workstation (W_4) can test only one product family at a time with a maximum capacity of 30 units. Testing different product families requires significant software setup time for the transition. Assembly workstation (W_3) is also critical. Total time spent to assemble a unit varies among different product families and there are a maximum of 60 sub-workstations in which each operator works on one unit at a time. Ineffective decision-making in these two workstations can greatly impact the overall scheduling performances. Note that the average time to operate a unit at W_1, W_2, W_5, W_6, and W_7 is relatively similar among product families.

Current Scheduling Rules

For W_3 and W_4, WIP totes are currently assigned to the sub-workstation based on the judgment of authorized test engineers. Usually, the Earliest Due Date (EDD) scheduling rule is utilized to assign the priority to the jobs with the earliest due date first with the objective of minimizing lateness. If work orders released have the same due date, First In First Out (FIFO) is used to set the priority to the waiting jobs that arrive at the queue first in order to minimize the variation in the waiting times of the operation. In some circumstances, the Service in Random Order (SIRO) is used when no priority is given to the waiting jobs and the next job is selected randomly.

Proposed Information Visibility-based Scheduling Rules

We present a novel information visibility-based dynamic scheduling rule that utilizes the real-time traceability systems (RTLS) to track those WIPs, parts and components, and raw materials in shop-floor operations. Figures 17 and 18 show the pseudo code of the scheduling algorithm at W_3 and W_4 as a result of improved information visibility and traceability through RFID.

For example, the operating engineer might set the priority on product family “3” first at W_3 because the system indicates that the majority of product family “3” are being processed in both the assembly (W_3) and performance testing (W_4) workstation. As a result, the setup time on the software packages at the performance testing workstation

(W_4) can be reduced. The system can also compute the accurate quantity of WIPs and fail-test units at each workstation. This information can be used to improve scheduling and assignments. For example, the operating engineer may notice that the ratio of fail-test units of product families “2” is very high. With a low performance-testing yield, he then sets the priority to test other models first in order to smooth the operations at the performance testing workstation and to conduct root cause analysis for product family #2.

The RFID-based traceability system can keep track of the status of critical variables such as $\ddot{A}$, α, ω, and $\hat{C}$ in real time. The production planner can utilize this valuable information to facilitate scheduling appropriately. For instance, the system will immediately notify the shop-floor operators when the average waiting time (ω) of F_1 is above a threshold value of, say, 50 hours or when the average assembly time ($\ddot{A}$) of F_4 at W_3 for this week period is significantly longer than that for last week. Appropriate actions or root cause analysis can be made to tackle such problems.

RFID can also facilitate any changes due to disruptions, which normally occur in the shop-floor operations and impact the production scheduling activities. These disruption scenarios include (1) the arrival of new urgent work orders released, (2) changes to a job’s due date, (3) delays in the arrival of raw materials, and (4) limited resource capacity (machine failure). For instance, when the current scheduling plan is delayed due to the raw material shortages, the production planner can then set the priority of WIPs at assembly workstation to the product family that has the lowest penalty costs per backlog or when rush orders are released, shop-floor operators can dedicate the facility resources to fulfill such orders in real time.

```
STEP #1:
COMPUTE the total quantity of WIPs in real-time at each workstation ($N_f$) AND determine both utilized
and available capacities (either workstations or machines)
  IF there are any rush jobs waiting:
    THEN Set priority to those rush work order released AND go to STEP #4
  ELSE

  STEP #2:
  DETERMINE group number of incoming WIPs (product family, $F_f$) through RFID
    IF the incoming WIPs are from the same product group as being run on the machine currently
        THEN Set priority to those groups (to reduce setup time) AND go to STEP #4
    ELSE

    STEP #3:
    COMPUTE the waiting time of those unprocessed WIPs for each product family ($\omega$) through RFID
        IF the average waiting time is greater than some predetermined threshold: ($\omega_f > \omega_{Threshold}$)
           THEN Set the priority in the order of waiting time longest to shortest AND go to STEP #4
        ELSE
           Schedule the selected units using the traditional scheduling rules (EDD) AND go to STEP #4

STEP #4:
COMPUTE: The total quantity of reworked (failed) WIPs (RFID)
  IF the percentage of failed units is greater than the predetermined threshold:
     THEN Stop the production run, conduct root cause analysis, and select another product groups AND
            go to STEP #1
  ELSE
     Termination of the scheduling rule
```

Figure 17: Pseudo Code for Scheduling Algorithm at W_4

```
STEP #1:
COMPUTE the total quantity of WIPs in real-time at each workstation ($N_f$) AND determine both utilized
and available capacities (either workstations or machines)
   IF there are any rush jobs waiting:
      THEN Set priority to those rush work order released AND go to STEP #5
  ELSE

  STEP #2:
  UPDATE the status of critical raw materials required PCBA and mechanical assembly at $W_3$ through
   RFID
     IF Production delays due to raw material shortages
         THEN Set priority to the product family that has the highest penalty cost per backlog AND go to
                    STEP #5
    ELSE

    STEP #3:
    COMPUTE the total quantity of WIPs for each product family ($F_f$) waiting and being tested at $W_4$
     through RFID
        IF the incoming WIPs are from the same product group that are mostly processed at $W_4$
           THEN Set priority to those groups (to reduce setup time at $W_4$) AND go to STEP #5
        ELSE

        STEP #4:
        COMPUTE the waiting time of those unprocessed WIPs for each product family ($\omega$) through RFID
             IF the average waiting time is greater than the same predetermined threshold: ($\omega_f > \omega_{Threshold}$)
                THEN Set the priority in the order of waiting time longest to shortest AND go to STEP #5
            ELSE
                 Schedule the selected units using EDD rule AND go to STEP #5

STEP #5:
COMPUTE the assembly time of those processed WIPs ($\ddot{A}$) through RFID
  IF the average assembly time is longer than that from the previous period (historical data)
    ($\ddot{A}_f > \ddot{A}_{previous\ period}$)
    THEN Stop the production run, conduct root cause analysis, and select another product groups AND
      go to STEP #1
  ELSE

STEP #6:
COMPUTE: The total quantity of reworked (failed) WIPs through RFID
   IF the percentage of failed units is greater than the predetermined threshold:
      THEN Stop the production run, conduct root cause analysis, and select another product groups AND
                go to STEP #1
   ELSE
      Termination of the scheduling rule
```

