TRACEABILITY OF FINANCIAL ASSETS THROUGH THE APPLICATION OF THE INTERNET OF THINGS

A Dissertation

by

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ABSTRACT

Cash continues to be a vital payment method within the United States monetary system, and the use of money continues to grow despite common perception. This research explores the operational behaviors of an armored truck company (ATC) and its interactions with banks, retailers, automatic teller machines (ATMs), and their competitors and establishes a simulation that closely represents a typical branch. Provided data, observed data, and discussions with the management of an ATC validated the simulation model. Next, the research focused on technologies that could be applied to this branch to reduce costs, increase capacity, and improve visibility for all parties in the cash movement process. Through this exploration, passive RFID (radio frequency identification) was chosen as the most optimal solution with the most significant application at the lowest cost of ownership to the ATC branch.

After establishing the choice of technology, the simulation model was adapted to include RFID within the operational behaviors of the branch. RFID enables complete system visibility, improves operational behaviors, and significantly decreases operational costs. Adding in an RFID-based sorting robot reduces error and prevents bags from being sorted multiple times by different tellers within the branch. For the branch example used, adding an RFID system saved the ATC branch $2.1 million annually in operational costs and covered the cost of the system deployment. ATCs that deploy RFID within their branches save money, increase capacity, and improve cash visibility.

DEDICATION

My wife, Tammy Decker, has been my rock throughout this research and Ph.D. program. Needless to say, she has endured many hardships and challenges over these years, yet she has stood beside me with constant encouragement and energy.

Because of his constant encouragement and sincere concern for my education, life, and future, I would like to thank Dr. Ben Zoghi. His relentless drive is contagious, as is his love for life-long learning. I have been honored to work with someone of such high moral character and genuine endearing care.

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Contributors

This work was supervised by a dissertation committee consisting of Professor Ben Zoghi, advisor of the Department of Multidisciplinary Engineering, Professor M. Cynthia Hipwell of the Department of Mechanical Engineering, and Professors Mark Burris and Ivan Damnjanovic from the Department of Civil Engineering.

All other work conducted for the dissertation was completed by the student independently.

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NOMENCLATURE

AoA	Angle of Arrival
API	Application Programming Interface
ASK	Amplitude Shift Keying
ATC	Armored Truck Companies
ATM	Automatic Teller Machine
BER	Bit Error Rate
BLE	Bluetooth Low Energy
CIT	Cash In Transit
CMS	Cash Management System
CRT	Chinese Remainder Theory
CSS	Chirp Spread Spectrum
CW	Carrier Wave
DF	Direction Finding
EID	Ephemeral ID
EPC	Electronic Product Code
FDMA	Frequency Division Multiple Access
FRB	Federal Reserve Bank
GFSK	Gaussian Frequency Shift Keying
IEEE	Institute of Electrical and Electronic Engineers
IETF	Internet Engineering Task Force

IoT	Internet of Things
ISM	Industrial, Scientific, and Medical
IT	Information Technology
JSON	JavaScript Object Notation
LAN	Local Area Networks
LNA	Low Noise Amplifier
LPWA	Low Power Wide Area
LPWAN	Low Power Wide Area Networks
LTE-M	Long Term Evolution for Machines
MMS	Miller Modulated Subcarrier
NDP	Neighbor Discovery Process
PAN	Personal Area Networks
PDA	Personal Digital Assistant
PIE	Pulse Interval Encoding
POE	Power Over Ethernet
PSK	Phase Shift Keying
RA	Random Access
RF	Radio Frequency
RFID	Radio Frequency Identification
ROI	Return on Investment
RSSI	Received Signal Strength Indicator
RTLS	Real Time Location System

SDN	Software Defined Networking
SIG	Special Interest Group
SJC	Self-Jamming Controller
TDMA	Time Division Multiple Access
TID	Tag ID
UID	Unique ID
URL	Uniform Resource Locator
WPAN	Wireless Personal Area Networks
WSN	Wireless Sensor Networks
WWAN	Wireless Wide Area Networks

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CHAPTER 1

INTRODUCTION

Current Cash Movement Process

In most economies today, cash is a vital component of the monetary system. Cash is a liquid financial asset that is easy to access and use in everyday life. While the usage of cash is changing with the new forms of payment, cash is still used by most citizens to some extent. With the continued use of cash in the United States (U.S.) economy, there is a need to transfer cash from banks to retailers and retailers to banks. To avoid robbery while transporting cash, retailers turn to armored truck couriers (ATCs) to securely move that cash. In addition, banks use ATCs to transport cash between bank branches and with the Federal Reserve Bank.

Contrary to common thought, the supply of cash in the cash cycle was at an all-time high in 2022. While cashless transactions and cryptocurrencies are widespread today, cash is still used extensively. According to Mr. Robert Bujas, the Assistant Vice President of Supply Chain Engagement at the Federal Reserve Bank, there are more than $2.1 trillion in circulation today. Figure 1 is a graphic of the cash in circulation as of April 2021, showing a marked increase in currency in circulation due to Covid-19.

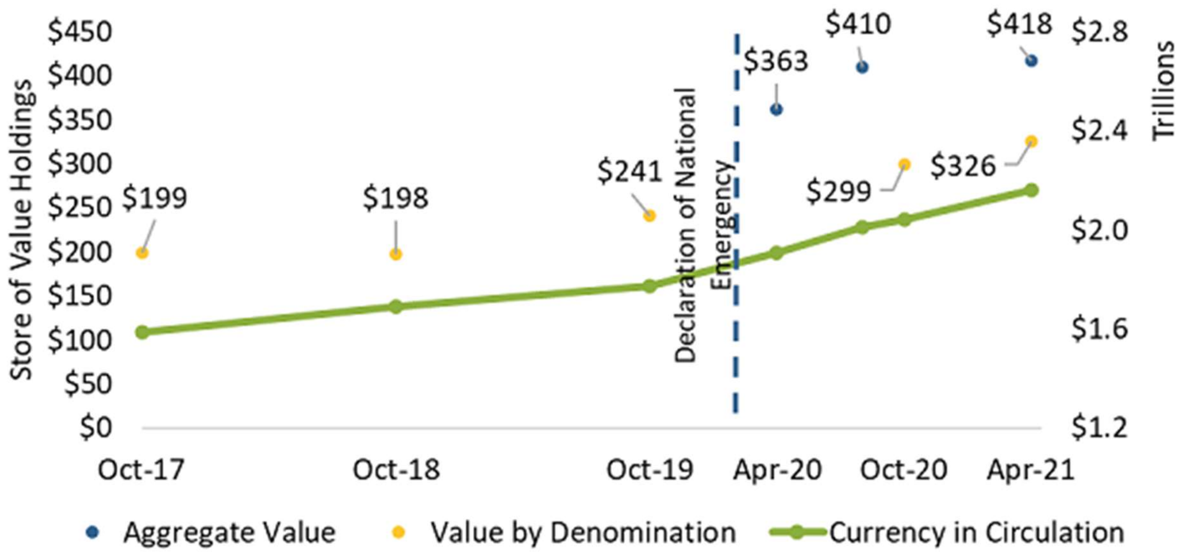

Figure 1 - Cash in Circulation Since 2017

Note: Taken from (O'Brien, S. (2021). Consumer Payments and the COVID-19 Pandemic: Findings from the April 2021 Supplemental Survey. https://www.frbsf.org/cash/publications/fed-notes/2021/september/consumer-payments-covid-19-pandemic-diary-consumer-payment-choice-supplement-3/

Trading Economics (*United States - Currency in Circulation*, 2022) provides a graphic for cash in circulation from 1918 through 2022, estimating that the money in circulation is $2.284 trillion (see Figure 2), clearly showing a consistent climb in cash circulation. Large amounts of cash in circulation require safe and effective means of movement and standards for properly identifying cash-in-transit (CIT) containers.

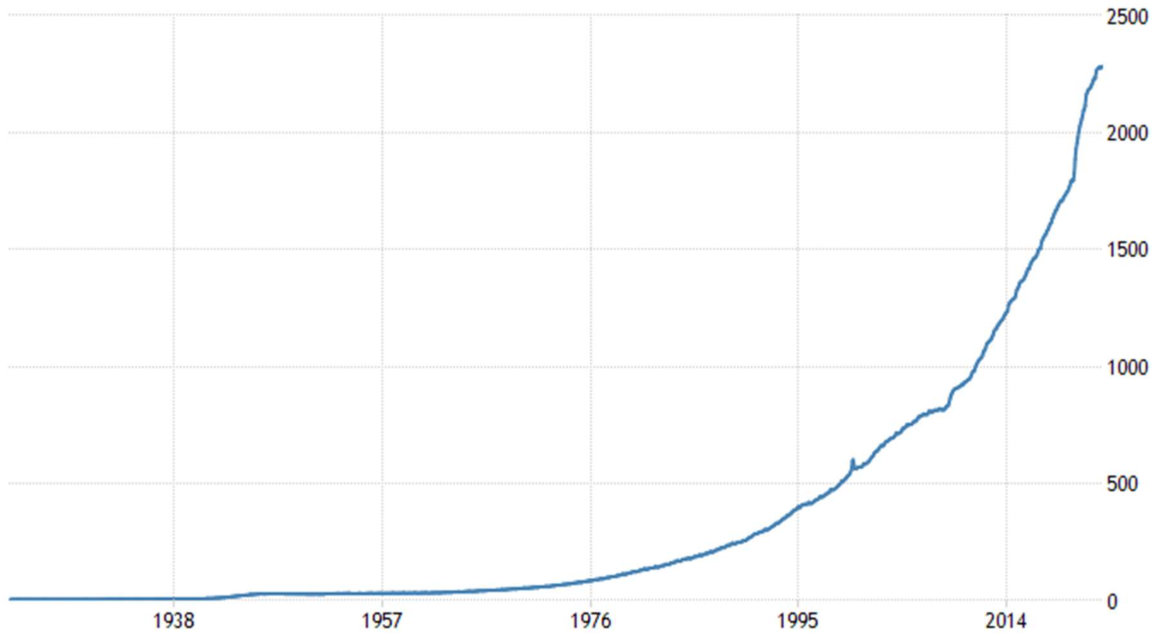

Figure 2 - Cash in Circulation Since 1918

Note: Taken from Cash in Circulation since 1918 (United States - Currency in Circulation, 2022).

https://tradingeconomics.com/united-states/currency-in-circulation-bil-of-$-m-nsa-fed-data.html

ATCs operate fleets of heavily armored cash transport vehicles staffed with armed security professionals. These armed security professionals are highly trained in the security processes of cash movement. ATCs protect cash and transport valuables, including precious metals and priceless artworks.

Retailers rely on ATCs to efficiently move their cash assets to and from the bank as needed in a timely way. Retailers execute strict contracts with ATCs ensuring specific performance metrics for the transportation of their cash. Retailers have limited options for ATCs in most areas of the U.S. because there are very few competitive couriers in each market. While ATCs are insured for the liabilities they transport, the retailer is ultimately responsible if money is lost during transport. They must launch time-consuming investigations with proof of the transaction before the ATCs insurance pays out the claim. While the investigation and claim are in process, the retailer's cash is tied up for months and unavailable for commerce.

Once a retailer transfers custody of a cash bag (e.g., a deposit) to an armored courier, the retailer does not understand the cash's movement until it shows as a deposit in their bank account. Retailers must wait for a contractual period of time (the contract between the retailer and the courier mentioned earlier) before launching an investigation of a missing deposit. The ATCs also require that missing bags are reported and investigations launched before a maximum date (e.g., 90 days from pickup). Retailers state frustration with the lack of visibility inside the ATC system.

The traceability of financial assets (e.g., cash, coin, checks) has been a topic of conversation since 2016, when GS1, a standards organization for barcoding and Radio Frequency Identification (RFID), issued a series of specifications and recommendations for improving the traceability of financial products between entities. Money transfers occur daily between banks, processing facilities, the Federal Reserve Bank, and customers (e.g., retail establishments). These assets move by armored trucks with a staff of one to three people.

By and large, most of the cash management process is still conducted with paper receipts between entities. Some companies have instituted barcode scanning as a means of transfer, but the methods are disjointed and often backed up by physical paperwork. The Federal Reserve Bank appears to have the most automation regarding cash management because the volume of cash moved there requires a greater level of technology.

All transactions within the cash management industry have a chain of custody requirement where one entity transfers the liability of the cash to the receiver. A cash shipment may require ten or more custody transfers before being finally delivered to the appropriate endpoint.

In addition, some armored truck companies (ATC) also act as bank storage and processing facilities. In these cases, banks keep substantial inventories of cash and coin in remote vaults at these ATCs. An ATC with these services segregates cash in their vaults by the banks they service. These are stored in lockers, containers, and small inner vaults.

The Current State of Cash Visibility

Most cash-handling bodies (e.g., banks and ATCs) have participated in developing the GS-1 Cash Visibility Standard (GS-1, 2020). This standard breaks down the elements of cash visibility and is a guide to a numbering system for packages of cash. The standard focuses entirely on barcodes as a means of traceability.

Based on interviews with ATCs and the Federal Reserve Bank, the industry has implemented barcodes as a standard on bags, with the leading characters of the barcode representing the organization that produced the bag. The GS-1 U.S. Guide for Cash Visibility Standards (USGCVS) calls this barcode a Serial Shipping Container Code or SSCC. This barcode contains up to 18 digits, with the leading digits identifying the GS1 Company Prefix and the remainder indicating a serial reference. The intent of this in the USGCVS is to provide traceability from its source to its destination. While this code is acceptable as an identifier, it does not provide routing information.

Beyond the barcodes, very little of the USGCVS has been implemented. Part of the issue with implementation is the voluntary nature of businesses to adopt a Global Location Number – GLN. GLNs are intended to identify every business entity in the cash movement system. Some banks require GLN registration to open a new business banking account, but not all. In addition, access to the entire GLN database creates tension between banks and ATCs. These entities are concerned that populating this database effectively gives away their customer list, making them reluctant to participate. Even within organizations, some support the full deployment of GLNs, while others oppose the registration. Because each company has its own account numbering system, each entity continues to operate without GLNs preferring to use its proprietary account numbering system. Using proprietary account numbering creates silos of information and reduces the opportunity for intercompany software integrations.

Some companies that utilize the same software systems have integrated on a smaller level. Integrations between banks and ATCs that process deposits vary significantly. Some banks get a daily settlement report emailed, while others have extranet access to see more detail.

Retailers are frustrated with the lack of visibility of change orders and deposits. Large retailers with many branches spend much time researching missing deposits. With more than 9,000 stores making daily deposits, Walgreens struggles with daily deposit reconciliation and regularly spends hours researching missing deposits (Kim Clark, Walgreens Employee, Personal Interview, November 22, 2022).

The current state of cash visibility is hampered by distrust, lack of interoperability, and a valid means of tracking SSCC (cash bags) beyond barcoding. The remaining portion of this document explores the application of IoT to the cash management system while seeking to improve visibility, optimize behaviors, and reduce costs.

CHAPTER 2

PROBLEM STATEMENT & HYPOTHESIS

Problem Statement

Cash management companies are a crucial component of the United States system of commerce, yet these companies are not taking advantage of IoT technologies that have been proven in many similar industries. Walmart (Tao et al., 2022) and Delta Airlines (Wyld et al., 2005) have adopted IoT successfully. These companies track low-value items (Walmart – cases of goods to stock and sell in stores, and Delta – customer baggage). In contrast, cash management companies transport high-value items at best utilizing barcodes. Walmart and Delta have successfully improved customer satisfaction, reduced loss, and increased the visibility of assets. Cash management companies offer minimal visibility, and there is a lack of interoperability between companies. The cash movement ecosystem is generally unfamiliar with IoT and operates on narrow profit margins, so they are skeptical about exploring IoT technology. The cash management industry is mired in antiquated technology and uses arcane methods while handling high-value assets.

Hypothesis

Adding an IoT technology into the cash movement ecosystem reduces costs, improves capacity, and provides visibility to parties involved in the cash movement.

CHAPTER 3

RESEARCH OBJECTIVES

The first objective of this research is to review the cash management system's operational behaviors and processes, thoroughly mapping their existing processes, their functional purposes, and their perceived benefits. Secondly, a simulation model of the operational behaviors of cash movements is created and tuned according to observational and supplied data and establishes a baseline of operational timing and cost. Thirdly, the researcher identifies three IoT technologies with bank and ATC operations applications, evaluating each according to system requirements. Fourthly, the researcher adapts the simulation model with the chosen IoT technology and compares the model baselines to the adjusted model, indicating the potential return on investment and payback period. Finally, a recommendation for the cash management industry is made based on the findings of the aforementioned objectives.

CHAPTER 4

METHODOLOGY

This research used a mixed methodology approach utilizing both qualitative and quantitative methods. The investigation began with a detailed process mapping exercise at an armored courier facility for five days, with several additional trips to the courier branch to discuss findings and resolve errors in the process mapping. The process mapping was accomplished through more than 60 hr of observation and interviews with employees and management (see Appendix A for the complete process map and associated discussion).

Following the process mapping exercise, technologies were analyzed to choose the appropriate technology based on the constraints offered by the armored courier. Each technology was viewed through the lens of a potential installation at the armored courier branch, where the process mapping was accomplished. Technologies were evaluated based on various characteristics and system costs. Once a technology was selected, the possible options for equipment and IoT device characteristics and performance measures were narrowed down. Once a technology and devices were chosen, the researcher reviewed the application of the technology to several use cases (e.g., RFID application in a vehicle). The details of the analysis of technologies are summarized in Chapter 7.

Once the technology evaluation was completed, a simulation model was developed using AnyLogic software, a simulation tool specifically designed for business process modeling. Much effort was made to ensure that the simulation model accurately reflected current processes through tuning and validation.

The system behaviors, observation, and financial information acquired from an armored courier were used to create a base business cost model. This model is based on ATC employee behaviors and transactions and through interviews and discussions with the armored courier to validate the existing business model. The discussion of the current state simulation model and cost model are discussed in Chapter 6.

Having completed the baseline model, the researcher applied the chosen technology to the AnyLogic current state model simulation. The focus of this process is to evaluate the difference between the two models (current and future state) in terms of the processing time of cash bags within a branch operation, which, in turn, alters the business cost model. The future state model simulation and the business model are detailed in Chapter 8.

Following comparing models and business case evaluations, recommendations are provided based on the completed research and results. These recommendations are presented in Chapter 9.

CHAPTER 5

LITERATURE REVIEW

Cash Visibility

The topic of cash visibility with IoT in Cash-In-Transit (CIT) operations is an area that has very little literature in academic journals. In cooperation with the standards organization GS-1, the industry has developed a document under the title U.S. Guide for Cash Visibility Standard (GS-1, 2020). This guideline establishes the terminology and the primary traceability of cash bags through the use of barcodes. Mostly, barcodes have been adopted by the majority of the industry, but little else from the guideline has been implemented.

Valentine (2011) describes the transfer of typical banking behaviors from banks to processing facilities like ATCs. The author describes how the consolidation of banking services at ATCs reaches an economy of scale and allows bank customers to be serviced more safely and logically. In addition to regular banking services, ATCs enable a smart-safe option to bank customers that immediately sorts and counts cash credits and deposits into the customer's account.

Several researchers have attempted to provide recommendations for better CIT security by optimizing the routing of armored vehicles (Allahyari et al., 2021; Tikani et al., 2021; Wu, 2021; Xu et al., 2019; Yan et al., 2012). This area of research seeks to save money, reduce the risk of robbery, and optimize operational behaviors. Xu et al. (2019) suggest that the risk of armored vehicle robbery correlates with the amount of cash on the truck and the distance the vehicle is required to travel. They also indicate that travel in areas of low socio-economic status dramatically increases risk.

In Automatic Teller Machine (ATM) servicing, researchers have explored several paths to predict the supply of cash availability in these machines and optimized operations (Ágoston et al., 2016; Almansoor & Harrath, 2021; Chiussi et al., 2022; Ekinci et al., 2021; Fedets, 2021; Hasheminejad & Reisjafari, 2017; Ilagan et al., 2019; Nemeshaev & Tsyganov, 2016; Orlis et al., 2020).