Figure 18: Pseudo Code for Scheduling Algorithm at W_3

6. Simulation Model

In this study, a simulation approach is applied to examine the benefit of information visibility-based scheduling (VBS) rule that utilizes the real-time traceability systems. Simulation modeling is a widely used and effective analytical methodology used to imitate the operation of a real-world process over time (Banks, 1998). Simulation can be used to model both existing and conceptual systems and can support both practice and research for a variety of contexts including industry, government, education, or healthcare (Amini, Otondo, Janz, & Pitts, 2007; Banks, 1998). We create a simulation model for the job-shop OPT manufacturing facility using the Simio simulation program. Simio^{TM}, version 4.0, is a simulation modeling framework software package based on intelligent objects (Pegden, 2007). The purpose of our simulation model is to test the performance of information visibility-based schedule (as presented in Figures 17 and 18) against the classical scheduling rules. Although there are several ways to carry out dispatching for the planning and scheduling decisions, we only compare the VBS rule against two different dispatching rules: FIFO and EDD for the model comparison.

Table 6 presents an example of the weekly work orders released for all four product families with an individual inter-arrival distribution “Random.Triangular (Min, Mode, Max).” The assigned distribution is based on an analysis of historical demand from the historical 5-quarter timeframe.

Table 6: Work Order Released

Product Family (F_f)	**The Inter-arrival distribution (Units/week)**	**Price ($)**
F_1	Random.Triangular(40,150,300)	$1,000
F_2	Random.Triangular(20,75,150)	$5,000
F_3	Random.Triangular(0,60,80)	$3,000
F_4	Random.Triangular(0,60,80)	$8,000

The total time required to operate the work orders for each product family at each workstation such as kitting time (*ũ*), material inspection time (*Ë*), assembly time (*Ä*), testing time (α), final inspection time (*ÿ*), and packaging time (ρ) are captured with an individual inter-arrival distribution in both uniform (Min, Max) and triangular (Min, Mode, Max), (see Table 7 as an example of partial parameter estimates used in this simulation model). In the case of RFID scenarios, RFID tagging time, information retrieving time, or system updating time are considered in this simulation. Even though this study is based on real manufacturing process data, a limited amount of data for the RFID case such as time to code the RFID tags or time to update the system were developed from a pilot study tested on the RFID reader model ALR-9800 (Alien Technology).

Table 7: Parameter Estimates for Product Family #1 (F_1)

Work Station	**Parameter**	**Function (Minutes/Unit)**
W_1	Kitting time (ũ)	Random.Uniform (4,7)
W_2	Material inspection time (Ë)	Random.Uniform (1,2)
W_3	Assembly time (Ä) – regular WIP unit	Random.Triangular (60,70,80)
W_4	Testing time (α)	Random.Triangular (80,90,100)
W_5	Final inspection time (ÿ)	Random.Triangular (1,2,3)
W_6	Packaging time (ρ)	Random.Triangular (1,2,3)
I_2	Assigning and brief training task time	Random.Triangular (1,2,4)
I_3	Time to rearrange the incoming unit	Random.Uniform (1,3)

Only data in the steady-state condition is considered in order to remove the potential effects of a typical initial system condition. Kelton et al. (2010) explain that too short a warm-up period can lead to start-up bias and too long a warm up period can increase the sampling error (Kelton, Smith, Sturrock, & Verbraeck, 2010). We also follow the application of Welch’s procedure to determine the warm-up period and the run length (Welch, 1983). The scatter diagram of average cycle time is generated as a function of time with multiple replications to determine the appropriated warm up length. Consequently, a warm-up period of 2,000 hours (approximately 4,000 work orders released for all product families) is reasonable to carry out for steady state data to eliminate an effect of initialization bias. The simulation was run for a quarter (thirteen weeks, assuming a regular working period of 40 hours per week) excluding the warm-up period. We address the issue of random variations of the results obtained from the simulation model by running the model with various number of replications (30, 100, 200, and 1,000 replications). In order to obtain a precise estimate of the true mean, we increase these number of replications, making the confidence interval on the mean of the random variable arbitrarily small (Banks, 1998; Kelton, et al., 2010). We then compare the confidence intervals of average cycle time such that the probability that the true value of cycle time lies in the interval is 0.95. We choose to conduct 200 replications for each simulation run to ensure that appropriate confidence interval has been met. Lastly, common random numbers are employed for all scenarios to reduce the variability of our simulation results. We follow the guidelines of Welch (1983), Sari (2010), Banks (1998) and Law and Kelton (1982), which contain a detailed discussion of the model development, variance reduction techniques, experimental design, and validation of the simulation model.

7. Simulation Output Analysis

Results of a comprehensive simulation of this visibility-based scheduling (VBS) model and its comparison with the traditional scheduling rules are presented in this section.

7.1 Impact of RFID-enabled Scheduling Rules

We first investigate the impact of information visibility-based scheduling rule on cycle time, backlogs, and a cost of penalty when the demand is not met for all product families. As depicted in Table 8, the average cycle time ($\hat{C}$) for all product families is reported at 51.81 hours for FIFO, 54.78 hours for EDD, and 46.59 hours for RFID. When RFID is in use, the average cycle time improvement over FIFO and EDD for all product families is at 10% and 15%, respectively. As expected, a decrease in the average cycle time results in a decrease in backlogs. With an average quarterly demand of 4,045 units for all product families, total backlog orders in the case of FIFO, EDD, and RFID scheduling rules are 697, 748, and 560 units respectively. Clearly, RFID helps in reducing backlogs as opposed to the traditional scheduling rules (20% improvement over FIFO rule and 25% for EDD). These results are reasonable. With RFID, the facility can keep track of the flow of WIPs at each workstation and make better scheduling decisions using the scheduling approach described in Figures 17 and 18. Information visibility enables production planners to effectively and efficiently determine the quantity and timing of production for each product family at each workstation. at the shop-floor level, the testing engineer at W_4, for instance, knows the exact quantity of each product family in the waiting area and in the assembly workstation (W_3). Thus, priority is set to those with the highest quantity to reduce the setup time and to smooth the production flow.

Accordingly, the set-up time and testing time at performance testing (W_4) workstations decrease dramatically. As presented in Table 8, the average time spent in machine setup for EDD and FIFO rule is reported at 13.93 and 12.35 minutes. However the average time for setup gets better with RFID at 8.89 minutes, approximately 28% improvement over FIFO and 36% improvement over EDD. Without information visibility as in FIFO or EDD rules, shop-floor operators may continue working on a particular model without realizing that the weekly shipment requirement of that model has been met or shop-floor resources such as the labor and machines at W_3 and W_4 are not available for that model. As a result, the average cycle time and backlogs may increase.

Another key measure that management uses to gauge the shop-floor performance is a penalty cost for the number of units of demand that cannot be satisfied. The penalty cost is assessed at the end of the quarter and is charged at 10% of the selling price. Overall, the total penalty cost saving when RFID is in use is estimated at $38,272 and $55,778 more than FIFO and EDD rules.

Table 8: Comparison of Dispatching Rules

	FIFO			EDD			VBS		
Performance Measures	**Avg.**	**CI**	**SD**	**Avg.**	**CI**	**SD**	**Avg.**	**CI**	**SD**
F1									
Cycle Time (hrs.)	49.57	0.84	5.97	52.15	1.15	8.24	42.21	0.61	4.37
Work orders released	1,900.61	27.89	199.23	1,904.83	29.22	208.69	1,889.92	26.80	191.42
Work orders shipped	1,582.75	20.42	145.84	1,564.58	20.59	147.09	1,650.49	22.16	158.29
Backlogs	317.86			340.25			239.43		
Penalty @ $100/backlog	$31,786.00			$34,025.00			$23,943.00		
F2									
Cycle Time (hrs.)	40.71	0.97	6.96	51.30	1.22	8.71	41.67	0.68	4.85
Work orders released	947.26	14.43	103.09	954.69	13.52	96.56	944.63	14.35	102.46
Work orders shipped	802.00	11.96	85.42	786.16	10.96	78.27	817.79	12.32	88.02
Backlogs	145.26			168.54			126.84		
Penalty @ $500/backlog	$72,627.50			$84,267.50			$63,417.50		
F3									
Cycle Time (hrs.)	64.40	1.02	7.31	62.57	1.32	9.42	57.33	0.80	5.70
Work orders released	603.48	8.60	61.44	603.43	7.91	56.52	599.64	8.10	57.83
Work orders shipped	483.86	7.18	51.29	482.20	7.11	50.78	502.52	7.57	54.08
Backlogs	119.63			121.24			97.12		
Penalty @ $300/backlog	$35,887.50			$36,370.50			$29,136.00		
F4									
Cycle Time (hrs.)	62.00	1.02	7.29	61.69	1.25	8.91	53.86	0.78	5.60
Work orders released	601.29	8.77	62.66	595.71	8.56	61.15	608.50	8.29	59.21
Work orders shipped	487.50	7.46	53.29	477.99	7.34	52.41	512.79	7.97	56.92
Backlogs	113.79			117.72			95.71		
Penalty @ $800/backlog	$91,032.00			$94,176.00			$76,564.00		
Overall									
Testing Time (hrs.)	1.71	0.00	0.01	1.74	0.00	0.01	1.64	0.00	0.02
Setup Time (mins.)	12.35	0.12	0.87	13.93	0.09	0.67	8.89	0.16	1.15
Testing Utilization (%)	94.03	0.46	3.27	95.12	0.43	3.05	91.99	0.49	3.53
On-time Delivery (units)	3,448.42	18.50	132.10	3,404.95	16.88	120.55	3,548.24	23.07	164.81
Overall Cycle Time (hrs.)	51.81	0.83	5.90	54.78	1.14	8.12	46.59	0.45	3.22
Backlogs (units)	696.53			747.74			559.09		
Total Cost of Penalty ($)	$231,333.00			$248,839.00			$193,060.50		
Reduction in Penalty Cost by RFID ($)	$38,272.50			$55,778.50					

7.2 Impact of RFID on Disruptions

Table 9 provides a detailed overview of simulation results when disruptions occur in the operations. RFID-based scheduling rule achieves better performance compared to both FIFO and EDD rules. The average backlog for FIFO and EDD rules increases to 1,266 and 1,114 units, respectively. The average backlog for RFID (560 units) is relatively low compared to the other rules. This is because with the existing operations, assembly (W_3) and testing (W_4) workstation are bottlenecks that can delay the entire production. The capacity of these two workstations along with disruptive occurrences limits the overall production process, resulting in delays in the production schedule and shipment dates. However, improving information visibility through RFID enables managing bottlenecks. For example, Figure 19 confirms that the testing utilization for RFID remains closely the same at approximately 92%; meanwhile, the testing utilization for both FIFO and EDD rules get worse with unforeseen disruption.

RFID enables shop-floor operations to react to circumstances such as rushed orders, machine downtimes, and delayed raw materials and change the order of WIP priorities at very short notice to adjust the production schedules. In other words, RFID facilitates such activities with the up-to-date status of raw materials, current operating WIPs, and available capacities at each workstation. Production planners are able to reprioritize current production schedule to utilize current shop-floor capacity in order to minimize the consequence of these unexpected incidences. Similarly, better capacity utilization from smoother flow of WIPs results in lower cycle time. As presented in Figure 19, when disruptions occur, the average cycle time for FIFO and EDD rules increases approximately 80% (from 51.81 to 94.6 hours) and 25% (from 54.78 to 68.47 hours), whereas the average cycle time for RFID remains stable roughly from 46.59 to 49.83 hours. Clearly there is a considerable difference between visibility-based scheduling and traditional scheduling rules.