Technology

A wireless system in this proposed application comprises wireless technologies, security, and sensors. Wireless technologies range from Personal Area Networks (PAN) to Wireless Wide-Area Networks (WWAN). A key concern with every network is the security of the data that moves through the system and is stored for future use. In addition to wireless technologies and security, sensors are required to gather data from equipment or cargo to identify the condition or status of the items monitored.

Internet of Things (IoT)

Kevin Ashton of Proctor & Gamble coined the phrase "Internet of Things" in 1999 in his work with supply chain management and radio frequency identification (RFID) (Awadelkarim Mohamed & Abdallah M. Hamad, 2020). Before this, IoT has many other names, including machine-to-machine (M2M) and the basic term "telemetry." Regardless of the terminology, Qadir et al. (2018) describe the Internet of Things (IoT) solutions as "IoT applications are characterized by their low data rates, power consumption, and cost." The Internet Engineering

Task Force (IETF) defines IoT as "the network of physical objects or "things" embedded with electronics, software, sensors, and connectivity to enable objects to exchange data with the manufacturer, operator, and other connected devices" (Awadelkarim Mohamed & Abdallah M. Hamad, 2020). The following section discusses a review of wireless connectivity, sensors, and security to understand each topic better.

Wireless Connectivity

Several methods exist for moving data within Wireless Sensor Networks (WSN). The network's topology relies on the system's constraints. Wireless technology has the well-deserved reputation of being the most significant power consumer for any IoT WSN; therefore, it is crucial to consider battery-powered devices' power consumption and expected lifespan in system design. De Almeida et al. (2019) propose that IoT devices may be required to operate on a single battery for ten years or more.

Wireless technologies may be very short-range networks called PANs or personal area networks. The most typical PANs are Bluetooth, Zigbee, passive RFID, and passive Bluetooth. Next, Local Area Networks (LANs) provide a more extensive range of coverage and may also provide more significant data bandwidth than PANs. Typical LAN architectures are ethernet and Wi-Fi. In moving the coverage to larger areas, wide-area networks provide a much larger device footprint, typically at a higher cost and lower bandwidth. Finally, WWANs offer a wireless connection which avoids the need for physical connections to each device. WWANs are also called Low Power Wide Area (LPWA) or Low Power Wide Area Networks (LPWAN). LPWANs include cellular technologies of Long Term Evolution for Machines (LTE-M) and

Narrow Band IoT (NB-IoT.) Unlicensed LPWANs include LoRa, Ingenu (RPMA), and Telensa. Each of these technologies is discussed in subsequent paragraphs.

Qadir et al. (2018) compare several wireless connectivity network technologies and present Figure 1 comparing many technologies that exist for IoT. These authors compare the range and data rate available for each technology.

Wireless Area/Personal Area Networks

The class of shorter-range networks is categorized as personal area or wireless area networks. For this study, the limitation on wireless area networks is set to approximately one mile of network range.

Bluetooth

For Bluetooth, Ding et al. (2020) describe the history and evolution of the Bluetooth specification. Nokia originally developed Bluetooth, but today it is managed by the Bluetooth Special Interest Group (SIG) and standardized under the Institute of Electrical and Electronic Engineers (IEEE) standard 802.15.1. Starting as what today is referred to as Classic Bluetooth, the original use of this technology was to wirelessly connect peripherals like keyboards, mice, and headphones to computers and phones. Classic Bluetooth is very inefficient from a power consumption point of view. There have been significant improvements in this technology in recent years, including the release of Bluetooth 4.0, which includes many power improvements and the concept of Bluetooth Low Energy (BLE) and Bluetooth Beacons. Bluetooth 5.0 introduces meshing and direction finding (DF).

Ding also describes the modulation type as employing both time division multiple access (TDMA) and frequency division multiple access (FDMA). He describes using the 40 channels in the 2.4 GHz ISM (Industrial, Scientific, and Medical) frequency band. Specifically, in BLE, devices advertise their availability for connection on channels 37, 38, and 39. Those advertisements allow master nodes (phones, computers, BLE readers) to connect with and negotiate a connection on the remaining 37 BLE channels. This pairing behavior allows for a very smooth and low-energy connection (Nikodem et al., 2020).

These advertisements in BLE can also transmit small fragments of sensor data in a fully connectionless way. These Bluetooth beacons are ultra-low-power devices that transmit on one of the advertising channels in a unidirectional transmission that may or may not be received by a master node. The advantages of a wireless sensor network are significant in the areas of power savings and data collection. Beacons take measurements at intervals and then transmit those on one of the three advertising channels. Most beacons randomly hop between the three advertising channels to avoid collisions and add robustness to the WSN. One key disadvantage of BLE beacons is that sensor data has no network acknowledgment of reception of the sensor data advertisements. Because of this, beacons are transmitted even when there is no master node within range. Another disadvantage is that the master nodes also frequency hop on the advertising channels and may miss beacon transmission on non-monitored channels. An improved receiver may have three channel master nodes, but the cost often is prohibitive to do so (Park & Kwon, 2021).

Park and Kwon also introduce an improved quadrature low noise amplifier (LNA) into the Bluetooth Low Energy (BLE) receiver for IoT. These researchers have identified a better architecture than many BLE receivers' low-intermediate frequency (IF) receivers. Park and Kwon focus on low-power and low-voltage IoT applications, which applies to the proposed research. According to this study, adding a quadrature LNA to the circuit improves the detection mechanism's symbol detection accuracy, improving demodulated data recovery. This new circuit employs an "active-type poly-phase filter," which when implemented, provides better quadrature signals without additional power draw on the power source. The active-type poly-phase filter reduces gain and phase error in the quadrature signal, improving the image rejection ratio, reducing the noise factor, and increasing receiver gain. Park and Kwon's research informs the proposed research because many sensors are challenging RF conditions.

Hernández-Rojas et al. (2018) provide an excellent overview of Bluetooth beacon technology and its associated protocols: iBeacon, Eddystone, and AltBeacon. These three beacon structures are illustrated in Figure 3.

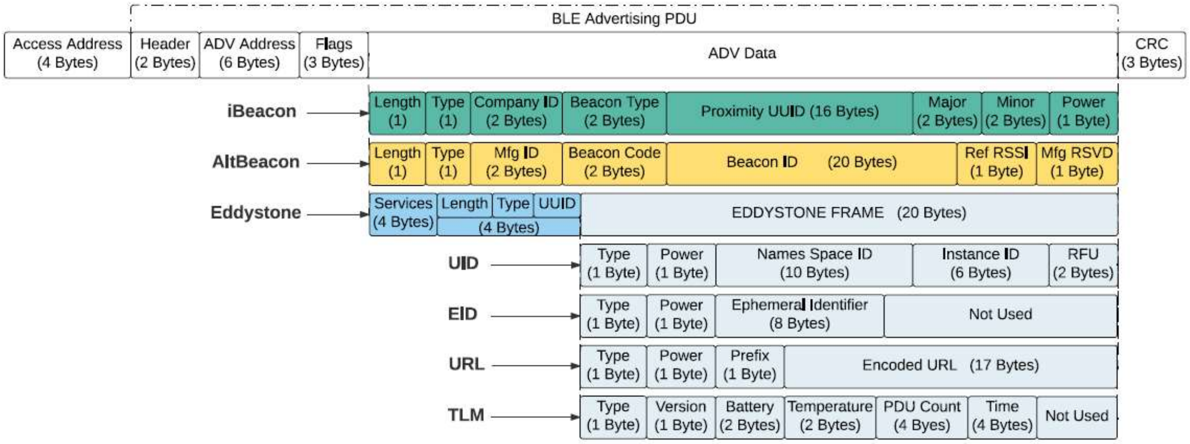

Figure 3 - BLE Advertising Cash Bag Structure

Note: Taken from Hernández-Rojas, D. L., Fernández-Caramés, T. M., Fraga-Lamas, P., & Escudero, C. J. (2018). Design and practical evaluation of a family of lightweight protocols for heterogeneous sensing through BLE beacons in IoT telemetry applications. Sensors (Switzerland), 18(1), 6. https://doi.org/10.3390/s18010057

According to Hernandez-Rojas, the first beacon structure is called iBeacon. iBeacon was defined by Apple for use initially only with iPad, iPhones, and iPods. Since then, many others have implemented iBeacon in their products. Radius Networks, recognizing the proprietary nature of iBeacon, created a new open-source beacon structure called Altbeacon. Altbeacon, as seen in the diagram above, for the most part, is compatible with iBeacon, but opened up the use of beaconing to the entire market. After Altbeacon's release, Google entered the BLE beacon competition with the Eddystone beacon structure, which is compatible with the Android operating system. Eddystone broadened the beaconing formatting by offering four different frame types: UID, EID, URL, and TLM. Unique ID (UID) broadcasts a specific ID corresponding to an application database. The UID format resembles active RFID system behavior but is based on the Bluetooth industry standard. Ephemeral ID (EID) is a barely used format intended for greater security for beacon IDs. Uniform Resource Locator (URL) simply broadcasts a web address for local receivers. This method has been applied most often in retail environments offering sales on specific products in the store. Finally, TLM is for telemetry and provides some basic temperature, battery status, and time for simplistic sensor monitoring. Hernández-Rojas proposes three IoT "lightweight protocols" types for three different beacons. Beacons are Bluetooth Low Energy (BLE) advertisements commonly used for presence detection but transmit additional sensor-based information during the advertisement for a session-less transmission of sensor data. These beacons are typically on some interval transmission (e.g., 10 s between messages) and are transmitted even when no receiver may be in range. The objective of BLE beacons is to allow many devices to be present in the same space transmitting beacons at intervals. If a collision occurs at the receiver, the nature of the transmission sequence will most likely transmit on different channels or in different time slots on the next interval. BLE devices are usually specified to have very long battery life.

Hernandez-Rojas also introduces a series of protocols with three types of beacon purposes. The LP4S-6 is used for Type-1 beacons that have limited capability. This is also true of most BLE beacons today. These Type 1 beacons have little or no internal data processing capability or decision-making ability. The following protocol is the LP4S-X which is used for Type-2 beacons. Type 2 beacons have more hardware resources and can utilize the GATT (Generic Attribute Profile) information. The GATT protocol is very typical in sensor-based BLE beacons. GATT services are IoT protocols that apply to very specific applications of BLE beacons. For instance, blood glucose monitors and cycling cadence counting devices have GATT services, as do BLE-enabled heart rate monitors. These GATT services create interoperability between devices and applications. The third protocol is for much stronger Type 3 beacons and is called LP4S-J, which supports JSON (JavaScript Object Notation) scripting to occur on the device. Type 1 devices consume the least power, while Type 3 devices consume the most.

Nikodem et al. (2020) propose a third method of Bluetooth Low Energy beacon methodology where devices that normally beacon periodically without knowledge of reception are acknowledged (ACK) by the reader/scanner, and the interval rate can be turned off for extended periods. This does several things for the data transmission. 1) The node has confirmation that the message was received intact. 2) The node can assume a longer interval which reduces battery consumption. 3) The RF channels used by the nodes are less congested, which improves the network quality.

Nikodem calls this process active scanning. Usually, a reader/scanner scans advertising channels 37, 38, and 39 listening for advertisement beacons; this is considered passive scanning. Passive scanning does not prevent collisions in the network, however. Passive scanning is a one-way communications path, and the node never knows if the message was received or if a reader/scanner is within range. Active scanning is a means that requires three messages of interaction between the node and the reader/scanner. The node transmits an advertisement, the reader/scanner responds with a SCAN_REQ response, and then the node responds with a SCAN_RESP fulfilling the communication. According to these researchers, active scanning allows more nodes to be within the zone of the master because of reduced channel congestion.

One advantage of active scanning is that 31 bytes of sensor data can be passed from the node to the reader/scanner in the advertisement and the SCAN_RESP message. At the point of the acknowledgment, the node can go into sleep mode until additional data needs to be transmitted.

Lou et al (2019) brings to light a method of discovering Bluetooth neighbors using a Chinese Remainder Theory (CRT). This process is called the Neighbor Discovery Process (NDP) and is a known issue in Bluetooth Low Energy (BLE) advertising where BLE devices may not be able to communicate node to node. In the Bluetooth 5.0 standard, it allows for meshing/node-to-node communications. The advantage of this is that distance from the BLE reader can be extended significantly within an IoT network. This team of researchers focused on an advertising algorithm that improves the detection of BLE advertising beacons between nodes. This is especially important in a beacon-only solution where IoT devices advertise sensor data in normal advertising channels. The technology of node-to-node retransmission of beacons in a mixed, blocked, or long-range sensor network is essential. This research can improve the capture rate of sensor beacons and advance the overall performance of a BLE beacon-based IoT sensor network.

Zigbee

Zigbee networks are defined by IEEE specification 802.15.4. Zigbee is a mesh communications protocol with a coordinator, a router, and an end device. The coordinator and router are usually fully powered devices, while the end devices are battery powered. The coordinator is the key element of the system and makes connections outside of the network through the router to other Zigbee or management networks. Zigbee typically operates in the 900

MHz ISM band but has variants in the 2.4 GHz ISM band. Ding et al. (2020) draw a direct comparison to Bluetooth, comparing and contrasting various features and benefits. The key drawback to Zigbee is that nodes can only pass on the information and cannot consume the data from other nodes. Zigbee networks can also be disrupted by the lack of contiguous range mesh nodes that halts the network function. Finally, battery consumption in a Zigbee network is significantly more than that of a BLE beacon sensor network. However, one key advantage of the Zigbee network is that the network is always on and able to quickly move data from node to node, creating a self-healing network of devices that may be stationary or in motion.

Kahn et al. (2019) created an interoperable Bluetooth and Zigbee network allowing both technologies to be used simultaneously. The combination of these technologies can develop a solution in which the strengths of both networks are used in areas where those attributes are most needed.

RFID

The GS1 Innovation Board and EPC Global Board of Governors manage the EPC Gen 2 specification for passive RFID. This is the standard from which all passive RFID systems gain interoperability. Passive RFID suffers from some international roaming issues because of the frequency allocations of individual countries.

Figure 4 illustrates a typical diagram of an RFID system (courtesy of Researchgate.net) showing the reader/interrogator communication process with an RFID tag. Generally speaking, a fixed RFID system, as shown, is constantly scanning a specific area or zone of activity. When an RFID tag enters the RF field of the antenna, the RF energy is harvested by the RFID antenna, which powers the RFID chipset of the tag. The tag then reflects a response to the reader with its unique ID and perhaps additional data depending on the type and configuration of the tag. The information from the tag is decoded in the reader/interrogator and then available for processing by software.

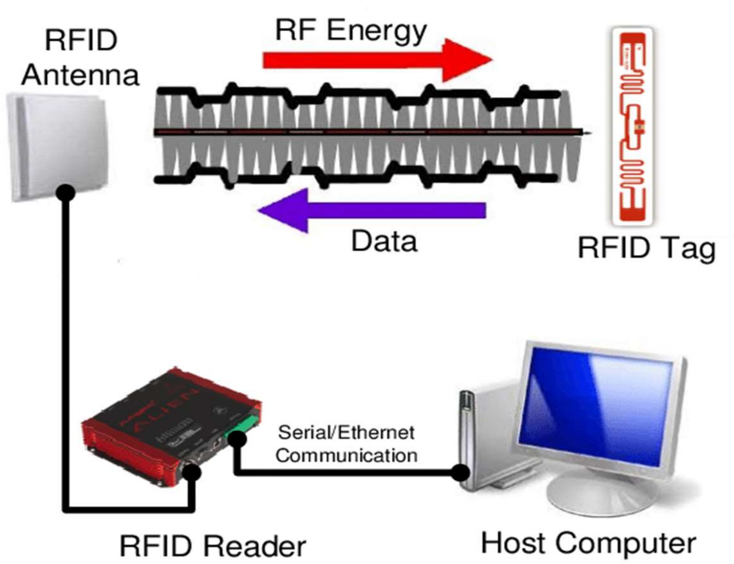

Figure 4 - Typical RFID System

Note: Taken from Shaaban, K. (2013). Typical Passive RFID System. https://www.researchgate.net/figure/Typical-Passive-RFID-System_fig1_260791266

RFID tags have several memory locations. The most basic memory area is a non-editable area called the tag ID (TID). This number is unique in every tag. Next is the electronic product code (EPC) memory location. The EPC is an editable field in the tag with variable storage length depending on the chip manufacturer. EPC and TID memory locations are typically queried in readers' “scan for tags” function. The EPC can be filled with a product identifier or serial number. This area may be used for any operation the system designer sees fit. Finally, some

RFID tags have user memory. Depending on the chipset manufacturer, user memory may have just a few data bits up to kilobits of storage. Some tags may also have some reserved space for tag passwords or other management memory, which is not accessible by the user. See Figure 5 for a graphical representation of memory in an RFID chip.

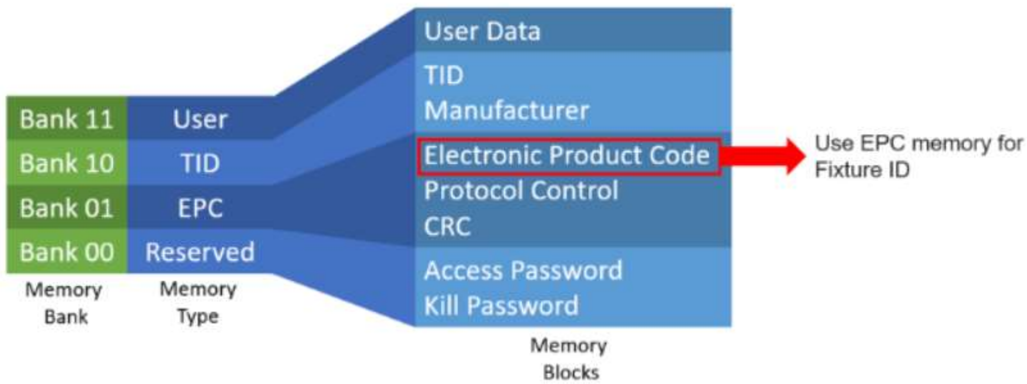

Figure 5 - RFID Memory Locations

Note: Taken from Lee, K. W. (n.d.). RFID for Test Fixtures. https://www.keysight.com/blogs/tech/2020/09/13/rfid-for-test-fixtures

Wi-Fi WPAN

Released in 2017, Wi-Fi WPAN networks, specifically IEEE 802.11ah, are one of the latest IoT-related networks. This technology is also called HaLow or Wi-Fi HaLow. Operating in the 900MHz ISM band, it has better building penetration and extended range. This network can support thousands of devices at distances up to 1km, but the bandwidth is limited to 300 Mbps. (Ding et al., 2020). More research is required in this area as more systems are deployed.

Low Power Wide Area Networks

Low power wide area (LPWA) is a designation given to networks covering a much wider area than the previously discussed networks. Ding et al. (2020) focuses on LPWA networks; however, they provide a short review of many of the technologies listed in Table 1.

Table 1 - Various Forms of LPWANs

Parameter/Protocol	LoRaWAN	SigFox	RPMA	Telensa
Band	902-928MHz	902-928MHz	2.4GHz	902-928MHz
Data rate	0.3 - 5kbps	UL: 100/600 bps DL:600 bps	UL: 624 bps DL:156 bps	UL: 62 bps DL:500 bps
Occupied bandwidth	125kHz	1.5kHz	1MHz	100kHz
Modulation	FSK	UNB/DBPSK, GFSK	DSSS	UNB 2-FSK
Range	5km (urban), 15km (rural)	10km (urban) 50km (rural)	15km (urban) 500km (LOS)	3km (urban) 8km (rural)
Link budget	171	146-162	180	unknown
MAC	Pure ALOHA	R-FDMA	CDMA-like	unknown
Topology	Star-of-stars	Star	Star/Tree	Star/Tree
Max payload (bytes)	250	UL: 12, DL:8	64	65k
Link symmetry	Yes	No	No	No
Handover	Yes	Yes	Yes	Yes
Error Correction	CRC-8/16	CRC-8/16	CRC	Yes
Security	AES-128 b	done at upper level	16 B hash, AES-128 b	Yes

Note: Taken from Qadir, Q. M., Rashid, T. A., Al-Salihi, N. K., Ismael, B., Kist, A. A., & Zhang, Z. (2018). Low power wide area networks: A survey of enabling technologies, applications and interoperability needs. IEEE Access, 6, 77480. https://doi.org/10.1109/ACCESS.2018.2883151

These researchers point out that unlicensed LPWA networks must have several key characteristics, including long-range coverage, low data rates, low power consumption, low-cost end devices, support for large numbers of end devices, and simplified network topology. At the time of this study, the key players in the unlicensed LPWA network space are Semtech

(LoRaWAN), SigFox, Ingenu (RPMA), and Telensa. Table 1 compares these technologies with NB-IoT, a cellular-licensed IoT solution.

Ding also details each technology and then transitions to various applications for each technology. They focus on aligning LoRaWAN, SigFox, RPMA, and Telensa into one interoperable protocol stack. Next, Ding transitions to a discussion regarding licensed LPWANs, specifically 5G and LTE. According to the author, LTE is a fourth generation (4G) and a fifth generation (5G) technology. 5G provides 100 times the bandwidth of LTE and reduces latency by a factor of ten. The discussion is relatively short on this subject because the authors expand more under low power wide area networks (LPWANs), and these technologies are not as applicable to IoT.

LoRa/LoRaWAN

The first unlicensed LPWAN to cover is called LoRa, which stands for Long Range. It is also called LoRaWAN. This technology is based on a solution by Semtech Corporation. LoRa networks are low bandwidth long-range networks based on chirp spread spectrum (CSS) modulation. The system has a trade-off of distance and data rate. As distance needs increase, the system spreading factor can be increased, which inversely affects the bandwidth. If more bandwidth is required, the spreading factor and the distance for reliable communications are reduced.

NB-IoT and LTE-M

Shifting to licensed LPWAN technology, the focus is on cellular networks with LTE-M and NB-IoT. These technologies are based on 4G LTE technology, so the random access (RA) process is the same. A four-step process for licensed LPWAN devices to access the network starts with a preamble selection from a pool of 54. Next, an RA response from the base station (BS) is sent, followed by a radio resource control (RRC) request from the device, and finally, an acknowledgment (ACK) from the BS or a notice of a collision. Collisions cause devices to back off and reattempt connection. This process is called a physical random access channel (PRACH) procedure (Ding et al., 2020).

The main differences between LTE-M and NB-IoT are bandwidth and symbol rate. Because NB-IoT is narrower in bandwidth and has a longer symbol width, it can penetrate structures better. LTE-M offers much higher symbol rates to move more data and operate in full-duplex. Table 2 below shows the overall comparison between the two technologies.

Table 2 - Comparison of LTE-M and NB-IoT

Parameter/Protocol	LTE-M	NB-IoT
RA Protocol (based on PRACH)	Slotted-ALOHA	Slotted-ALOHA
Modulation Type	QPSK/QAM	BPSK/QPSK
Frequency	Licensed LTE bands	Licensed LTE bands
Bandwidth	1.4MHz	200kHz
Bidirectional	Full/Half-duplex	Half-duplex
Link Budget	153dB	164dB
Maximum data rate	1Mbps	250kbps
Maximum payload length	1000bits	1000bits
Coverage	Few kilometers	1km (urban), 10km (rural)
Interference immunity	Low	Low
Battery life	10 years	10 years
Localization	Yes	Yes
Mobility	Yes	Yes

Note: Taken from Ding, J., Nemati, M., Ranaweera, C., & Choi, J. (2020). IoT connectivity technologies and applications: A survey. IEEE Access, 8, 67654. https://doi.org/10.1109/ACCESS.2020.2985932

De Almeda et al. (2019) thoroughly discuss several IoT technologies beyond 5G to draw comparisons to the challenges of IoT on 5G networks. While this journal article is somewhat dated, the authors give some timely information regarding IoT technologies and the general uses of each. An assumption proposed in their article is that IoT devices would be high-bandwidth network users, leaving out low-bandwidth devices. The authors also suggest that IoT devices demand a ten-year battery life which may be a stretch based on advancing technology. Their treatment of LoRa and Bluetooth is straightforward and based on the specifications.

IoT Security

Mohamed & Buniyamin (2000) introduces the need for a formal IoT security standard and recommends some system characteristics. They coined the acronym FIFAC from the elements “Formal, Inclusive, Future, Agile, and Compliant,” which the authors believe are the key attributes needed in an IoT security solution. These researchers believe that future studies in IoT security should leverage as many existing standards as possible from existing boards for internet security.

Iqbal et al. (2020) describe security vulnerabilities and countermeasures using software-defined networks (SDN) and the IoT. These researchers bring forward the challenges of the exponential growth of IoT devices and the lack of well-defined security. They provide an overview of the security threats in many technologies used in IoT today and explain the various challenges. Further, Iqbal spends considerable effort in a gap analysis of security in protocol stacks. Finally, Iqbal proposes a series of techniques based on SDN to resolve the threats and fill the gaps presented earlier.

Roukounaki et al. (2019) recommend a Big Data oriented end-to-end IoT security solution for IoT systems. The investigators explain that IoT security must be based on machine learning and deep learning to “monitor, analyze, and act” on intrusion attacks. This group of researchers suggests a “SecureIoT Architecture” composed of five layers: an IoT Systems layer, a Data Collection and Actuation layer, a Security Intelligence layer, a Security Services layer, and finally, a Security Use Case layer. They spend considerable effort explaining a reasonable security solution for future IoT research.

CHAPTER 6

CURRENT STATE

Current Cash Movement Process

When a change order (a withdrawal of funds from a customer account to be physically transferred to that customer location) is made by a customer, the bank or ATC withdraws the requested cash and coin from the vault locations (cash and coin are most often stored in different vaults) and package it for delivery to the customer. These packages are often large, durable plastic bags with security seals, tamper-evident markings, and barcodes associated with the entity packaging the order. Change orders are delivered to customers by armored truck, typically one business day after the request, as seen in Figure 6.

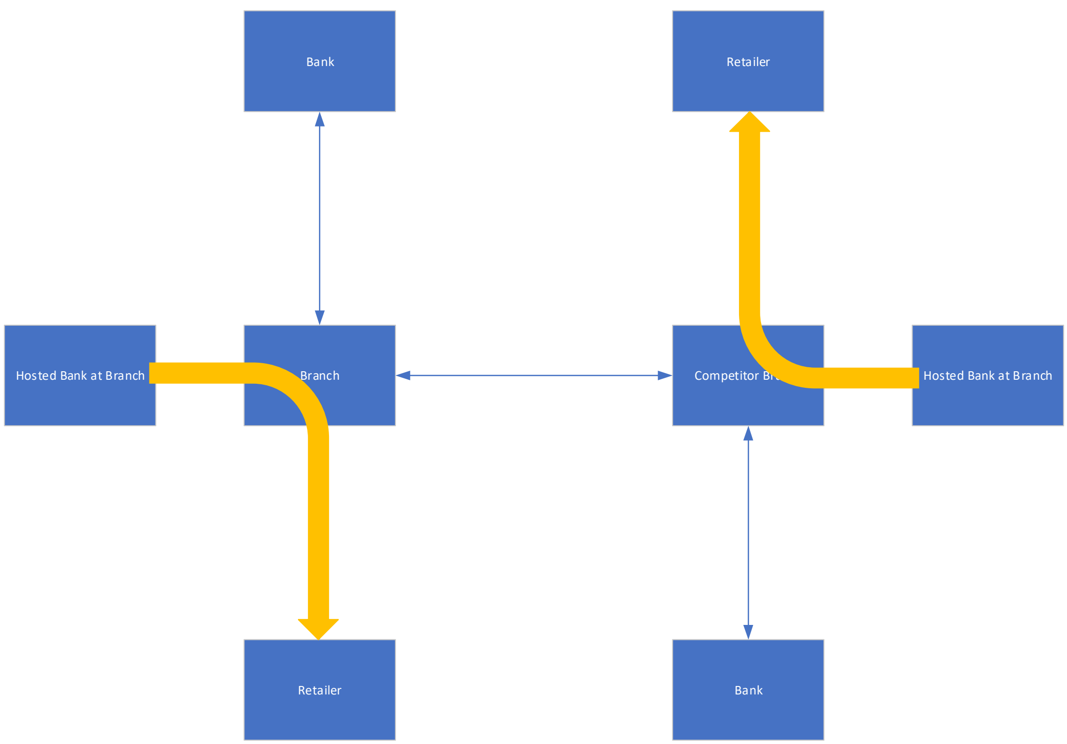

Figure 6 - Change order from a Hosted Bank to a Retail Customer

Conversely, when a customer wishes to make a deposit, the deposit is packaged into a secure plastic bag for armored truck pickup. The deposit is returned to the bank or ATC, where cash, coin, and checks are separated, counted, and deposited into the customer account, as seen in Figure 7.

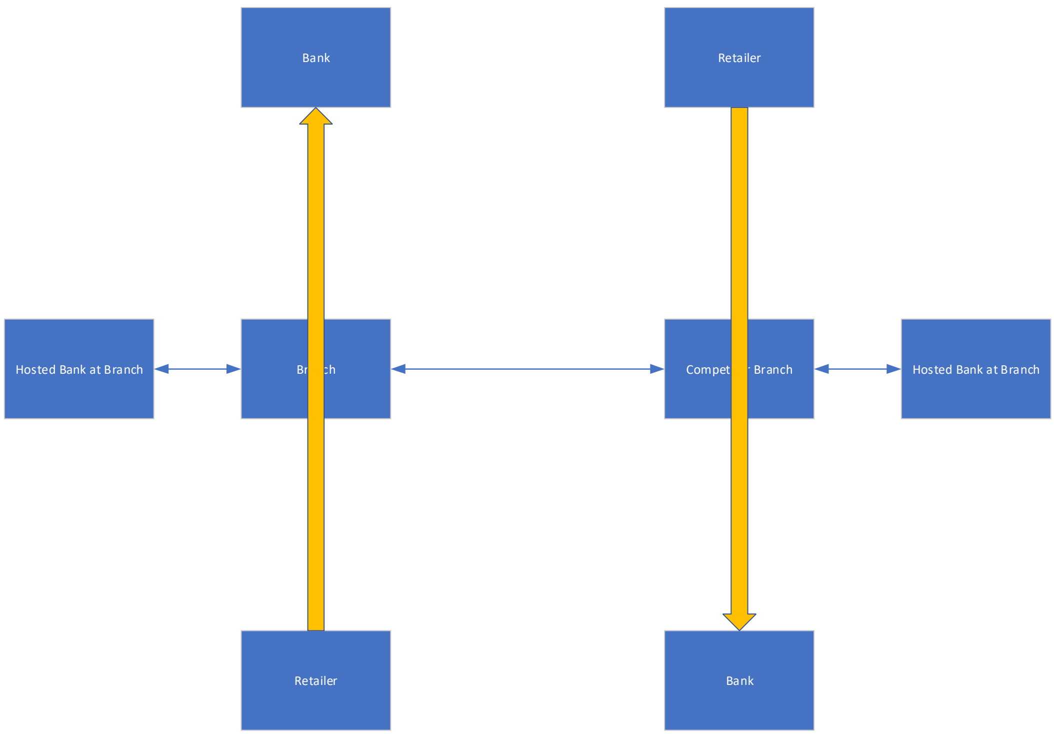

Figure 7 - Deposit from Retailer to Bank Serviced by the Same ATC

Deposited checks are scanned and stored for 90 days in case of a dispute, while cash and coins are compiled, wrapped, and placed back into the vault for storage. Deposits are always accompanied by a deposit slip from the customer, either filled out by hand or generated by a printer. These customers make arrangements with ATCs to pick up deposits regularly (e.g., one time per week on Monday, every day except Sunday, or on odd days of the month). The ATC crew visits each contracted location according to the schedule set forth within the contract.

Customers may request additional service if needed. It is important to note that ATC crews stop at each location on the planned route whether there is a deposit or not. There is no pre-transmitted information about the deposit before the arrival of the crew. ATC crews operate on a very narrow time window for each customer stop. The crew has a predefined and contractual period that they can wait for the customer to prepare a deposit if not prepared when they arrive. This window can be as little as five minutes.

In addition, transfers are made between ATCs, the Federal Bank, and other banks. Some deposits are not processed by the ATC that collects the deposits by armored truck. These deposits are transferred to other entities. A competitor ATC may pick up or deliver the deposits to the receiving company's branch, as seen in Figure 8.

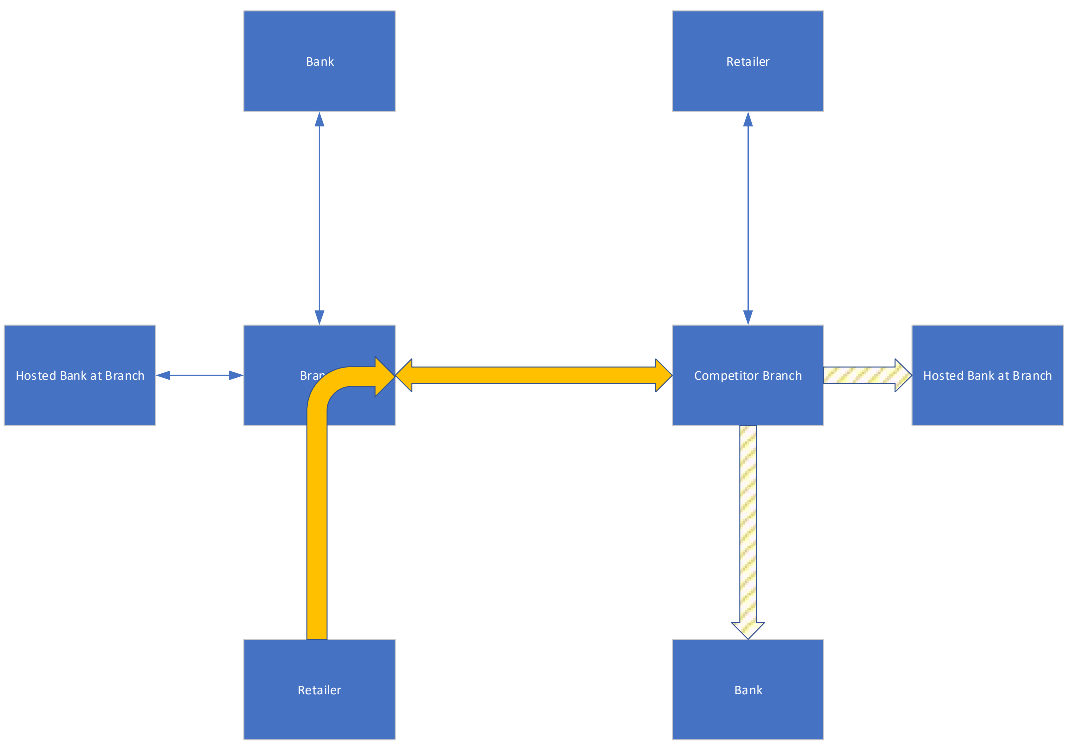

Figure 8 - Deposit from Retailer Transferred to Competitor

An ATC may process change orders for a customer, but a competitor ATC may deliver it to the customer. These change orders are processed and compiled for pickup by the competitor's truck, as seen in Figure 9.

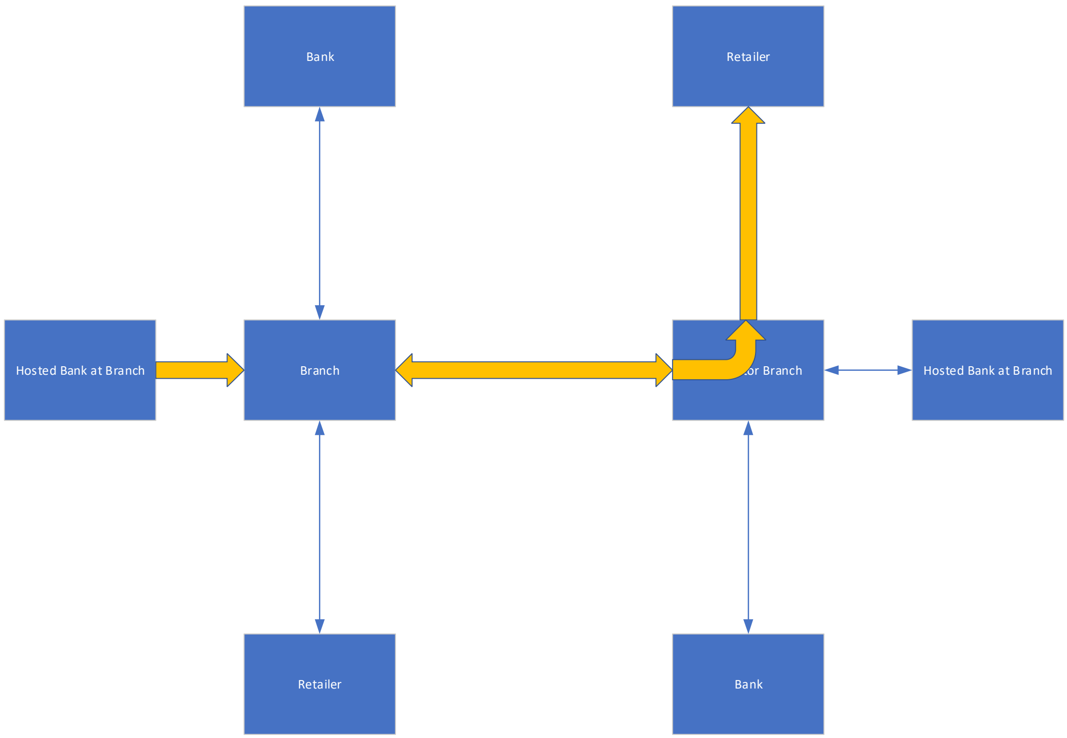

Figure 9 - Change Order from Hosted Bank Transferred to Competitor for Delivery

This inter-ATC transaction is often manual because competitors have little or no system integration. When a bank or ATC has prepared the shipment for another ATC, the shipping entity creates a manifest. That manifest may be emailed to the receiving ATC or provided as a paper copy. When a manifest between two ATCs exists, because of the lack of integration between ATCs, many hours are spent manually entering the inbound shipments into the receiving ATC's management system. This manual entry process is also accurate when a bank transfers change orders to an ATC for delivery. There is no standard for ATC and bank interoperability for moving change orders between companies. Often this creates a situation where a company has a liability (a shipment of cash) on an armored vehicle for which it does not have a record in its systems.

Many ATCs also have the responsibility of servicing ATMs with cash. Much like a change order, ATM funds are processed and bagged. The messenger pulls the remaining cash from the machine, called the “residual,” and reloads the ATM with the new cash. The residual cash and the ATM receipt are returned to the ATC for processing as a deposit or transfer to the associated bank or external processing entity. Some ATCs also offer an emergency fill service for ATMs low on cash. Some crews carry additional bags, called “e-cash,” just in case a customer requests to refill an ATM. These bags, if not used, pass to the crew in the morning and back to the vault team in the afternoon each day.

Finally, some ATCs offer on-premises safes to customers that count deposited cash as it is loaded. As cash is deposited, the bank credits the customer's account immediately. ATC armored trucks periodically withdraw the cash from the on-premises safe along with the printed deposit slip, where the deposits already made are verified in the ATCs processing department.

Current State Processes

Cash bags are created in the packing room based on customer change orders (banks or retailers). The bag creation process is defined in Appendix A. Bags are then issued to a teller that assigns bags to either a route or storage location for foreign courier pickup. Bags destined for a route are picked up by another teller and placed in lockable storage cash carts for each route. This teller maintains a constant inventory for each route as bags are added. An armed security guard helps the teller and protects the cash carts while opened. See Figure 10 for a graphical representation of this process. Foreign couriers arrive to pick up change orders for delivery to their customers, and CMS tellers manage the transfer of custody to the foreign courier. The interaction with the foreign courier is not part of this research.