Table 9: Comparison of Dispatching Rules in the Presence of Disruptions

	FIFO			**EDD**			**VBS**		
Performance Measures	**Avg.**	**CI**	**SD**	**Avg.**	**CI**	**SD**	**Avg.**	**CI**	**SD**
F1									
Cycle Time (hrs.)	88.50	2.58	18.46	64.65	1.38	9.84	45.42	0.75	5.38
Work orders Released	1909.38	28.14	200.98	1886.37	27.83	198.79	1901.84	30.27	216.23
Work orders Shipped	1328.30	16.22	115.87	1381.33	17.41	124.32	1654.74	24.49	174.89
Backlogs	581.09			505.04			247.10		
Penalty @ $100/backlog	$58,108.50			$50,504.00			$24,710.00		
F2									
Cycle Time (hrs.)	80.06	2.52	18.01	62.13	1.39	9.90	45.41	0.76	5.44
Work orders Released	936.07	15.16	108.26	943.49	13.68	97.72	950.12	14.48	103.42
Work orders Shipped	661.77	11.79	84.22	700.21	10.79	77.04	819.44	12.44	88.88
Backlogs	274.30			243.29			130.68		
Penalty @ $500/backlog	$137,147.50			$121,642.50			$65,340.00		
F3									
Cycle Time (hrs.)	113.33	2.90	20.68	84.78	1.49	10.64	60.17	0.87	6.20
Work orders Released	605.59	7.96	56.87	598.10	8.67	61.90	599.62	8.61	61.51
Work orders Shipped	394.61	7.90	56.41	413.54	7.49	53.52	500.98	8.21	58.67
Backlogs	210.98			184.56			98.64		
Penalty @ $300/backlog	$63,294.00			$55,366.50			$29,592.00		
F4									
Cycle Time (hrs.)	108.15	2.77	19.81	82.77	1.56	11.12	57.11	0.91	6.49
Work orders Released	592.74	8.88	63.46	603.21	8.67	61.93	606.07	8.24	58.87
Work orders Shipped	392.28	7.64	54.59	421.96	7.53	53.75	507.41	7.64	54.55
Backlogs	200.47			181.25			98.66		
Penalty @ $800/backlog	$160,372.00			$144,996.00			$78,928.00		
Overall									
Testing Time (hrs.)	1.66	0.00	0.02	1.73	0.00	0.01	1.63	0.00	0.02
Setup Time (mins.)	10.03	0.13	0.91	13.53	0.10	0.69	8.30	0.18	1.31
Testing Utilization (%)	75.15	0.59	4.23	77.96	0.64	4.54	91.32	0.49	3.53
On-time Delivery (units)	2303.93	68.07	486.23	2633.14	27.12	193.71	3536.59	24.20	172.86
% On-time Delivery	76%			87%			94%		
Overall Cycle Time (hrs.)	94.26	2.55	18.24	68.47	1.24	8.83	49.83	0.60	4.30
Backlogs	1,266.83			1,114.13			575.08		
Total Cost of Penalty ($)	$418,922.00			$372,509.00			$198,570.00		
Reduction in Penalty Cost by RFID ($)	$220,352.00			$173,939.00					

Integrated information visibility in scheduling activities also enables substantial improvements in on-time delivery. The average on-time delivery for RFID (Figure 20) remains constant at about 94%; meanwhile missed delivery dates seem to be a major problems for FIFO (76% on-time delivery) and EDD (87% on-time delivery) rules. Better utilizing the facility capacity where resources are constrained and the ability to reprioritize the current schedule for operating units that are due sooner clearly influence on-time delivery performance.

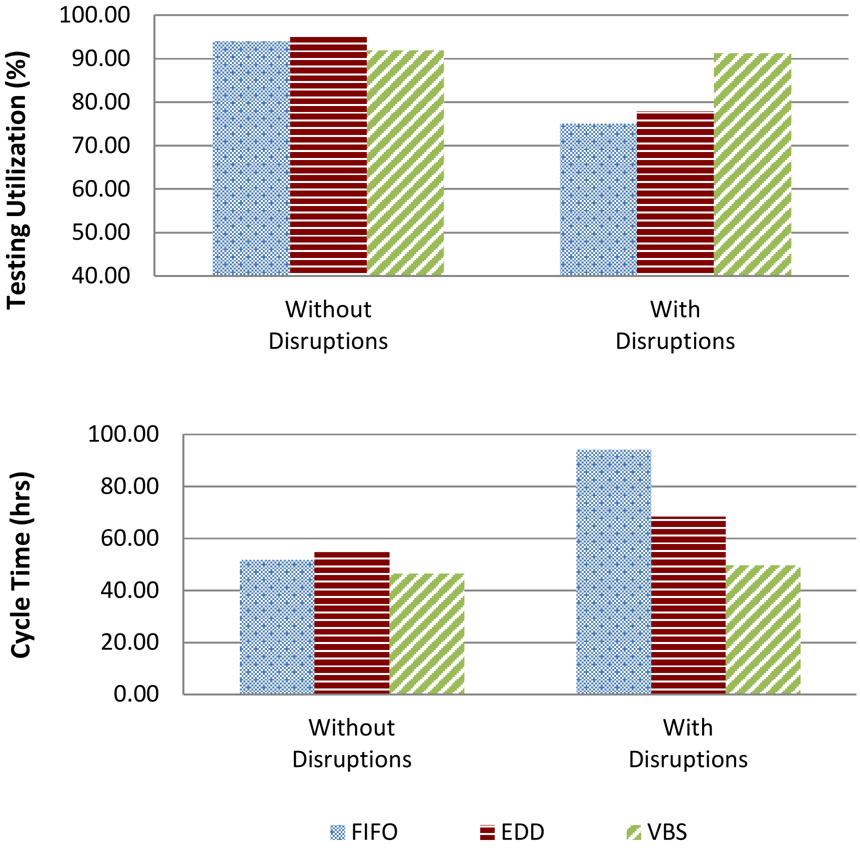


Figure 19: Comparison of Testing Utilization and Cycle Time with/without Disruptions

Considering the penalty cost due to the contract-schedule delay, the facility always tries to minimize penalty costs of backlogs as much as possible especially when parts and components are delayed from another assembly line or from suppliers. The priority is usually set to the product family that has the highest penalty cost per backlog. As presented in Tables 8 and 9, the penalty cost for F_1, F_2, F_3, and F_4 is set at \$100, \$500, \$300, and \$800, respectively. RFID system can automatically notify the planner whether raw materials are enough for the current released work orders. Consequently, the planner can communicate the rescheduling tasks to shop-floor coordinator in real time. On the other hand, when operating under EDD or FIFO rule, shop-floor operators may focus on product family #1, for example, which has the lowest penalty cost per unit at $100 at both assembly and testing stations. As a result, the on-time delivery level for product family #1 remains satisfied but overall cost of penalty is relatively high as well. Figure 20 depicts this issue and shows that RFID handles the disruption practically with a slight increase in penalty costs, compared to the traditional scheduling rules where penalty costs increase considerably at 80% (from $231,333 to $418,922) for FIFO rule and 50% (from $248,839 to $372,509) for EDD rule.