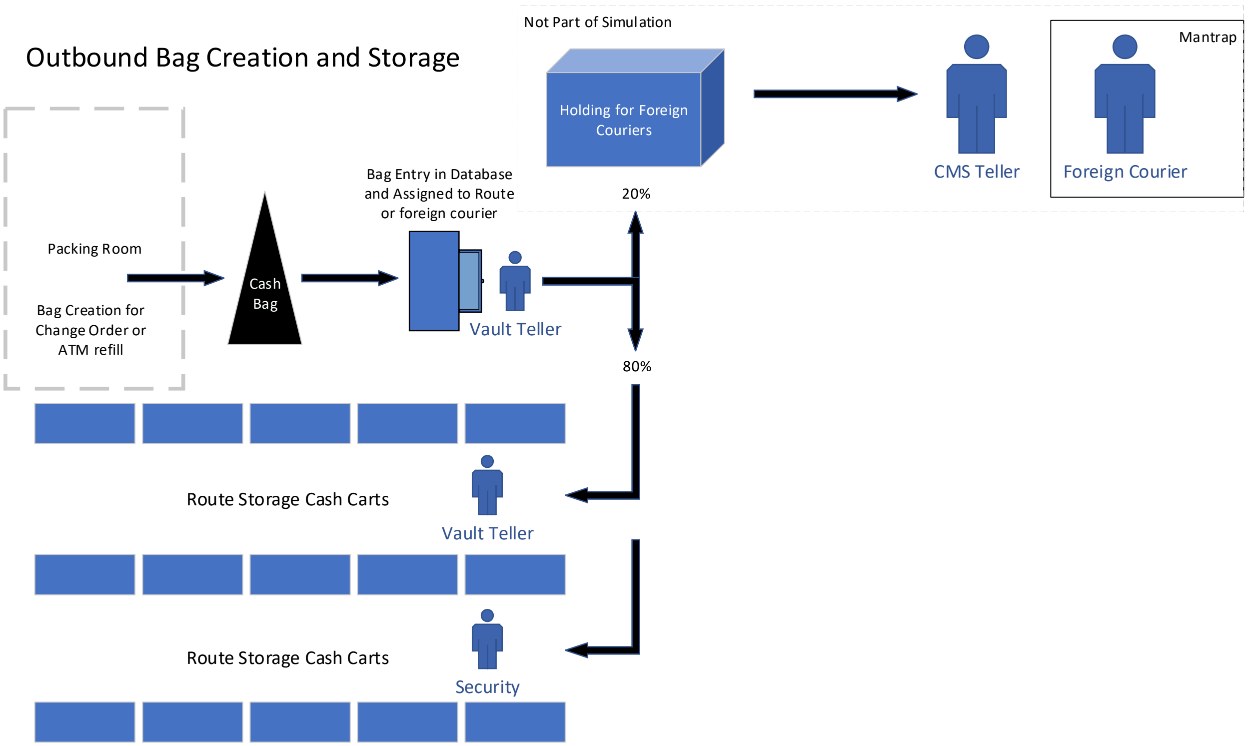

Figure 10 - Outbound Cash Bag Sorting and Storage

Some bags from the previous day are added to the cash carts overnight, and each cart's manifest is updated (see additional information below regarding inbound bag sorting). The following day, CIT crews (a messenger and a driver) arrive to pick up the bags to be delivered. The messenger issues accessories (phones, tablets, keys), and the messenger accepts custody transfer. The teller then pushes the cash cart for that route to the mantrap, and the messenger accepts the cart and goes to the truck. The driver and messenger work together to validate the manifest (paper and electronic on handheld) as each bag is placed on the truck. Once completed, the messenger returns the cash cart to the teller and signs the transfer of custody of the bags, accepting responsibility for all items. If there is an error (missing or extra bag), that is resolved with the teller before accepting custody. See Figures 11 and 12 for a graphical view of the process and a swim lane chart of the transaction, respectively.

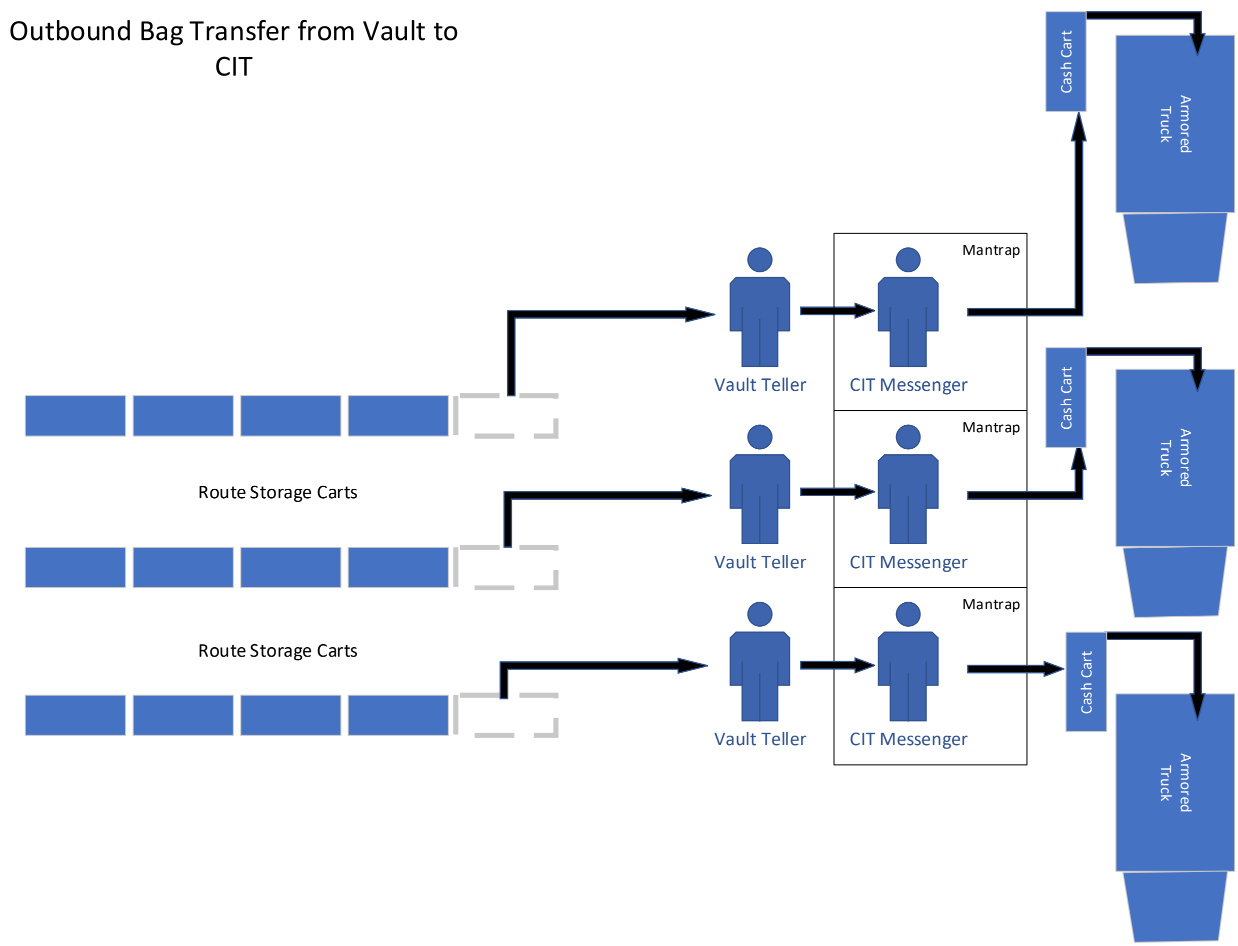

Figure 11 - Transfer of Cash Bags from Vault to CIT

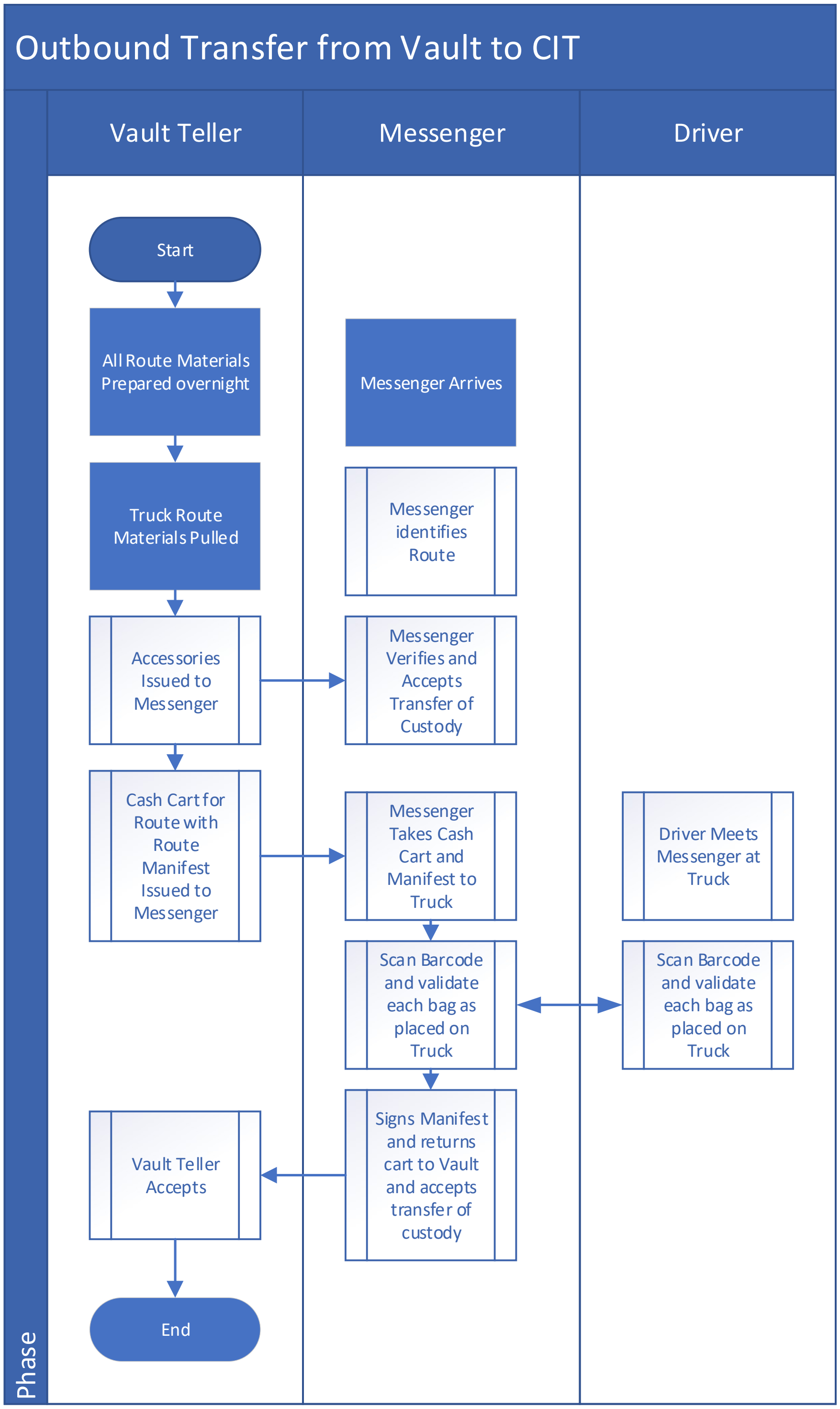

Figure 12 - Swimlane Chart of Transfer of Custody from Vault to CIT

After acceptance of the bags and accessories, the armored truck team runs their assigned route and interacts with retailers, banks, ATMs, and competitors. These processes may include dropping off change orders, picking up deposits, servicing smart safes, servicing ATMs, or picking up change orders from banks or competitors. Each armored truck team operates a route in the same area daily. The contractual arrangements with the customers determine what day(s) the armored truck team services that client each week. The route may have 120 customers, but the truck may stop at only a fraction of the clients daily. See Figure 13 for a simplified route diagram.

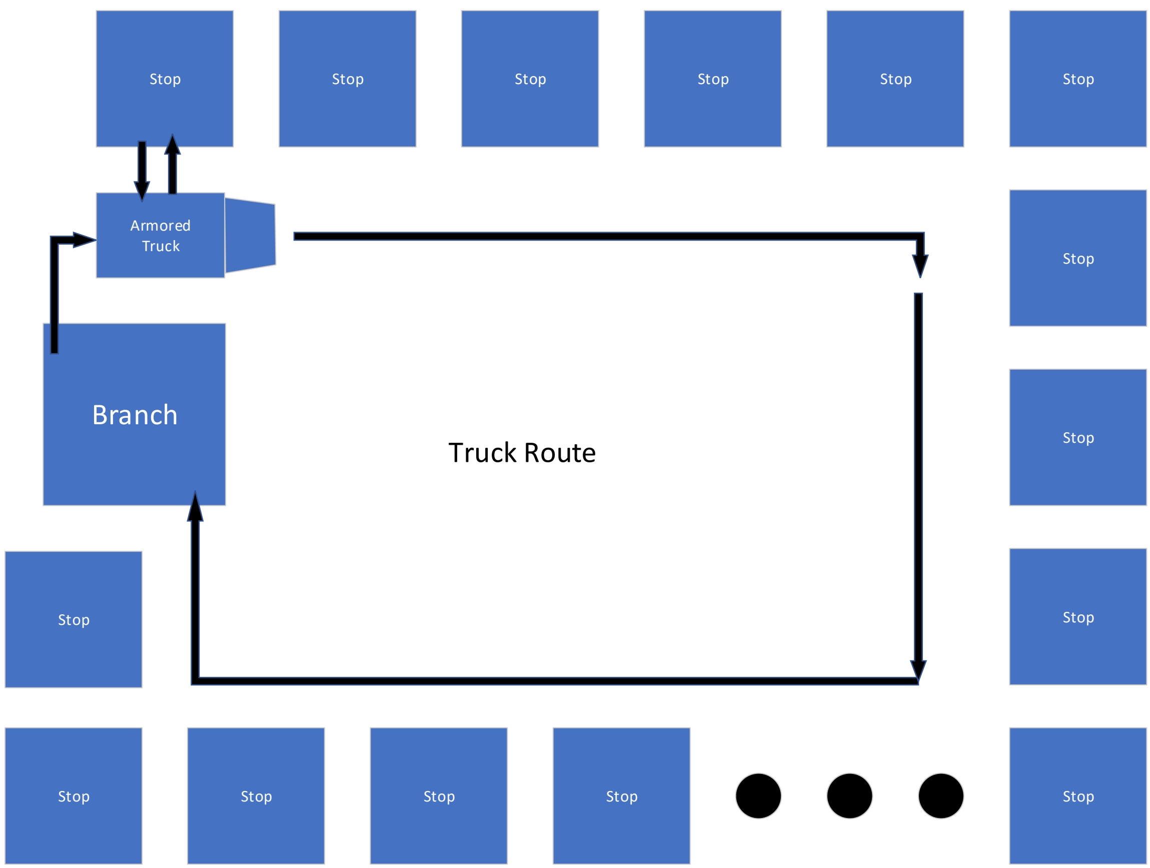

Figure 13 - Simplified Truck Route Diagram

At the end of the route, the armored truck crew returns to the branch with deposits, undeliverable change orders, ATM residuals, smart-safe deposits, and change orders from banks and competitors. When the truck arrives at the branch, it is inspected by an armed guard outside and then enters the truck processing area. The messenger and driver empty the truck's contents (cash bags) and place them in tubs on trollies. The messenger enters a mantrap if there is one available. During busy times, congestion can occur when more truck crews wait for an available mantrap. Once the messenger enters the mantrap, the teller and messengers start the transfer of custody of the accessories and cash bags to the vault. Generally, the messenger places keys, phones, tablets, and ATM service manuals on a table so the teller can scan the barcodes on all the issued accessories.

Once satisfied that all issued accessories are present, the teller accepts the transfer of custody of the accessories. Next, the messenger takes one bag at a time and hands it to the vault teller. The teller locates the deposit slip in the bag, writes the bank name on the bag, scans the bag, and checks the bag off of an electronic manifest. The teller then inspects the bag six-sided to ensure no tampering has occurred. The teller then presorts the bag separating the bags to be processed internally and those going for repackaging. This process continues until all bags are checked into the vault. The teller and messenger sign a transfer of custody form, and the check-in process for that messenger is complete. The crew moves the vehicle to a parking location and then clocks out for the evening. See Figure 14 for an illustration of the check-in process.

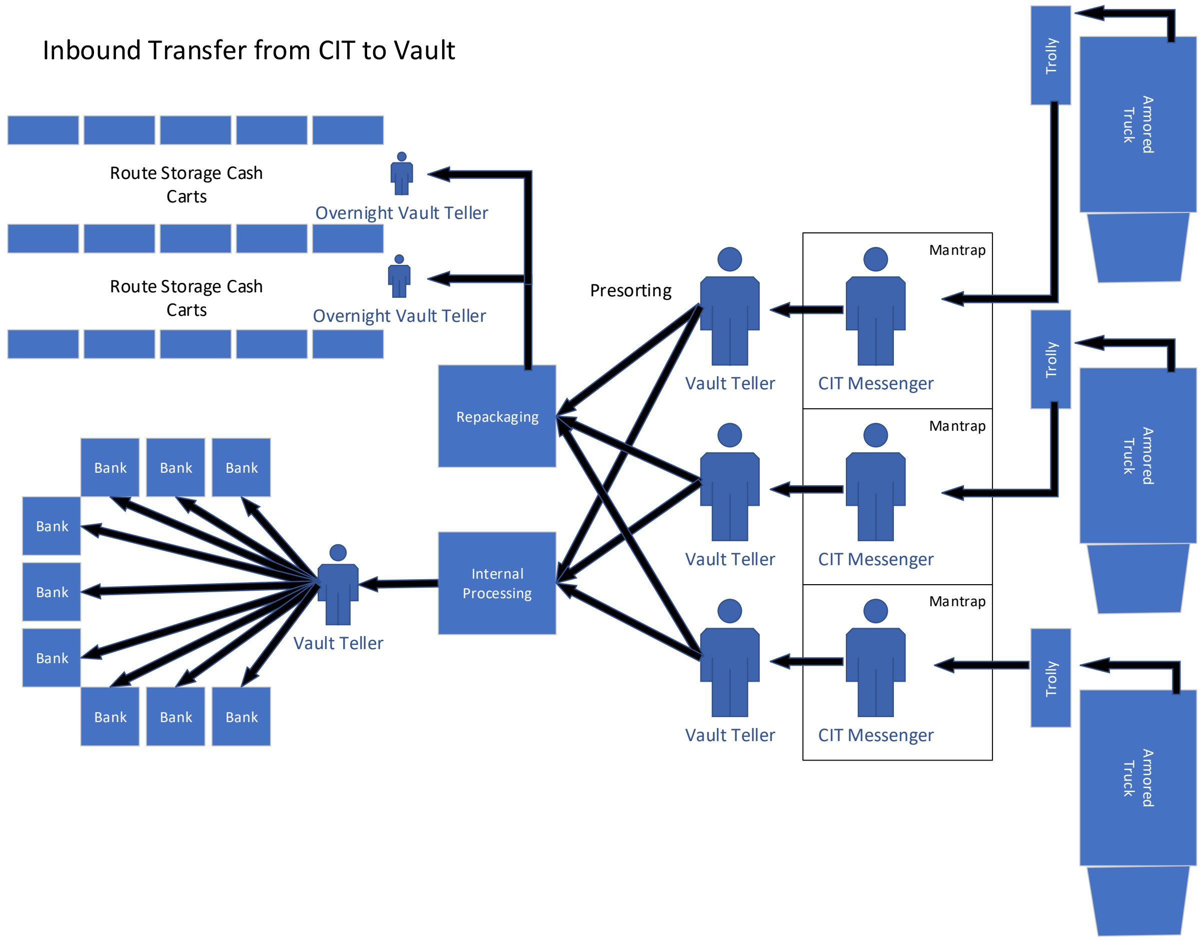

Figure 14 - Inbound Transfer from CIT

Also shown in Figure 14 are the two sorting processes for both the repackaging and internally processed bags. Bags redirected to the next day's armored truck operations are called "repackaged" because bags are put into routes. For some banks, the number of bags is so significant that the small cash bags are placed in large bags and sealed with a security seal. These bags also have a manifest showing the over bag's contents. When the value of repackaged and over-bagged shipments is too high, a larger bank truck crew must deliver the bag to the bank. The large transfers to external banks are not part of the research or simulation.

Some repackaged bags may be destined for the Federal Reserve Bank. All Federal Reserve Bank transactions are consolidated and put in large “Fed Cases” for transport to the Federal Reserve Bank. These transactions are also not part of this research or simulation.

A single teller sorts bags processed internally according to the destination bank. Even though a great deal of care is taken, this manual sorting produces several errors attributed to human error between the tellers.

At around 5 a.m., five tellers from CMS arrive and re-sort the bags to be processed that day. In addition to resorting, they assign bags to CMS teller groups and place them in order of priority for processing. This process takes about 2 hr to complete. At 7 a.m., CMS tellers start processing bags for deposit to customer accounts. The actual processing of bags is not part of this research or simulation. See Figure 15 for an illustration of this process.

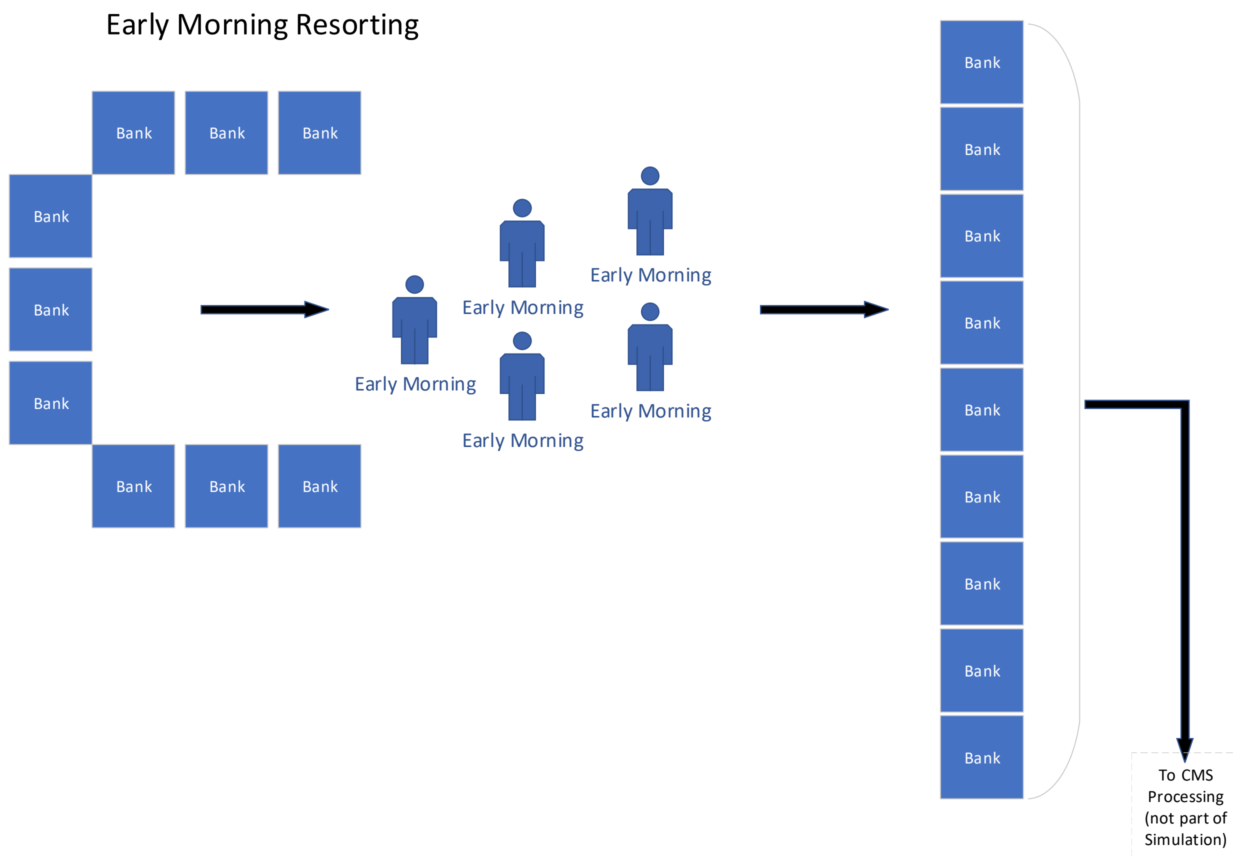

Figure 15 - Early Morning CMS Teller Resort of Bags

Model Simulation

Robert Sargent (2010) defines model validation as "substantiation that a model within its domain of applicability possesses a satisfactory range of accuracy consistent with the intended application of the model." Because of the nature of this model, validation is based on a set of experimental conditions, which are the measure of validity based on the acceptable range of accuracy. In looking at the key output variables in this model, typically time, an acceptable range must be chosen that represents the system variables (observed system operational times) or outputs of the existing system. The system variables and the simulation variables should produce similar outcomes. For instance, a straightforward comparison of the system to the simulation may be the time of an operational behavior. The mean and standard deviation of the simulation output should reasonably match the system. Because the system and the simulation are dynamic, some broad choices of the accuracy range must be determined. The overall dynamics of the branch can change significantly day-to-day and month-to-month. For validation processes, a 15% difference from the observed data is considered acceptable for observed data vs. simulation data. The observed processes and additional information provided by the armored courier were used to tune the model to match an armored courier branch processes reasonably.

A 95% confidence interval is calculated for observed or provided operational data where possible. This is achieved by utilizing $CI = \sqrt{\frac{2\left(Z_{\alpha}+Z_{1-\beta}\right)^{2}\sigma^{2}}{n}}$ where Z_{α} is the probability of committing a Type I error (probability of rejecting the null hypothesis when the null hypothesis is true), and $Z_{1-\beta}$ is the power test based on the probability of committing a Type II error (probability of not rejecting the null hypothesis when the null hypothesis is false). Simulation data standard deviations are compared/validated utilizing this technique.

The simulation model was developed in AnyLogic software and focused on processes and interactions between individuals (bag sorting, customers - messenger, vault teller – messenger, CMS teller). The model breaks down each process into actions and delays that mimic the actual processes discussed earlier. An example of a process is shown in Figure 16.

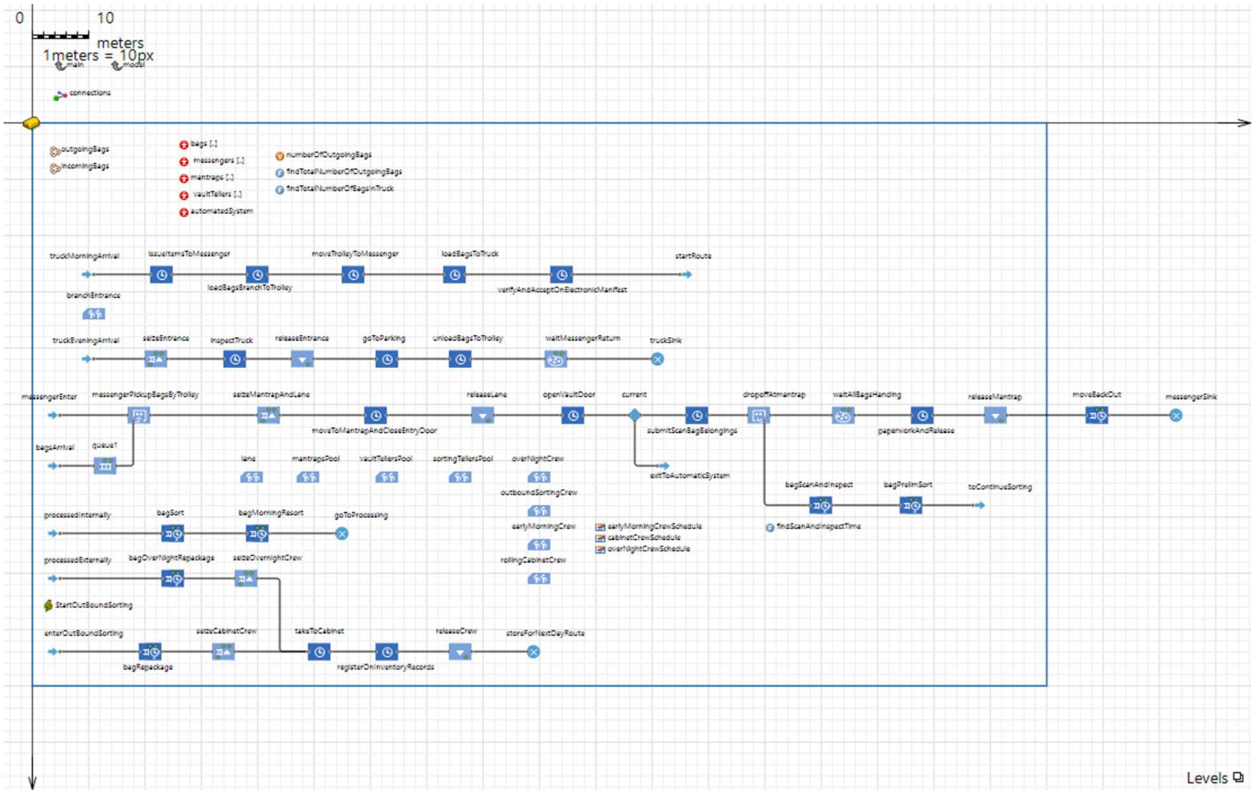

Figure 16 - Branch Process Model

Because time and the use of resources are the critical variables in the model, one can see a series of tasks and associated delay blocks. Each task has an associated resource pool used to accomplish a task. For instance, when a messenger (a resource) enters a mantrap (the location where bags are passed), a delay block indicates the timing of that particular process. A teller must also be allocated from the resource pool to accept the bags; thus, the process is timed to complete the transaction. In addition, a series of parameters are established with purposeful variation to indicate normal human behavior. These parameters are stored in an Excel spreadsheet that is consumed during the compilation of the simulation. Table 3 is an example of the branch processing times variables.

Table 3 - Example of Model Parameters

parameter	value	units
inspect truck at entrance	uniform(3,5)	minutes
truck move from entrance to parking and park	triangular(20,30,60)	seconds
unload one bag from truck to trolley/ load bag from trolley to truck	2	seconds
messenger move from branch entrance to the mantrap along the lane or backwards and close/open the entry door	triangular(20,30,60)	seconds
open vault door	5	seconds
submit, scan, and bag messenger belongings	uniform(1,2)	minutes
one bag inspect and scan by vault teller	uniform(4,10)	seconds
one bag preliminary sort by vault teller	uniform(15,30)	seconds
one bag sort by sorting teller	uniform(15,30)	seconds
paperwork and release	uniform(2,3)	minutes
one bag overnight re-sort	uniform(15,30)	seconds
issue keys, manuals, phone/PDA(s), radios, a manifest, and a detailed route sheet for that day to the messenger	uniform(1,2)	minutes
load bag from branch to trolley	5	seconds
move trolley from branch to truck	triangular(20,30,60)	seconds
verify and accept bag to the electronic manifest on the phone/PDA	5	seconds
one bag sort by early morning crew member	uniform(15,30)	seconds
assign outbound change order bag to route or competitor	uniform(15,30)	seconds
take bag to relevant rolling cabinet	triangular(4,5,6)	seconds
register bag on inventory records	5	seconds

The model focuses on time and resource allocation to inform the business model. The processes in Table 4 are the critical areas of interest.

Table 4 - Key Areas of Interest in the Model

Process	Measure	Resource
Retailer Interaction	Time	Messenger
Bank Interaction	Time	Messenger
ATM Service	Time	Messenger
Transfer from CIT to Vault	Time	Messenger and Vault Teller
Inbound Bag Sorting	Time	Vault and CMS Tellers
Outbound Bag Sorting	Time	Vault and CMS Tellers
Route Completion	Time	Driver and Messenger
Branch Processing Multiple Truck Crews	Time	Messengers and Tellers
Congestion at Vault Teller	Time	Messengers

Data Collection and Validation

The researcher collected many quantitative and qualitative operational behavior data (process mapping) on-site and during subsequent interactions. An objective of the research was a time-motion study of teller-messenger interactions in the mantrap, but the ATC did not allow much time for a time-motion study of quantitative data collection. Some activities were observed and timed, and other activities were explained by ATC personnel but not observed. Three days of time-motion study data collection for a single teller were observed and timed. Additionally, quantitative data was provided by the ATC indicating the bag processing for the top 30 branches within the company and hourly employee work hours for 22 weeks. The remainder of the data was collected anecdotally through observations and interviews. In addition, some assumptions made by the researcher were validated through meetings with the ATC operational management team.

The time-motion study provided 46 observations of vault tellers receiving bags and accessories from messengers. Two of the observations were excluded from the analysis because of the operational behavior in the process (e.g., passing one emergency ATM refill bag and a truncated route with 12 bags). The values of total time in the mantrap, time passing bags, time passing accessories, and time for checkout were collected. The observed data were collected by observing one vault teller for three shifts on a Wednesday, Thursday, and Friday. For this investigation, the researcher considers this information equivalent to one day for one teller.

Therefore, the observed data is regularly compared to a single day/single teller of simulation data.

The simulation model was developed based on the holistic operation of an ATC branch with 45 armored vehicles that conduct outsourced bank operations. The primary purpose of the simulation is to look at operational times when bags are handled through the CIT and vault operational procedures. The model does not evaluate or simulate CMS processing but includes CMS's bag sorting behaviors. The model is evaluated based on general operational timing that is observed (e.g., total time frame for transfer of bags from the vault to CIT and reverse) and from data provided by the ATC. In addition, where possible, the model was validated by comparing the mean, first and third quartile, and median of observed quantitative data with model simulation data.

Discussing sample sizes, the observational data, and the provided data established the value of n for all cases. For the simulation data, the model has a limit of 100 days. This constraint is a software memory utilization limit. A single day of the simulation produces 3,000+ bags, 45 truck routes, and 12,000+ bag touches. Running the model at a maximum of 100 days produces a multiple of the single-day values.

In some cases, large data files were manipulated through R first and then Microsoft Excel. For instance, bag touches by tellers for 100 days produce 1.2 M transactions. Those transactions were sorted by the teller type in R, and new files were created to evaluate further in Excel (e.g., pivot tables, box plots, histograms). In all cases, the simulation data from the model were used as a complete dataset (no sampling). In addition, when daily values were required, the simulation data was manipulated into a pivot table by date, and totals or value means were taken for each date. These values appear as 100 samples in some tables, but each is a total or summary of many additional samples.

Evaluation of Transfer of Custody

One key area of focus for the research is the time it takes for a messenger from CIT to transfer bags picked up from the route to a vault teller. The observed branch collects bags for 45 trucks between 2 p.m. and 9 p.m. The flow of trucks peaks between 4 p.m. and 6 p.m. In addition, it was observed that tellers work more quickly during peak times and more slowly during slack times. In the model, the time to process a bag is established in a triangular distribution between 2 and 16 s with a mean of 8 s, but the values for time per bag are shifted during slack times by adding a multiplier to simulate the observed behavior accurately. An example is that bags collected during the 2 p.m. hour have a multiple of 1.2 which shifts the uniform distribution from 2.4 to 19.2 with a mean of 9.6 s per bag.

Figure 17 and Table 5 show a box plot comparison of observed and simulation runs of 1, 7, 30, and 100 days and the resulting results. The 100-day simulation data was compared with the observed data (highlighted in blue), indicating the model's accuracy for this process. Note that the mean, first and third quartiles, and median are well within the ascribed 15% threshold.

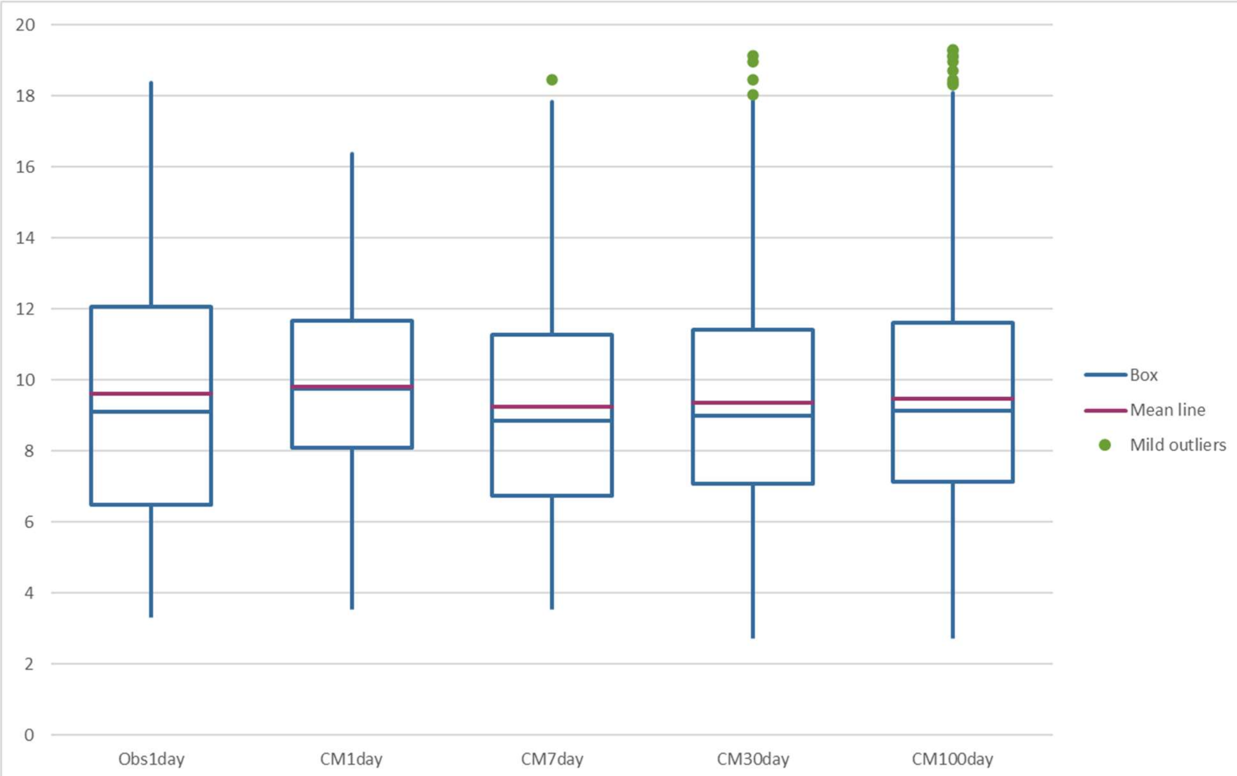

Figure 17 - Box Plot Observed and Simulation Transfer of Bags from CIT to Vault

Table 5 - Comparison Validation of Observed and Simulation Data

Variable	Count	Mean	Minimum	Lower whisker	Q1	Median	Q3	Upper whisker	Maximum
Obs1day	43	9.6225	3.3833	3.3833	6.4917	9.1000	12.0750	18.3833	18.3833
CM1day	44	9.7978	3.6079	3.6079	8.0836	9.7570	11.6683	16.3681	16.3681
CM7day	308	9.2408	3.6079	3.6079	6.7428	8.8423	11.2855	17.8486	18.4616
CM30day	1320	9.3614	2.7867	2.7867	7.0880	8.9967	11.4276	17.8646	19.1386
CM100day	4400	9.4597	2.7867	2.7867	7.1487	9.1478	11.6022	18.0965	19.3050
Δ Obs1day		98%	82%	82%	110%	101%	96%	98%	105%

However, the standard deviation of the data is approximately 25% more narrow in the simulation, as indicated in Table 6. The range of the model prevented a wider spread of the standard deviation while maintaining the mean and first and third quartiles. The researcher felt that the amount of observed data was too small to establish an accurate value for standard deviation and placed more value in the mean and first and third quartiles of the limited dataset.

Table 6 - Observed vs. Model Standard Deviation

Observed 1 day	Model 1 day	Model 7 day	Model 30 day	Model 100 day
4.002	3.059	3.060	3.105	3.086

Looking at a 95% confidence interval (CI) for the observed data, the $CI = \sqrt{\frac{2(1.96+\ .6449)^2 4.002^2}{43}}$ = 9.6225 ±2.783 min. The low number of samples for this observation significantly impacts the wider confidence interval. Referring back to Table 5, the simulation mean is well within the 95% CI.

The histograms of the observations from the observed data and the simulation data for one day are in Figure 18. The simulated data indicates a bi-modal response, and the simulation data show a single-moded but similar shape histogram. The observed data is for a single teller of 44 observations, and the simulation data is for 44 observations. As the simulation is run more, the simulation appears to become similar to the observed data. Figure 19 shows a histogram of the seven-day simulation run with 308 observations.