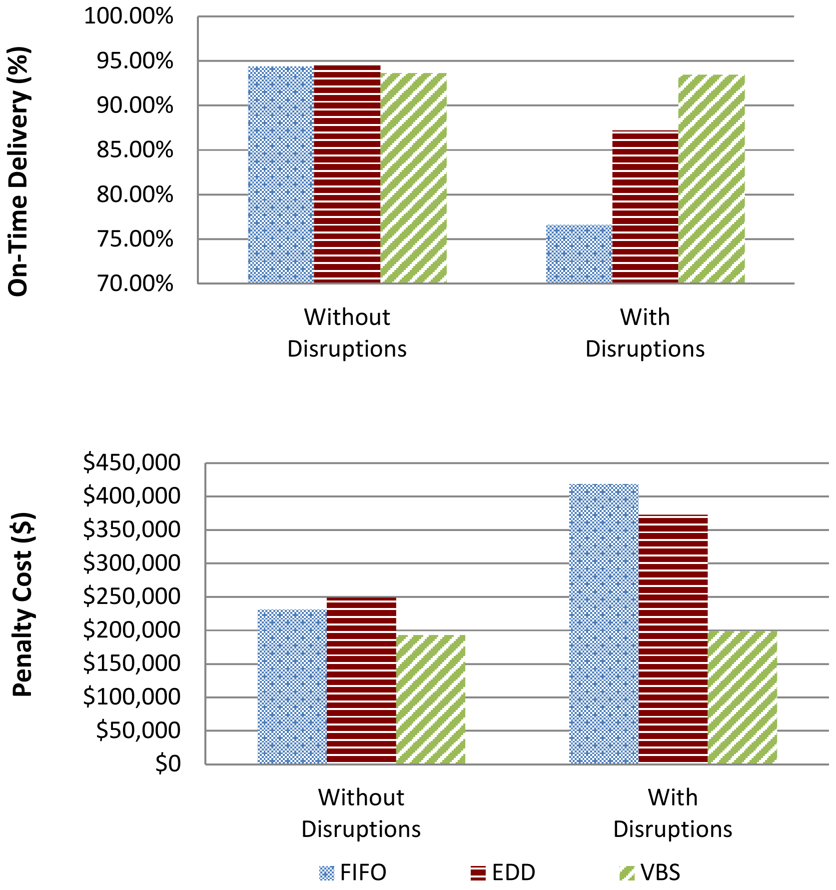


Figure 20: Comparison of On-Time Delivery and Penalty Cost with/without Disruptions

7.3 Impact of Capacity Utilization

In actual manufacturing systems, demand may vary over time. This is especially true in electrical and electronic equipment industry, where technology changes rapidly and affects the demand levels for different product families. In this section, we evaluate the impact of the change in demands on overall operational performances. Our goal is to determine at what level of capacity utilization (demand in relation to plant capacity) does it make sense to invest in RFID. We modify the level of demands in relation to the overall capacity for all product families to 50%, 75%, and 100%. Note that increasing the level of demand to capacity ratio over 100% in this experiment only results in increasing backlogs since the current operation is running at its full capacity where the testing utilization is estimated over 90% for all scheduling rules (see Table 8). For this analysis, we first focus on setup time at specific work station. Because EDD and FIFO rules tend to underperform the VBS rules, we compute the percent improvement (reduction) in setup time as a performance index for gains through a visibility based scheduling rule. Equations 15 and 16 present the performance index to depict the setup time (Ś) improvement for visibility-based scheduling rule (VBS) over EDD and FIFO rules.

$$Setup\ Time\ Improvement\ over\ EDD \;=\; \frac{\acute{S}_{EDD} - \acute{S}_{VBS}}{\acute{S}_{EDD}} \qquad (15)$$

$$Setup\ Time\ Improvement\ over\ FIFO \;=\; \frac{\acute{S}_{FIFO} - \acute{S}_{VBS}}{\acute{S}_{FIFO}} \qquad (16)$$

As presented in Figure 21, the setup time improvement for VBS increases considerably when the demand to capacity ratio is increasing. For instance, at 100%, the setup time improvement over EDD is approximately at 55%; meanwhile, at 50%, the setup time improvement decreases considerably to just 15%. Similarly, when the demand to capacity ratio is 50%, as presented in Figure 22, average cycle time, and backlogs decrease under all three rules, although still the lowest with VBS. This implies that the facility has plenty of capacity available for the production to meet the assigned demand. Hence, when the capacity is large enough, information visibility does not add much value and the difference between visibility-based scheduling rule and traditional scheduling rules is relatively modest. As depicted in Figure 22, at 50%, the cycle time improvement over FIFO and EDD rules is estimated at approximately 7%. Meanwhile, at 100%, the cycle time improvement is relatively larger at 10% over FIFO and 15% over EDD rules. These results suggest that as the demand to capacity ratio increases, scheduling production tasks are more complex with multiple product families on the same workstation under tight capacity constraints. The benefits gained from information visibility result in greater improvements of cycle time as well as backlog. Thus, we can conclude that when the capacity is tight, information visibility adds more value and the difference between visibility-based scheduling rule and traditional scheduling rules becomes more pronounced.

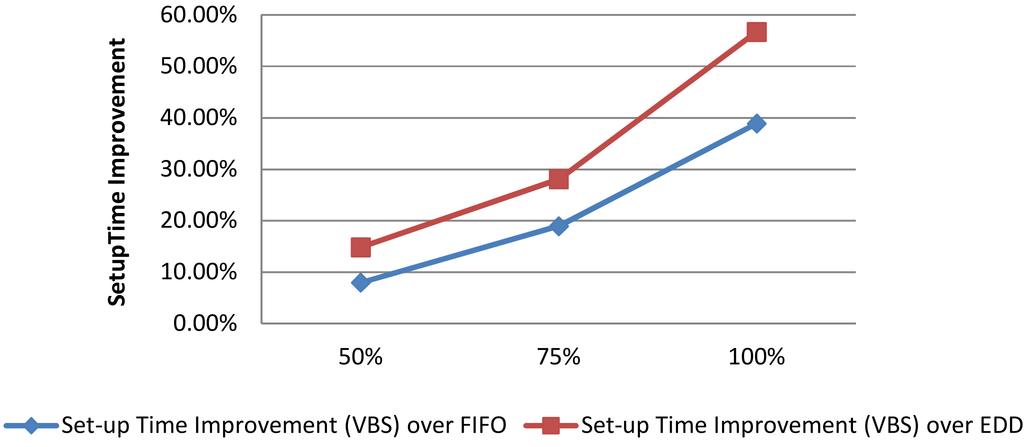


Figure 21: Comparison of Setup Time Improvement for Different Scheduling Rules

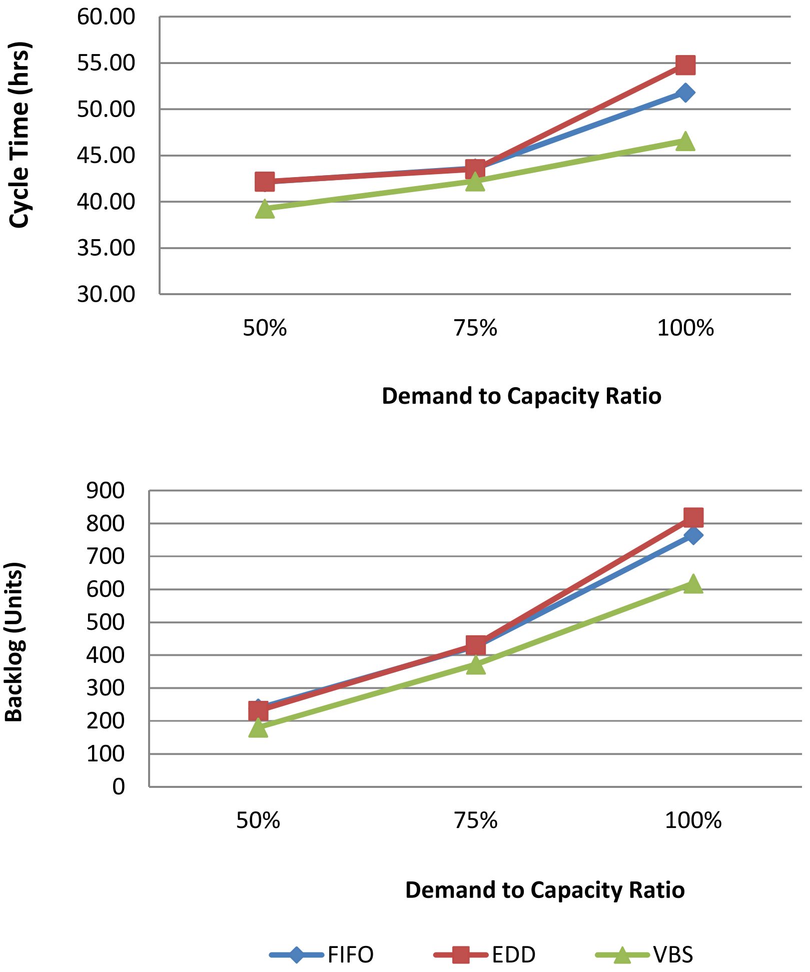


Figure 22: Comparison of Demand to Capacity Ratio for Different Scheduling Rules

7.4 Impact of Demand Variation and Disruptions

In this section, we evaluate the relationship between the demand behavior and disruptions under different scheduling policies. Specifically, we assess whether information visibility adds more value when demands become more variable. To understand the impact of the demand variation, the demand rates for all product families are changed to a discrete normal distribution so that the mean demand rates are matched up to the original demands as in the current operations. The demand variation is then changed by extending the standard deviation (1σ, 2σ, and 3σ). Similar to Equations 13 and 16, Equations 15 and 16 present the performance index to depict the cycle time improvement for visibility-based scheduling rule (VBS) over EDD and FIFO rules.

$$Cycle\ Time\ Improvement\ over\ EDD = \frac{\hat{C}_{EDD} - \hat{C}_{VBS}}{\hat{C}_{EDD}} \qquad (15)$$

$$Cycle\ Time\ Improvement\ over\ FIFO = \frac{\hat{C}_{FIFO} - \hat{C}_{VBS}}{\hat{C}_{FIFO}} \qquad (16)$$

In Figure 23, without any disruption, the cycle time improvement over both EDD and FIFO slightly increases as the demand variation increases. When the demand range is small (1σ) the average cycle time improvements are relatively small at approximately 5% on both rules. When the demand range is high (3σ), cycle time improvement increases to 7% over FIFO and 11% over EDD.

However, with disruptions, there is a considerable difference in cycle time improvement. By providing full visibility over facility resources at each workstation through RFID and increasing the capability to reschedule current production plan when critical events arise, such as changes in demands, raw materials, or capacities, the cycle time improvement increases to approximately 30% over EDD and 50% over FIFO when the demand ranges are estimated at 1σ and 2σ. On the other hand, the benefit gained from RFID reaches its best at approximately 48% over EDD and 62% over FIFO at 3σ. Thus, we can conclude that information visibility-based scheduling approach is more valuable when an organization faces significant demand variations and disruption occurrences.