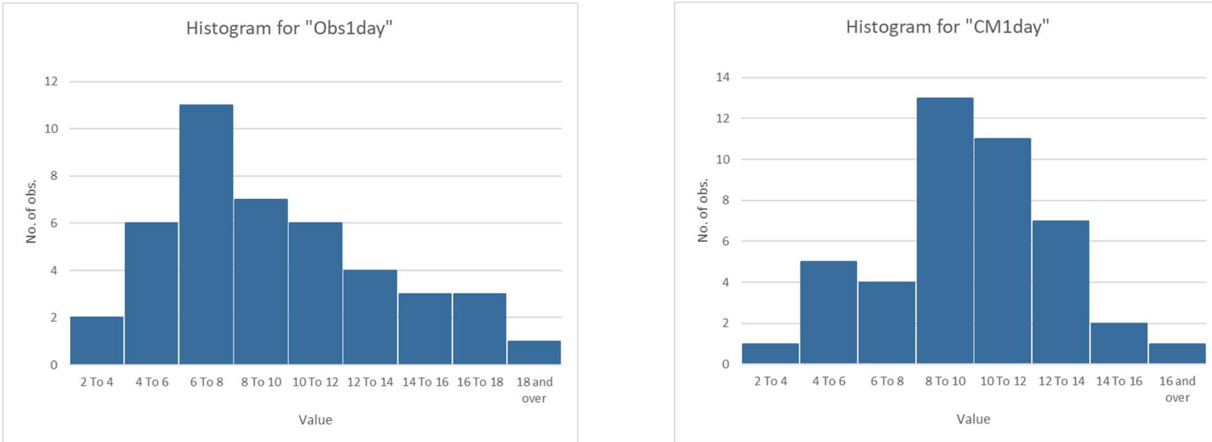

Figure 18 - Histogram Comparison of Observed and Simulation Data

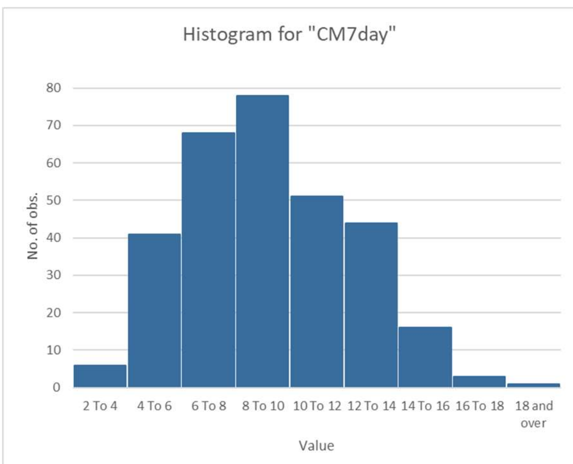

Figure 19 - Histogram for Simulation for Seven Days

Linear regression was also attempted and yielded uncertain results because of the limited number of observations and did not yield a conclusive correlation. Figure 20 illustrates the regression for the observed data and a single-day simulation run.

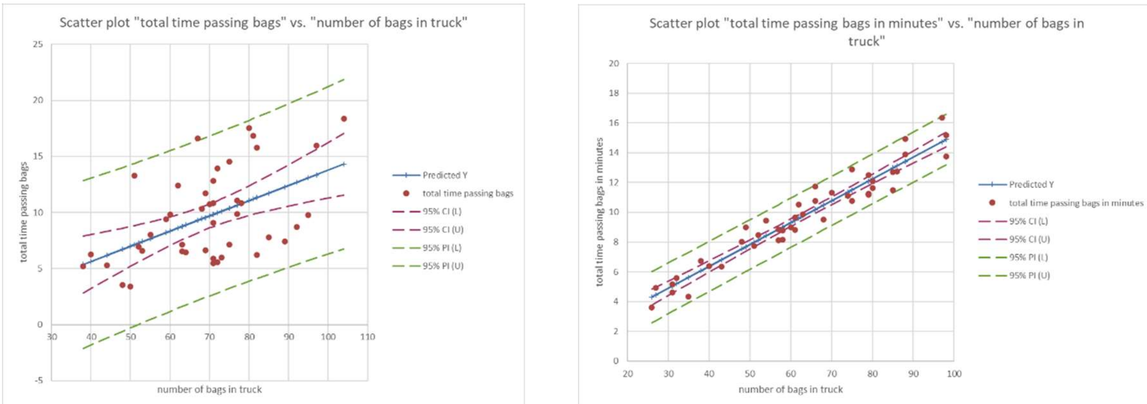

Figure 20 - Linear Regression Comparison of Observed to Simulation Data

The R^2 value of the observed data is low, at 0.2568, because of the limited number of observations. The R^2 value of the simulation model is 0.9296. Overall, the time involved in passing bags and the total time spent in the mantrap between the observed and simulated data is well within validation limits.

Bags per Truck

In addition to the time passing bags, the model can be validated through a report provided by the ATC indicating the number of bags the branch handles during a typical month. The report indicates that the observed branch handles approximately 85,500 bags of cash each month with 45 trucks. These bags break down further to 25% delivered (e.g., change orders, ATM refills) and 75% pickups (e.g., deposits, ATM residuals, bank-created change orders). The mean of this would indicate approximately 63 bags per truck per day. From observation and interviews, there are more bags on Monday and Friday, and Saturday and Sunday are fewer. Figure 21 shows box plot data from the observed and simulated periods of 1, 7, 30, and 100 days. Table 7 contains the statistics for the box plot. The variance from 63 (the average daily value provided by the ATC) is denoted in blue in the rightmost column. Also, note that the observed data included data from only weekday operations. The standard deviation for the number of bags per truck is 14.9814.

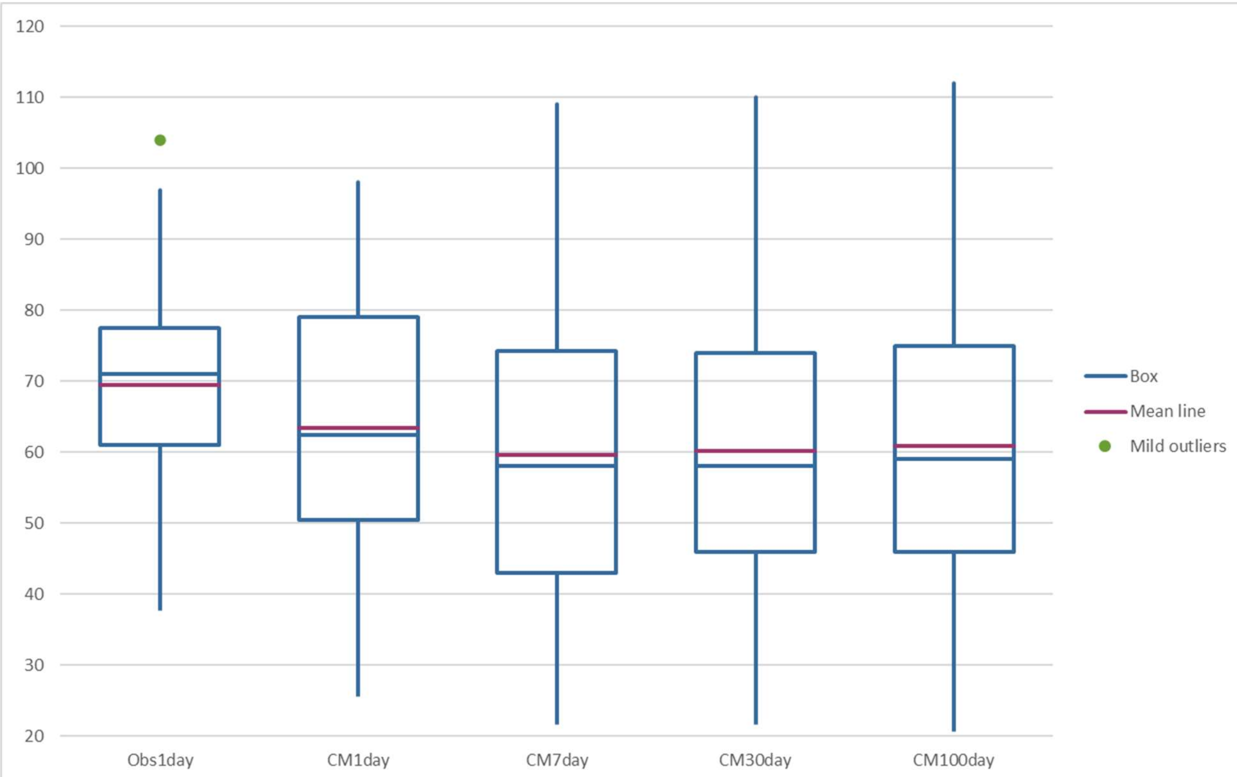

Figure 21 – Comparison of the Number of Bags Per Truck

Table 7 - Comparison of the Number of Bags Per Truck

Variable	Count	Mean	Minimum	Lower whisker	Q1	Median	Q3	Upper whisker	Maximum	Average 63
Obs1day	43	69.4419	38.0000	38.0000	61.0000	71.0000	77.5000	97.0000	104.0000	110%
CM1day	44	63.3864	26.0000	26.0000	50.5000	62.5000	79.0000	98.0000	98.0000	101%
CM7day	308	59.5487	22.0000	22.0000	43.0000	58.0000	74.2500	109.0000	109.0000	95%
CM30day	1320	60.2379	22.0000	22.0000	46.0000	58.0000	74.0000	110.0000	110.0000	96%
CM100day	4401	60.9275	21.0000	21.0000	46.0000	59.0000	75.0000	112.0000	112.0000	97%

Utilizing the 95% CI for the number of bags per truck, the $CI = \sqrt{\frac{2(1.96+1.6449)^2 14.9814^2}{43}}$ = 69.4419 ±11.647 bags per truck. The simulation mean for bags per truck is well within the CI limits of observed and ATC-provided data.

Teller Utilization

The remaining variables are discussed below based on observed behaviors and facility constraints. There are three teller windows/mantraps used for vault teller-messenger interactions. Three vault tellers work 8-hr shifts. The tellers work shifts that support the behaviors of the branch. During the reception of bags in the afternoon, the vault window tellers perform bag inspections (six-sided inspections), locate the deposit slip in the bag, annotate the bag with the receiving bank name, and presort bags. The pre-sort is done by identifying bags as internally processed, externally processed, and bags that need to be delivered to other entities in the following days.

A single teller accepts the bags that are internally processed and sorted by receiving bank. The observed branch processed bags for more than 50 different banks. This teller accepts the bank name written on the bag as truth as the bags are sorted. The bags are resorted again the following morning by five CMS tellers that verify the deposit slip inside the bag. Each day, approximately 3,000 bags are processed internally.

The overnight tellers sort the bags that are not processed internally. This process is referred to as "repackaging." These bags have a destination bank or customer, typically for the next day, and are sorted and prepared as outbound bags. Two overnight tellers perform this action. The overnight tellers also prepare all other outbound materials for CIT, including accessories (e.g., keys, manuals, radios).

During the day, a teller takes bags from the bag preparation room and assigns them to routes. A teller and a security guard place the bags in lockable carts and maintain a running inventory of each cart.

Finally, two vault tellers interface with CIT messengers in the mornings, moving carts and issuing accessories. They also supply route sheets and a truck manifest to each messenger.

The researcher focused on each teller's observed behaviors and the teller shift's limits to validate the teller transactions. For instance, it is known that afternoon vault tellers are receiving bags from messengers from 2 p.m. to 9 p.m. The model must support this. In addition, tellers and messengers have known shifts, and the researcher was provided overtime data for several employee types.

For the most part, the researcher knows the overall flow of the branch through observation, process mapping, and discussions with employees. The company's management validated many of the assumptions (or corrected them) during the observation period.

As accurately as possible, the simulation model attempts to simulate the branch's operational behaviors as the bags flow into and out. For instance, the manager of the vault operation indicated that 60% of the bags entering the branch from CIT each afternoon go to CMS for processing. Therefore, in the model, this proportion was maintained. See Figure 22 for inbound bags from CIT and Figure 23 for outbound bag preparation.

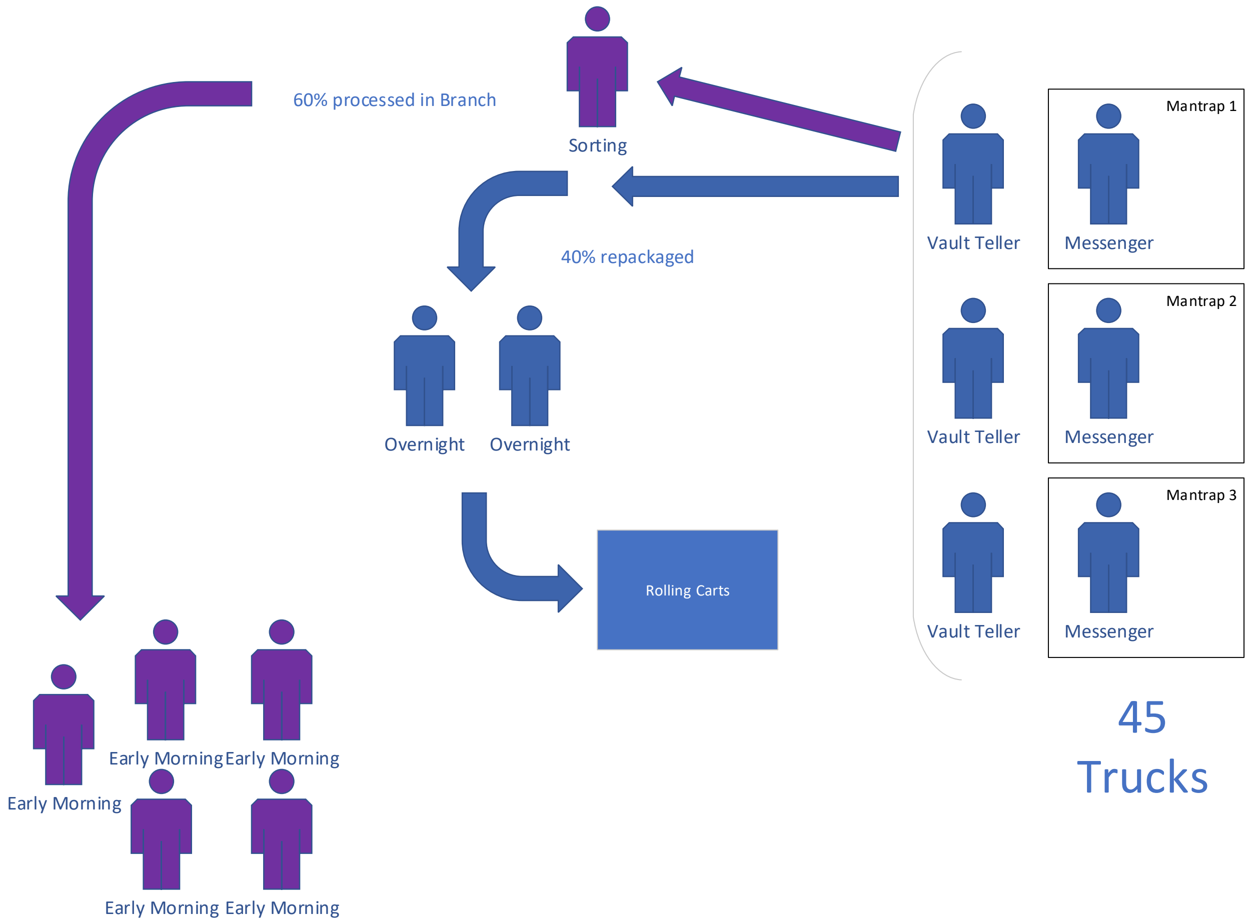

Figure 22 - Flow of Inbound Bags from CIT

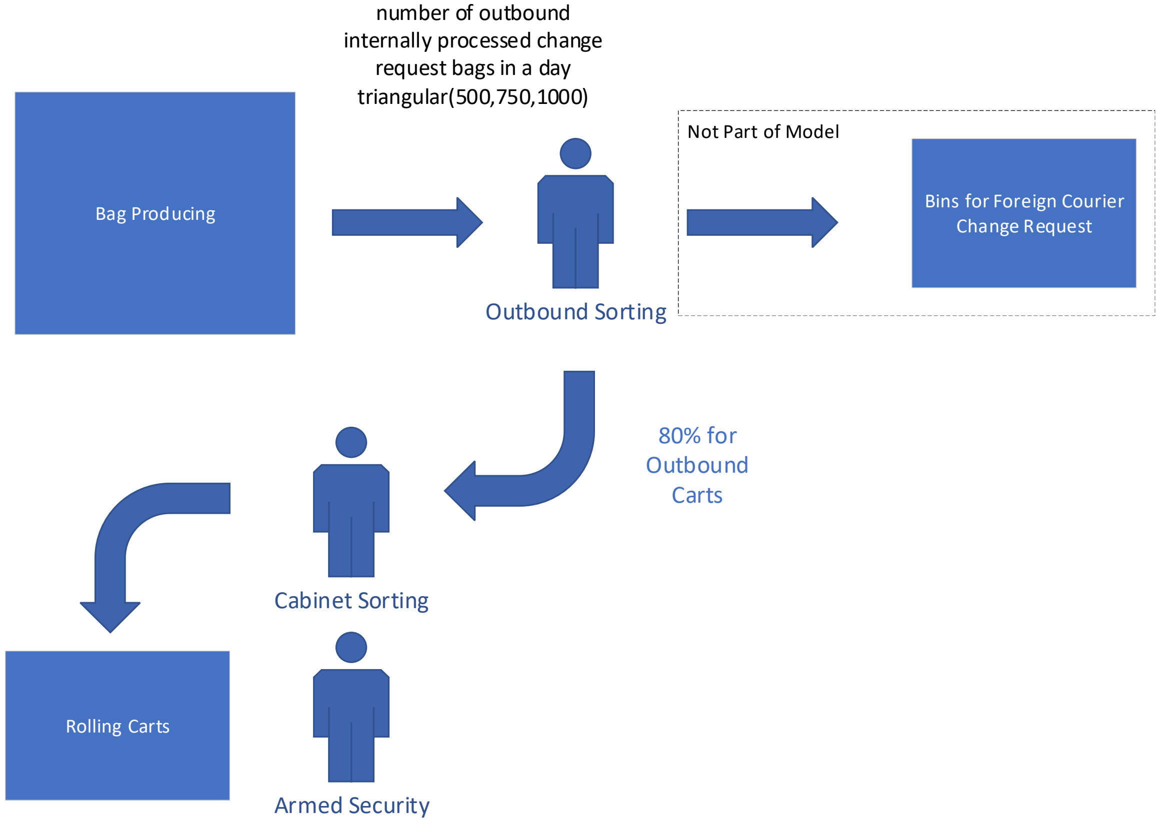

Figure 23 - Outbound Bag Preparation

The ATC supplied teller hours for 22 weeks. Figure 24 shows the average weekly work hours for 43 workers over 22 weeks. This document also includes partial weeks for employees that left and for new hires. The document also does not include paid time off for employees. This information skews the manpower hours lower. These data are also based on work weeks.