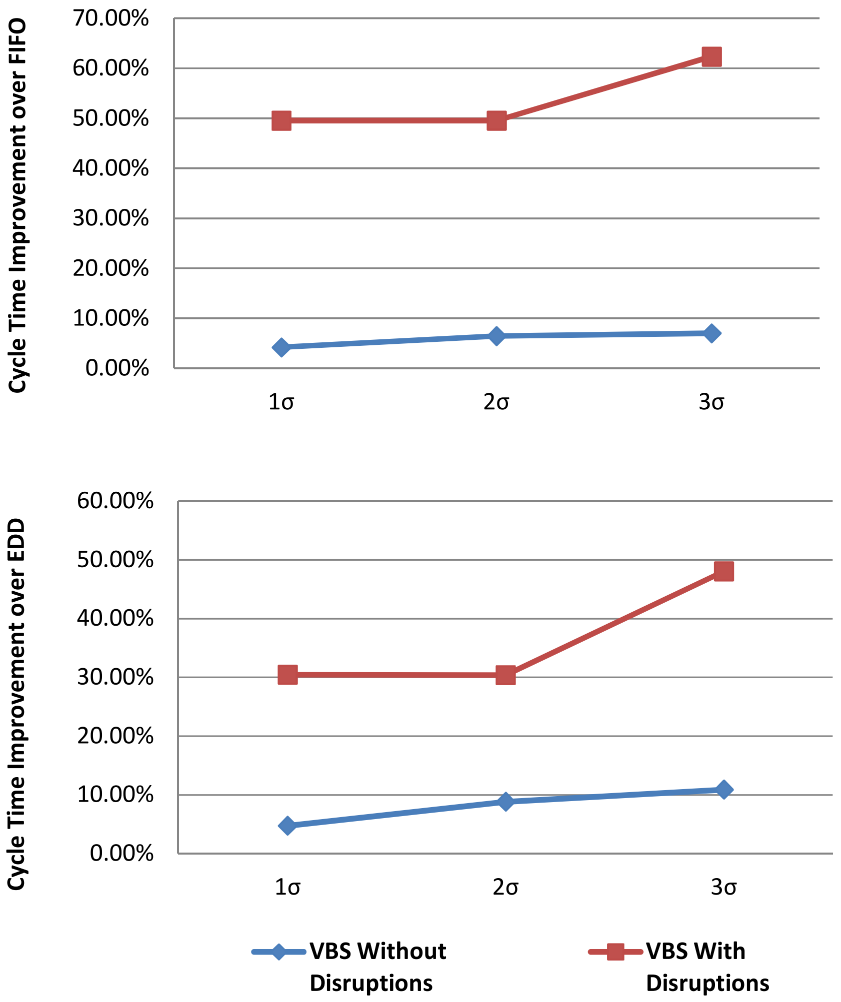


Figure 23: Comparison of Cycle Time Improvement with/without Disruption

8. Conclusion

In this study, we have presented and evaluated a novel information visibility-based scheduling (VBS) rule that can be applicable to any shop-floor operations. This scheduling rule allows production planners to reschedule or reprioritize the current production schedule when unforeseen events or disruptions such as the presence of rush orders, delayed raw materials, and limited resource capacity suddenly occurs in the shop-floor operations. We also test the performance of information visibility-based schedule against the classical FIFO and EDD rules that do not utilize any real-time location information. Using discrete-event simulation, we assess the value of RFID deployment in the context of an actual company's manufacturing operations. Our results show that:

1. Information visibility-based scheduling results in improving bottleneck operations (reduced set-up time, approximately 28-36%) and reducing cycle time (10-15%) and backlogs (20-25%), compared to the FIFO and EDD rules (Table 8).
2. *Value of information visibility increases when disruptions occur in the operations*. The testing utilization, average cycle time, on-time delivery, and penalty costs for RFID remains closely the same; meanwhile, those measures for both FIFO and EDD rules get worse with unforeseen disruption (Table 9 and Figures 19 and 20).
3. *Value of information visibility increases with increase in demand or decrease in capacity*. when the demand level is low, the difference between visibility-based scheduling rule and traditional scheduling rules is very minimal. The cycle time improvement for RFID over FIFO and EDD rules is relatively low (7%). When the demand level is high, the difference increases. The cycle time improvement is estimated at 10-15% (see Figure 22).
4. *Value of information visibility slightly increases with increase in demand variation:* the cycle time improvement over EDD and FIFO slightly increases when the demand range increases from 1σ (5%) to 3σ (7-11%), (see Figure 23).
5. *Value of information visibility increases when demand variation and disruptions occur in the operations:* the cycle time improvement over EDD and FIFO slightly

increases when the demand range increases from 1σ (30-50%) to 3σ (48-62%), (see Figure 23).

Our study contributes to both theoretical and managerial bodies of knowledge. For managers who seek to improve their shop-floor operations, it is essential not only to know where WIPs are and when they are transferred from one workstation to another, but also to understand how this granular level of information can be used to facilitate production scheduling activities such as rescheduling production tasks or prioritizing particular WIPs. More importantly, this study serves as a case example to show that the use of RFID can lead to significant improvement with regard to various performance measures such as reduction in cycle times and backlogs or improved capacity utilization.

Although that result by itself is not a surprising result, this study first demonstrates how RFID-based data capture can be converted into performance measures, and then through the simulation illustrates the order and magnitude of performance gains. As the results indicate, performance gains for RFID are modest when a manufacturing shop has much idle capacity at hand, but the gains are more pronounced under situation of increased capacity utilization, wide variation in demand, and interruptions in operations. The range of gains reported here can be used in performing specific cost-benefit analyses for a particular RFID investment decision situation. Additionally, unlike most RFID researchers that try to bring out the benefit of RFID in manufacturing through supply chain oriented angle (asset tracking, inventory improvement, or object location), this study contributes to the literature by providing in-depth analysis on the development of an RFID-based traceability system that can automatically keep track of the movement and path history of WIPs once they are transferred from one location to another.

This work has implications for further research. Although this study validates the view that information visibility-enabled track and traceability can improve manufacturing operations, this result should be validated in the other manufacturing environments such as different production lines or more complex production systems. Obviously, results of all simulation studies need to be validated in actual field situations. By providing a complete analysis on how RIFD can help in achieving a better manufacturing environment, both RFID and non-RFID adopters can make better decisions either to move forward with RFID or delay RFID investment for other familiar and less expensive alternatives. Finally, as RFID implementations still require significant investment, the decision to move forward with RFID depends on the return on Investment (ROI) analysis.

CHAPTER IV

CONCLUSION

In this dissertation we have focused on the application of RFID technology in manufacturing. We have presented simulation models to approach two key issues: Lean concepts and dynamic job-shop scheduling. The following two research questions are developed:

- Will more accurate information from RFID-based solutions help in achieving the goals of Lean initiatives in manufacturing plant performance and, if yes, in what specific ways?”
- Under what conditions information visibility-enabled track and traceability improve manufacturing performance and how?

To answer these research questions, two simulation studies of an organization that is considering implementing RFID on a production line of the optical receiver-transceiver, called OPT, used in telecommunication networks are presented.

For study #1 (Chapter 2), we focus on employing Lean concepts enabled by different automatic identification technologies (AITs): 1D barcode, 2D barcode, and RFID. This study examines the differences in operational performance due to information visibility offered by these identification technologies. To study the potential benefits of RFID technology through a Lean lens, the following research hypotheses are proposed:

H_1: Information visibility through RFID reduces *inventory waste* (producing more WIP than actually needed) compared to that in the non-RFID environment.