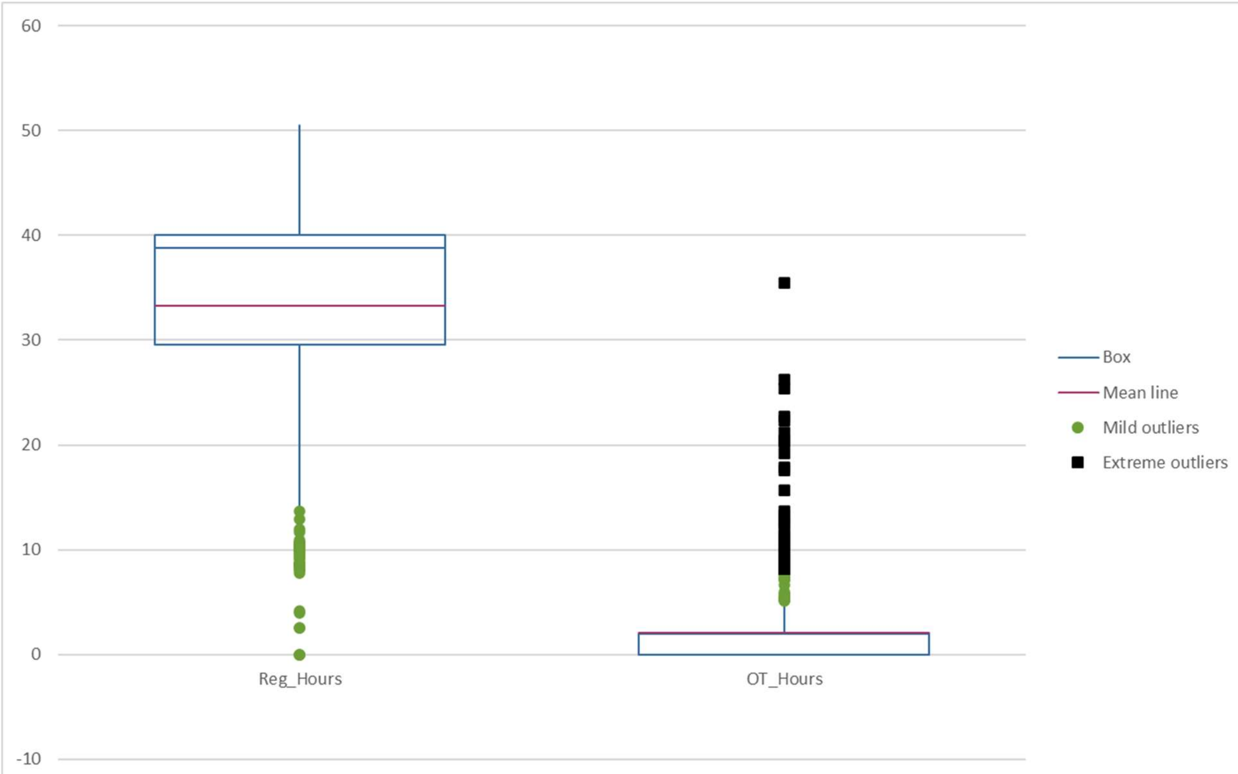

Figure 24 - Vault Teller Actual Work Hours over 22 Weeks

Table 8 - Vault Teller Actual Work Hours over 22 Weeks

Vault Teller	Count	Mean	Minimum	Lower whisker	Q1	Median	Q3	Upper whisker	Maximum
Reg_Hours	624	33.3206	0.0000	14.1000	29.5575	38.7600	40.0000	50.5400	50.5400
OT_Hours	624	2.0377	0.0000	0.0000	0.0000	0.0000	2.0075	5.0000	35.5100

Given the work hour standard deviation of 9.9122, the 95% $CI =$

$\sqrt{\frac{2(1.96+1.6449)^2 9.9122^2}{624}}$ = 33.3206 ±2.023 work hrs/week.

Given the overtime standard deviation of 4.1687, the 95% $CI =$

$\sqrt{\frac{2(1.96+\ .6449)^2 4.1687^2}{624}}$ = 2.0377 ±0.8508 overtime hours/week.

From the previous work hour data for tellers, by removing weeks for which the person worked less than 30 hr a week, the regular weekly work hours mean is 38.483, and the standard deviation is 3.636. For overtime hours, the new mean is 2.3629, and the standard deviation is 4.476. Both have n=452. Applying these values to the 95% CI yields these values: The Regular Hours $CI = \sqrt{\frac{2(1.96+1.6449)^2 3.636^2}{452}}$ = 38.483 ±0.8719 regular hours and Overtime $CI = \sqrt{\frac{2(1.96+1.6449)^2 4.476^2}{452}}$ = 2.363 ±1.073.

The model simulation also evaluates teller hours but focuses only on the sorting behaviors of each teller type. Tables 9 and 10 illustrate the sorting activities in minutes and hours, respectively. Comparing the values above and the "only sorting" responsibilities become a loose comparison. Some tellers only sort bags (e.g., outbound sorting, sorting 1), while others have additional duties beyond sorting.

Table 9 – Teller Sorting Utilization by Task in Minutes – Simulation

Variable	Count	Mean	Minimum	Lower whisker	Q1	Median	Q3	Upper whisker	Maximum
VAULT 1	31	265.0220	0.0000	235.7000	258.8250	270.8500	283.0000	311.9667	326.0667
VAULT 2	31	271.6161	0.0000	248.7000	263.6000	282.2667	289.2750	311.4333	311.4333
VAULT 3	31	266.5274	0.0000	239.9000	261.1833	271.8333	289.0750	313.2500	313.2500
SORTING 1	31	596.8759	106.4333	544.3167	581.7750	611.4833	640.9917	703.8167	703.8167
OUTSORT 1	31	430.6522	0.0000	388.2000	431.6833	444.8667	461.3833	486.2333	486.2333
CABINET 1	31	252.4992	0.0000	224.3333	246.2533	261.3000	276.9300	292.1000	292.1000
Security 1	31	252.5133	0.0000	224.7833	246.6383	261.6000	276.6217	291.6333	291.6333
OVERNIGHT 1	31	505.1129	180.0000	466.9333	504.8483	516.7833	537.3750	581.1267	581.1267
OVERNIGHT 2	31	505.1102	180.1667	466.9233	505.0450	517.1333	537.1083	581.2767	581.2767
EARLYAM 1	31	118.6118	0.0000	112.6167	117.4500	122.6833	125.7250	132.9500	141.5167
EARLYAM 2	31	118.6000	0.0000	112.9333	117.4833	122.5833	125.7167	133.0667	141.1167
EARLYAM 3	31	118.6070	0.0000	112.7333	117.3250	122.3333	125.7750	133.1500	141.3833
EARLYAM 4	31	118.5672	0.0000	112.7500	117.4167	122.3000	125.8083	132.8333	141.3333
EARLYAM 5	31	118.6129	0.0000	112.7167	117.2667	122.4500	125.9167	133.2167	141.3500

Table 10 - Teller Sorting Utilization by Task in Hours – Simulation

Variable	Count	Mean	Minimum	Lower whisker	Q1	Median	Q3	Upper whisker	Maximum
VAULT 1	31	4.4170	0.0000	3.9283	4.3138	4.5142	4.7167	5.1994	5.4344
VAULT 2	31	4.5269	0.0000	4.1450	4.3933	4.7044	4.8213	5.1906	5.1906
VAULT 3	31	4.4421	0.0000	3.9983	4.3531	4.5306	4.8179	5.2208	5.2208
SORTING 1	31	9.9479	1.7739	9.0719	9.6963	10.1914	10.6832	11.7303	11.7303
OUTSORTING 1	31	7.1775	0.0000	6.4700	7.1947	7.4144	7.6897	8.1039	8.1039
CABINET 1	31	4.2083	0.0000	3.7389	4.1042	4.3550	4.6155	4.8683	4.8683
SECURITY 1	31	4.2086	0.0000	3.7464	4.1106	4.3600	4.6104	4.8606	4.8606
OVERNIGHT 1	31	8.4185	3.0000	7.7822	8.4141	8.6131	8.9563	9.6854	9.6854
OVERNIGHT 2	31	8.4185	3.0028	7.7821	8.4174	8.6189	8.9518	9.6879	9.6879
EARLYAM 1	31	1.9769	0.0000	1.8769	1.9575	2.0447	2.0954	2.2158	2.3586
EARLYAM 2	31	1.9767	0.0000	1.8822	1.9581	2.0431	2.0953	2.2178	2.3519
EARLYAM 3	31	1.9768	0.0000	1.8789	1.9554	2.0389	2.0963	2.2192	2.3564
EARLYAM 4	31	1.9761	0.0000	1.8792	1.9569	2.0383	2.0968	2.2139	2.3556
EARLYAM 5	31	1.9769	0.0000	1.8786	1.9544	2.0408	2.0986	2.2203	2.3558

Driver-Messenger Utilization

The time utilization of the CIT crew (driver and messenger) are shown in Figure 25, and the values are in Table 11 below. These values were taken from an ATC-provided document that covers 22 weeks of driver-messenger hours for 167 crew members. Of note, while the mean hours are below 40, 47.8% of these employees earn some overtime each week, with some obtaining more than 20 hours of overtime pay. This document also includes partial weeks for employees that left and for new hires. The document also does not include paid time off for employees. This information skews the manpower hours lower. These data are also based on work weeks.

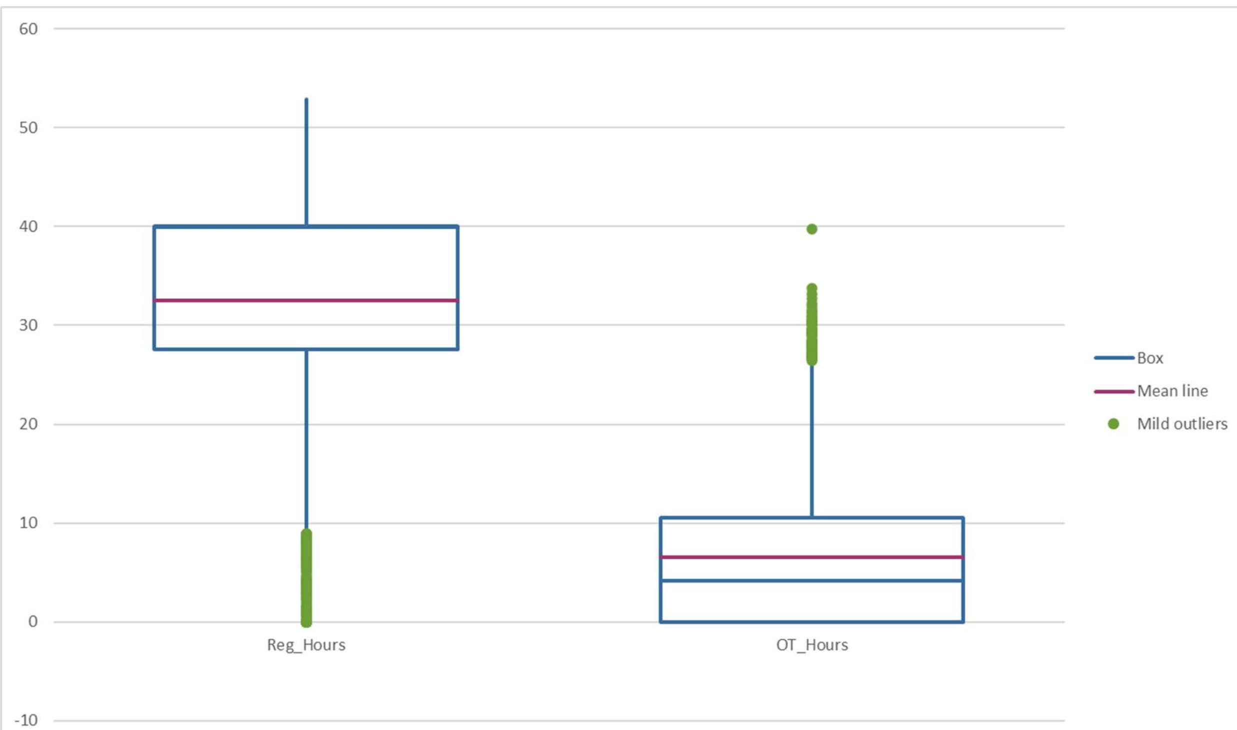

Figure 25 – Driver-Messenger Actual Weekly Work Hours for 22 Weeks

Table 11 – Driver-Messenger Actual Weekly Work Hours for 22 Weeks

Driver/ Messenger	Count	Mean	Minimum	Lower whisker	Q1	Median	Q3	Upper whisker	Maxi
Reg_Hours	3049	32.4797	0.0000	9.0500	27.6100	39.9900	40.0000	52.8600	52.86
OT_Hours	3049	6.5066	0.0000	0.0000	0.0000	4.1200	10.5600	26.3800	39.76

The Driver-Messenger regular work hours standard deviation from the provided information is 11.7348. Evaluating the 95% $CI = \sqrt{\frac{2(1.96+1.6449)^2 11.7348^2}{3049}}$ = mean ±1.083 regular hours per week @ 95%CI.

Overtime work hours for the Driver-Messengers are based on the standard deviation of 7.5445 derived from the supplied data. Evaluating the 95% $CI = \sqrt{\frac{2(1.96+1.6449)^2 7.5445^2}{3049}}$ = mean ±0.697 overtime hours per week.

From the previous work hour data for Driver-Messengers, by removing weeks for which the person worked less than 30 hr a week, the regular weekly work hours mean is 39.016, and the standard deviation is 2.997. For overtime hours, the new mean is 7.8605, and the standard deviation is 7.8013. Both have n=2,175. Applying these values to the 95% CI yields these values: The Regular Hours $CI = \sqrt{\frac{2(1.96+1.6449)^2 2.9970^2}{2175}}$ = 39.016 ±0.2376 regular hours and Overtime $CI = \sqrt{\frac{2(1.96+1.6449)^2 7.8605^2}{2175}}$ = 7.8605 ±0.8593.

The first comparison of Driver-Messenger model data involved running the simulation for 468 weeks with eight different route configurations to simulate a number of route lengths.

These routes ranged from 100 stops to 135 stops including retailers, banks, ATMs, and competitors. The results were compared to 36 hr and higher actual messenger data. Figure 26 is a probability density function comparing the historical data (N=1876 weeks, red line) to the simulation data (N=468 weeks, blue line).

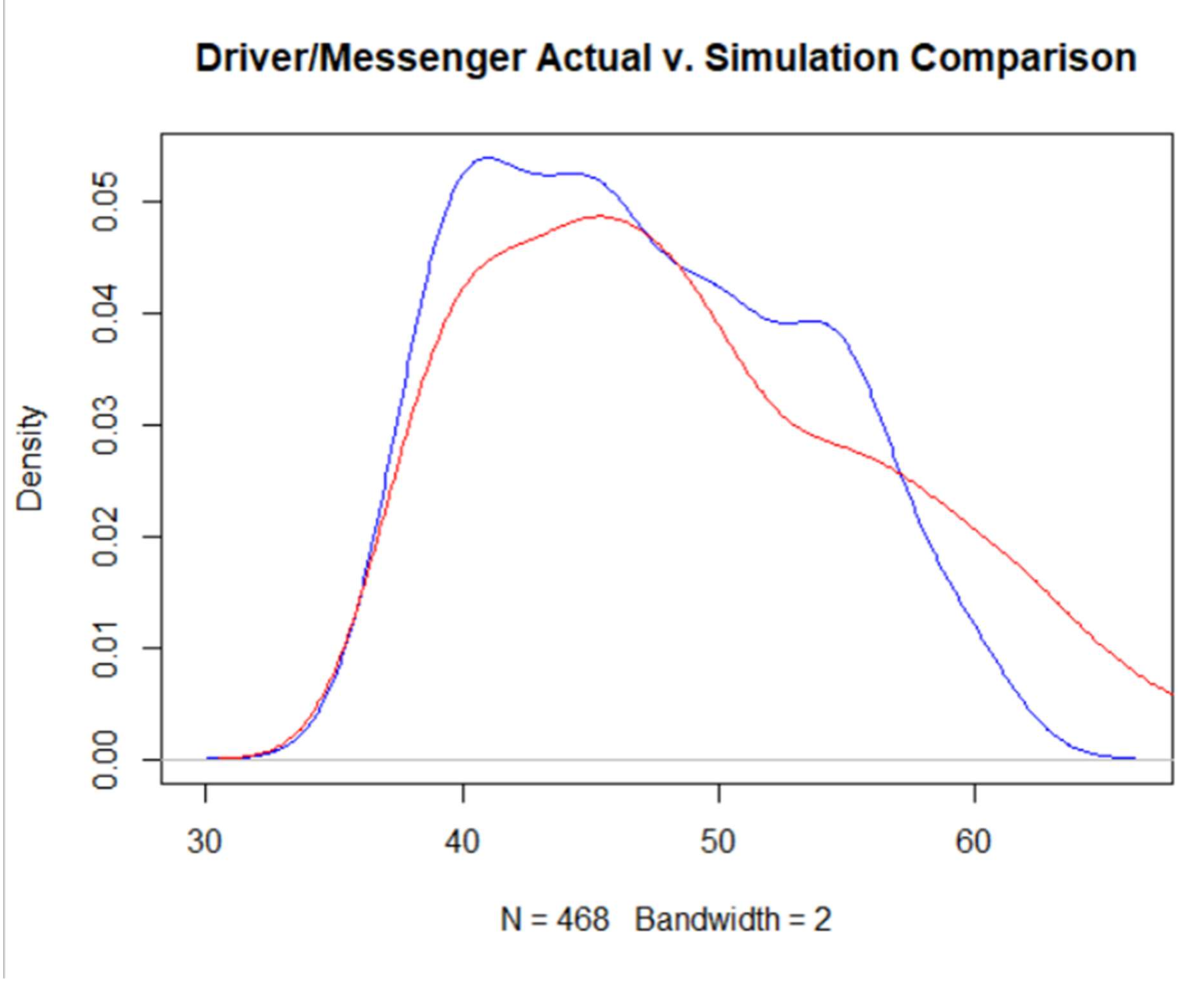

Figure 26 - PDF Comparison of Simulation v. Actual Driver-Messenger Work Hours

The simulation model created a single truck route to simulate a crew earning one to four hours daily overtime. The model assumes a truck route is operated seven days per week, with the weekend routes servicing fewer customers and developing less overtime. The data in Figure 26 and Table 12 assumes the same crew for five weekdays (excluding weekends). The model data for this route purposefully simulates a very busy route with high overtime for comparison purposes in Chapter 8. The 12 hours of overtime is expressly intended.

Figure 27 – Driver-Messenger Model Route Simulation for 14 Weeks

Table 12 - Driver-Messenger Model Route Simulation for 14 weeks

Variable	Count	Mean	Minimum	Lower whisker	Q1	Median	Q3	Upper whisker	Maximum
Average	14	52.0991	47.8247	51.0111	51.4709	52.6319	52.9278	53.7428	53.7428
Overtime	14	12.0991	7.8247	11.0111	11.4709	12.6319	12.9278	13.7428	13.7428

Another view of the Driver-Messenger utilization comes from the simulation model route simulation by evaluating the routes' daily start and finish times. The model was run for 100 days, and the results of the start and finish times for the model are shown in Figure 27 and Table 13.

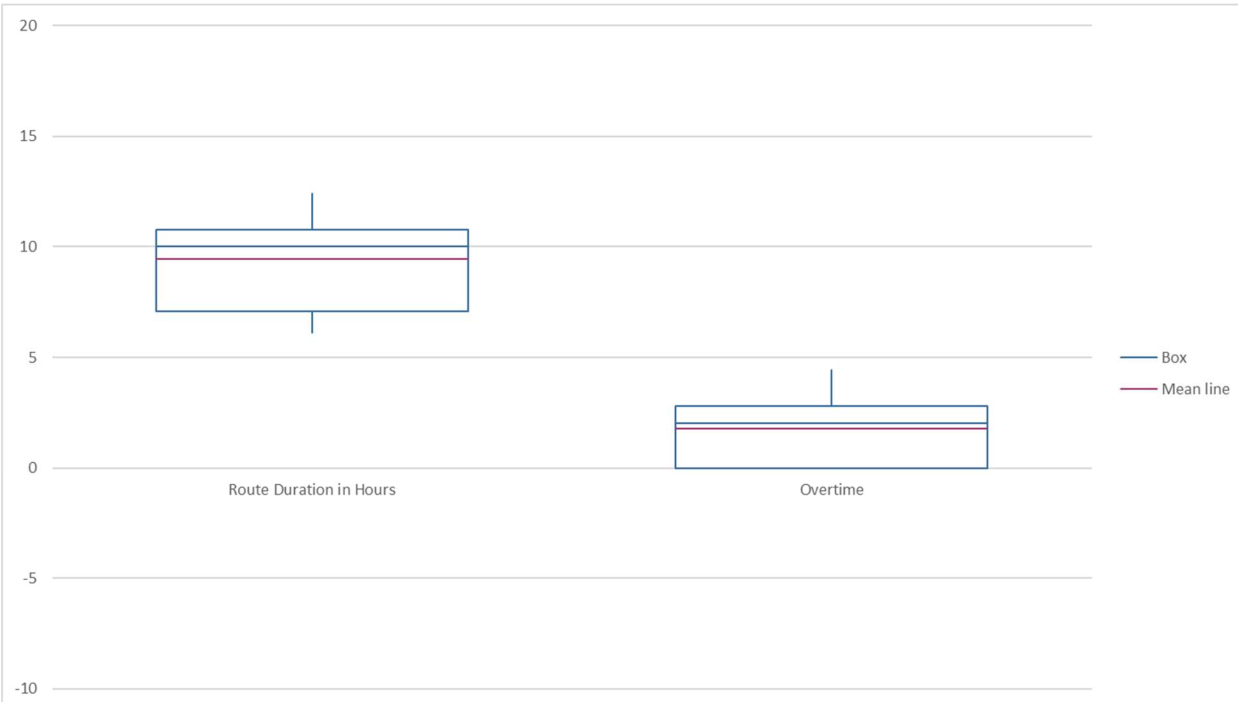

Figure 28 - Simulation Model Route Start and Completion

Table 13 - Simulation Model Route Start and Completion

Variable	Count	Mean	Minimum	Lower whisker	Q1	Median	Q3	Upper whisker	Maximum
Average	100	9.4488	6.2869	6.2869	7.3114	10.0590	10.6299	12.1214	12.1214
Overtime	100	1.7548	0.0000	0.0000	0.0000	2.0590	2.6299	4.1214	4.1214

Extending the daily value to a five-day workweek would approximate the overtime at 7.1 to 8.8 hr per week. Given the 95% CI for overtime as 7.8605 ±0.8593, the simulation model aligns with the provided data from the ATC.