H_2: Information visibility through RFID reduces *overproduction waste* (producing more WIP than the work orders released) compared to that in the non-RFID environment.

$H_{3.1}$: Information visibility through RFID reduces waiting time (*waiting waste*) compared to that in the non-RFID environment.

$H_{3.2}$: Information visibility through RFID reduces setup time (*waiting waste*) compared to that in the non-RFID environment.

$H_{4.1}$: Information visibility through RFID reduces assembly time (*processing waste*) compared to that in the non-RFID environment.

$H_{4.2}$: Information visibility through RFID reduces testing time (*processing waste*) compared to that in the non-RFID environment.

H_5: Information visibility through RFID reduces cycle time compared to that in the non-RFID environment.

H_6: Information visibility through RFID reduces the number of backlog orders compared to that in the non-RFID environment.

Our results show that RFID-enabled approaches to Lean initiatives hold much promise. The ability to capture the status of WIPs in real time can provide valuable information to aid in Lean objectives. When RFID is applied, the model exhibits a superior performance in almost all Lean aspects. Additionally, the results show that employing RFID in Lean manufacturing initiatives can reduce some wastes but not necessarily all types of waste. We observe an increase in overproduction waste in our setting, although other wastes are reduced with improved information visibility. Real-time tracking information of WIPs through RFID is utilized to facilitate production scheduling in the shop-floor operations where resource capacity is limited while demands fluctuate. Thus, overproduction waste is possible.

The second study (Chapter 4) extends the benefits of RFID in a shop-floor operation by testing the performance of RFID implementation against traditional production scheduling rules: First-In-First-out (FIFO), Earliest Release Date First (ERD). The goal of the second study is to examine how track and traceability through RFID can facilitate job shop production scheduling activities and under what settings such information visibility can add value to an organization. We propose a real time track and traceability-based scheduling rule (RTTT) that utilizes improved information visibility from RFID and evaluate how RFID helps generate effective and efficient scheduling and respond to disruption situations or unexpected events occur in the shop-floor operations. These disruption scenarios include (1) the arrival of new urgent work orders released, (2) changes to a job's due date, (3) delays in the arrival of raw materials, and (4) limited resource capacity. The results show that information visibility-based scheduling improve bottleneck operations by reducing set-up time, cycle time, and backlogs (20-25%), compared to the FIFO and EDD rules. Additionally, value of information visibility increases with increase in demand and disruption or decrease in capacity.

Our study contributes to both theoretical and managerial bodies of knowledge. This is the first study to have studied all of the wastes associated with Lean manufacturing in an RFID setting. The information visibility-based scheduling (VBS)rule proposed in this study can also be applicable to any shop-floor operations. For managers who seek to improve their shop-floor/job-shop operations especially when they are facing the problem of delayed raw materials or limited resource capacity, this study serves as a case example on how RFID can be applied in manufacturing settings with the goals of reducing cycle time or backlogs to increase customer satisfaction. For any Lean adopters who are responsible for continuous improvement, this study shows that RFID can complement Lean manufacturing. Specifically, this study outlines how more accurate information from RFID helps in eliminating wastes in the operations.

The two studies examined in this dissertation leave ample room for future research, which have been discussed in the individual chapters.

- First, although this dissertation validates the view that information visibility-enabled track and traceability can improve manufacturing operations by reducing various wastes commonly encountered in shop-floor operation, this result should be validated in the other manufacturing environments such as different production lines or more complex production systems. Additionally, the decision to move forward with RFID or delay RFID investment depends on the return on Investment (ROI). Thus, there is a continuing need to evaluate the economic impact of implementing RFID, which is the subject of a further study.
- Second, since many Lean practitioners usually relied on traditional Lean principles to eliminate non value added activities. Another possible research direction is to evaluate the shop-floor performance when traditional Lean practices (such as standardized work, process stability, pull level production, or quality at the sources) are established with and without the presence of RFID. The connection between Lean philosophy and RFID is still not very well understood

in the view of any Lean and RFID practitioners. This issue is still one of the top concerns among industry.

- Another possible extension of this study is to understand how RFID affects a master production schedule (MPS), which determines when and how much of each product will be executed at the higher level of production planning and control. Mixed integer programming (MIP) model is commonly used to assist in master production schedule decision. Thus, it would be very interesting to see how granular level of information gained from RFID can be combined with such optimization technique to better develop a production scheduling system to either efficiently utilize the facility's resources, maximize services levels, or quickly respond to customers' demand variation.

In conclusion, we believe that RFID technology can actually be applied in the manufacturing area. Both Lean practitioners and RFID adopters need to understand the appropriate conditions and areas under which investing in RFID technology is more attractive..

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Scope and Method of Study: This dissertation investigates the impact of radio frequency identification (RFID) in manufacturing. Two simulation studies of an organization that is considering implementing RFID on a production line are conducted. First, we investigate whether addition of RFID technologies in the manufacturing process can complement Lean initiatives. Specifically, will more accurate information from RFID-based solutions help in achieving the goals of Lean initiatives in manufacturing plant performance and, if yes, in what specific ways? Second, we examine how track and traceability through RFID can facilitate job shop production scheduling activities and under what settings such information visibility can add value to an organization. We propose and evaluate a novel information visibility-based dynamic scheduling rule that utilizes information generated from the real-time traceability systems for tracking work in processes (WIPs), parts and components, and raw materials to adjust production schedules.

Findings and Conclusions: Results of the discrete-event simulation suggest that employing RFID in Lean manufacturing initiatives can reduce some wastes but not necessarily all types of waste. Our results show that increasing information visibility reduces inventory, processing time, set-up time, waiting time, cycle time, and backlogs. However, we observe an increase in overproduction waste in our setting. Additionally, we test the performance of the proposed information visibility-based schedule rule against the classical scheduling rules such as FIFO and EDD rules. The results of the simulation suggest that RFID-based scheduling rule generates better performance compared to both FIFO and EDD rules with regard to cycle time, machine utilizations, backlogs, and penalty costs. We also note that the value of this information visibility is more relevant when disruptions and demand variations occur in the operations or when the capacity is tight in relation to demand.

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