Truck Route Timing

The truck stops at retailers, banks, ATMs, and competitors as part of a regular daily route. The duration of a stop includes finding the appropriate delivery bag(s) (if applicable), loading the bag(s) in a black canvas over-bag, leaving the truck and entering the facility, interacting with the manager (or ATM), exchanging bags, transfer of custody processes, placing cash bags (if applicable) in black canvas over-bag, and entering the truck. These processes were not observable at the ATC facility. The typical transaction timing was gathered through interviews with ATC managers and drivers/messengers. The time was also deduced from work-hour reports and observed transactions. Figure 28 and Table 14 illustrate the average simulation model timing for each type of encounter on a route. The model in Figure 21 was run for 100 days. The weighting for the simulation model stops is a retailer – 74%, ATM – 15%, bank – 8%, and competitor – 3%.

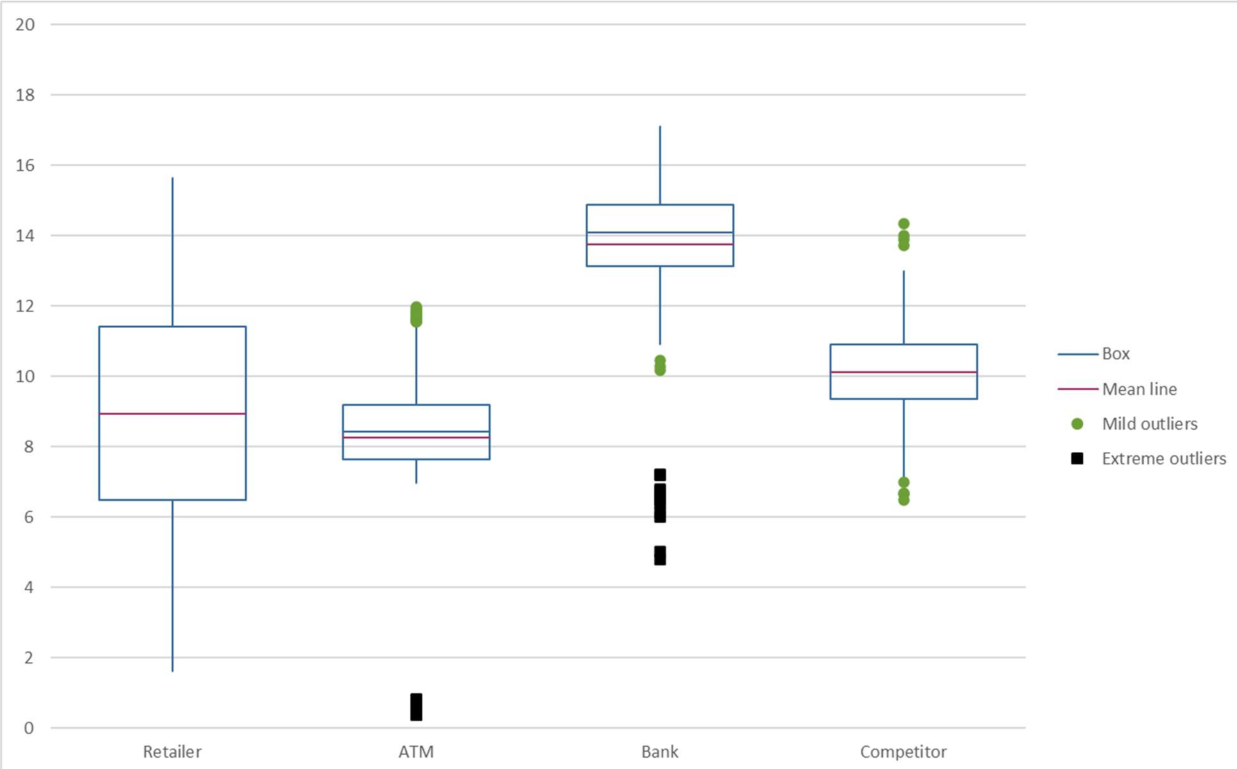

Figure 29 - Simulation Route Stop Timing by Type

Table 14 - Simulation Route Stop Timing by Type

Current State	Count	Mean	Minimum	Lower whisker	Q1	Median	Q3	Upper whisker	Maximum
Retailer	2680	8.9484	1.6333	1.6333	6.5000	8.9333	11.4208	15.6333	15.6333
ATM	531	8.2562	0.3667	7.0000	7.6417	8.4333	9.1917	11.5000	11.9833
Bank	288	13.7612	4.7833	10.9333	13.1292	14.0833	14.8833	17.1000	17.1000
Competitor	117	10.1101	6.4833	7.1167	9.3667	10.1333	10.9167	12.9833	14.3333

In summary, the metrics produced by the simulation model were validated by several methods to ensure a baseline model behavior. This baseline is used for building the business model and comparison to the future state in Chapter 8. See Table 15 for a summary of data, the source, and the means used to validate the simulation model.

Table 15 - Data Sources and Validation

Item	Source	Model Validation
Messenger Route Transaction Timing	Interview/Observation	Comparison to Operational Behaviors/Validation with Managers/Work hour data
Transfer of Custody from CIT to Vault	Time-Motion Study/Observation	Comparison Time-Motion Study/Work Hour Evaluation
Teller Utilization - Inbound	ATC Data/Observation	Work Hour Evaluation/Comparison to Operational Behaviors
Teller Utilization - Outbound	ATC Data/Observation	Work Hour Evaluation/Comparison to Operational Behaviors
Total Route Duration	ATC Data/Observation	Work Hour Evaluation/Comparison to Operational Behaviors
Bags Handled by Trucks	ATC Data/Time-Motion Study	Work Hour Evaluation/Comparison ATC Data

Current State Business Model

The business baseline is focused on time-able behaviors involving the movement of cash bags throughout the entire CIT and vault sorting processes. This business model is not intended to evaluate every function in the branch. Since the critical value of time correlates to employee wages, a financial model for these processes can be developed through observed, provided, and simulation model data.

The ATC provided fully loaded average wages for each type of employee. These wages were provided in 2021, so the cost-of-living adjustments are made, and the wages rounded to develop Table 16.

Table 16 - Fully Loaded Average Wages Per Job Title - Adjusted for 2023

Job Name	Average Wage per Hour	Average Wage per Minute	Average Wage per Second
Vault Teller Unarmed	$23.00	$0.383	$0.0064
Vault Teller Armed	$27.00	$0.450	$0.0075
CMS Teller	$23.00	$0.383	$0.0064
CIT Driver Armed	$26.00	$0.433	$0.0072
CIT Messenger Armed	$26.00	$0.433	$0.0072
Mechanic	$40.00	$0.667	$0.0111

Applying these wages to the activities listed above yields a baseline operational cost for a branch. Taking the data above, Table 17 illustrates the daily and annual staffing operating expenses of a branch with 45 trucks, showing each task and the model output of minutes worked per task.

Table 17 - Operational Cost Baseline for a 45-Truck Branch

Role	Task	Time on Task (Min)	Cost	#	Daily Cost	Annual Cost
Vault Teller Armed	Outbound Transfer to CIT	11.4483	$5.15	45	$231.83	$84,617.49
CIT Messenger Armed	Outbound Transfer to CIT	11.4483	$4.96	45	$223.24	$81,483.51
CIT Driver Armed	Outbound Transfer to CIT	11.4483	$4.96	45	$223.24	$81,483.51
Vault Teller Unarmed	Bag Sorting & Assignment	430.6522	$165.08	1	$165.08	$60,255.41
Vault Teller Unarmed	Cabinet Sorting	252.4992	$96.79	1	$96.79	$35,328.85
CIT Messenger Armed	Cabinet Sorting	252.5133	$109.42	1	$109.42	$39,939.19
Vault Teller Armed	Vault Sorting	803.1656	$307.88	1	$307.88	$112,376.25
Vault Teller Unarmed	Internal Processed Bag Sort	596.8759	228.80	1	$228.80	$83,512.89
Vault Teller Unarmed	Overnight Sorting Ext Bags	1,010.2231	$387.25	1	$387.25	$141,347.05
CMS Teller	Early Morning Sorting	592.9989	$227.32	1	$227.32	$82,970.43
Vault Teller Armed	Inbound Transfer to Vault	12.9690	$5.84	45	$262.62	$95,857.43
CIT Messenger Armed	Inbound Transfer to Vault	12.9690	$5.62	45	$252.90	$92,307.15
CIT Messenger Armed	Waiting Time for Mantrap	2.9506	$1.28	45	$57.54	$21,000.80
CIT Messenger Armed	Route Operation	465.0333756	$201.51	45	$9,068.15	$3,309,875.05
CIT Driver Armed	Route Operation	465.0333756	$201.51	45	$9,068.15	$3,309,875.05
CIT Messenger Armed	Route Operation (OT)	42.29558034	$27.49	45	$1,237.15	$451,558.19
CIT Driver Armed	Route Operation (OT)	42.29558034	$27.49	45	$1,237.15	$451,558.19
				Total	**$23,384.51**	**$8,535,346.46**

Summary

The researcher has spent countless hours understanding the business flow of an ATC, observing behaviors, and collecting historical data. A simulation model was built and validated by all available means. After validation, the model produced a series of baseline data which was then applied to a business model, which became a baseline for the future case. Having established the baseline, the following discussion is about evaluating various IoT technologies that may have an application to cash movements by armored vehicles.

CHAPTER 7

TECHNOLOGY EVALUATION

Requirements

Before evaluating technologies, it is critical first to establish a set of requirements for IoT applications to cash visibility. There are seven significant areas of traceability within the cash visibility network: chokepoints, trucks, mobile reading, office printing, mobile printing, sorting, and real-time location. In addition, several other areas must be addressed, including IoT device tamper identification, security, and overall system resilience. From a higher level, the proposed system should enable interoperability between competitors, customers, banks, and the Federal Reserve Bank. Finally, considering the relatively low margins ATCs operate under, the overall system cost should be evaluated.

Chokepoints are areas where IoT-enabled items pass within a small, enclosed, predictable space like a hallway or specified entry area. Within the context of cash traceability, this is most typically a mantrap where an exchange of cash bags takes place. This exchange of bags is always a transfer of custody operation where one person or organization is passing complete responsibility and liability for the item to another person or organization. Because of the nature of chokepoints, the area needs to be self-contained for reading everything within that area and nothing outside of the area. Adjacent chokepoints must have isolation of at least 30dBm so there is no leakage from one chokepoint area to another or a discernable difference in signal strength. For this evaluation, a man-trap area of a room approximately 3 m wide, 3 m tall, and 6 m long is considered. These measurements are based on an observed mantrap within an ATC organization.

The nature of the mantrap area in an ATC requires reading IoT devices on bags of cash and coins within a 54-square-meter area. The elevation from the floor is approximately 0.5 m. All bags must be detected within this area as the bags are carried or pushed through the door on a cart before reaching the pass-through door approximately 6 m away. The IoT equipment must be installed at least 2 m above the floor to avoid injury to people or equipment damage from carts or other means of bag movement. During a single transaction, the mantrap must support reading 250 bags and other items (e.g., keys, manuals, tablets). Because of the room's geometry, the maximum distance from an IoT reader is the hypotenuse of equipment mounted at 3 m to the opposite door, which is 6 m away, where the bags are 0.5 m above the ground, which is 6.5 m. Note that some IoT solutions have the option of multiple antennas, which is discussed within each IoT technology solution.

The requirements for an armored vehicle (armored vans, route trucks, and Fed trucks) are to read IoT-enabled bags on the entrance and exit from a side door and a back door. In addition, reading IoT devices must be accomplished when the doors are closed, providing a constant inventory of bags on a vehicle. These two functionalities should be able to operate with door open/close sensors indicating the reading mode desired. Some armored vehicles have internal cages with biometric controls to provide additional protection from robbery. These caged areas should be considered in the final IoT solution. The container area of an armored truck is approximately 2 m wide, 4 m long, and 2 m high. Cash is usually stored on the vehicle's floor but may be stored on shelves. The RF environment in an armored vehicle is isolated because of the armor and the nature of the vehicle's security features. This enclosed environment creates a

Faraday cage environment and RF reflections within the vehicle that are typically additive to the signal quality.

For mobile reading, employees are often required to use handheld devices that can read an IoT-tagged bag. These are used for very close-range reading of IoT devices in various operational environments, including banks, retail establishments, and CIT hubs.

Printing and encoding IoT devices for use within a cash visibility environment involve an association of the IoT device to the bagged cash. Some IoT devices support programming the asset/bag identification (ID) within the device's non-volatile memory. Others require the database association of a unique identifier with the asset’s unique identifier. This association would exist within a database only. Many forms of IoT allow tags to be printed with human-readable information on the face of the device, while remotely readable information is stored within the non-volatile memory. These are often label-based materials. Printing and associating must occur at the starting point of each bag. Change orders are typically made in a vault setting, so desktop printing or tag association can occur in a controlled environment. Deposits are created at the retailer, so printing and association need to be done by the retailer or the CIT truck messenger. ATM residuals require the CIT messenger to appropriately tag the bag with an IoT device through printing or association. In the future state, all bags should have an IoT device attached.

The sorting operation occurs when CIT trucks return to the ATC hub. Large ATC hubs have 40 to 50 trucks returning with 30 to 110 deposits or ATM residuals. Sorting and distributing bags is a challenge for ATC hub staff. Today, each bag has a deposit slip in the bag, and the crew must find the slip without opening the bag and mark the bag for the bank for which it is destined. Instituting an IoT device on each bag allows the robotic sorting of the thousands of bags brought to the ATC hub daily. Robotic sorting can be done in off-the-shelf equipment with minor modifications. The bags can be picked up by a robotic arm and placed near a low-power reader for identification and sorting.

Real-time location systems (RTLS) increase the visibility of large quantities of cash bags within a processing facility. Typically, the accuracy of these systems is between a few centimeters to a meter. RTLS systems require multiple phased array antennas supporting the protocol of a particular IoT device. The position of an RTLS system depends on many factors, including the number of phased array antennas, ceiling height, and the system's transmit power/receive sensitivity. RTLS systems should have at least a 10-m read range from each hub device. RTLS is discussed in more detail under each technology, but the requirement for cash visibility would be an accuracy of approximately half a meter.

Tamper, security, and system resilience are additional requirements for an IoT system. Each IoT device should have a visual indication if an individual tries to remove it from the bag. Security involves validating that the IoT tag is the same from the origin point to the final destination point. Security may also involve encrypting the information transmitted from the tag to the reader. System resilience describes the ability to continue to operate if computer systems are unavailable. Resilience can involve directly programming information into the IoT tag memory or sharing tag-bag association tables with remote devices.

Interoperability between diverse entities (e.g., banks, competitors, and various retailers) should be enhanced using IoT. While not the complete interoperability solution, the IoT solution should aid in the eventual solution. Interoperability also drives IoT device solutions towards a low-cost disposable solution; although some lower-cost reusable solutions may still fit the model, all parties must cooperate for sharing IoT devices. Today, systems between banks, retailers, and competitive ATCs are disconnected. This disconnection drives technology to paper manifests and manual entry of cash bags moved between entities. Having the manifest of each bag stored on that bag within the IoT device is desirable, which also aids in overall system resilience.

The Federal Reserve Bank (FRB) has promoted an Application Programming Interface (API) integration between banks, ATCs, and the FRB. This system allows for posting e-manifests of shipments to and from the FRB. The same API can be utilized between other entities allowing a more efficient transfer of information between entities in the cash value chain. For the most part, an assumption is made that an API integration is available to transfer e-manifests between organizations.

The cost pressures of adding IoT solutions to the cash management arena are intense. A portion of this research focuses on the business models, return on investment (ROI), and the expected payback period of deploying such a solution. Several critical cost pressures and opportunities to improve the system's flow are discussed later. The industry needs a solution with a relative cost per bag of $0.05 to $0.09. This price may be a single-use disposable tag or a higher-cost tag that supports reuse over months/years. Table 18 comprehensively lists the requirements for an IoT device to be successfully fielded within this use case.

Table 18 - IoT Device Requirements

Requirements	**Parameters**	**Notes**
RF Reading Range	0.5 – 10 meters	Handheld Reader to RTLS System
IoT Device Density	2500 devices in a 5000 square foot area	200 devices in a choke point 3500 devices in an open RTLS area
Isolation between mantrap/chokepoint	30 dBm	Avoiding crosstalk between adjacent chokepoints
Tamper	Shows signs of tamper attempt	A visible indication that an attempt was made to remove the device.
Security	Technology specific security	Prevents tampering with information stored on IoT devices.
Resilience/Encoding	Storage in device memory for basic manifest information	Allows for bag processing when IT systems are down.
Printing	Human readable bag routing information	Allows for bag processing when IT systems are down
IoT cost per bag	\$0.05 - \$0.09	It can be single-use disposable or amortized over time by device reuse.
Battery life	A passive device (no battery) or reusable device – 5 years.	Active devices with at least a 5-year battery life.

Bluetooth Low Energy

Technology Overview

Bluetooth Low Energy (BLE) supports a beacon behavior that periodically sends a predetermined cash bag of data at 2.4 GHz. These one-way beacons occur whether there is a Bluetooth observer/central device in range of the IoT device (commonly called a peripheral or broadcaster). Bluetooth peripherals are active devices and require a battery to operate. Bluetooth is a widely used and well-supported technology. The most significant advantage of Bluetooth is the ubiquity of the technology in tablets and cell phones. The disadvantages include the cost, the attachment means, and the theoretical limit of beacons in each area.

As mentioned in the literature review, Bluetooth uses a 40-channel schema to support many devices in a small area, having reserved channels 37, 38, and 39 as device beacon channels. These advertisements are limited to 37 bytes in length. In Bluetooth 5.0, the Bluetooth Special Interest Group (Bluetooth SIG) provided for extended advertisements of 256 bytes on up to eight additional channels. There is an assumption in BLE that beacons are missed because the peripheral and the central are both frequency hopping between channels 37, 38, and 39. Also, because there is no coordination of device timing, collisions are common when multiple BLE devices are advertising during the same period.

IoT Device Density

The capacity of a BLE central is based on the Physical Layer (PHY) limits. In BLE, the most typical data rate is 1 MB/s (also called PHY 1). There is an option for PHY 2 (2 MB/s), but it is less used. The assumption is that since there are three advertising channels, the aggregate data rate for advertising is 3 MB; however, that is not true. Because beacons transmit their beacons on all three channels spread randomly across time, the relative data rate remains at 1 MB/second. A typical beacon for an advertiser is 37 bytes of data, and, with the overhead (preamble, address, header, and CRC), the entire packet is 47 bytes in length or 376 bits. Because each bit is equal to a microsecond, the duration of the data is 376 ms. There is, however, a need to evaluate the entire transmission envelope, including the transmitter ramp-up and ramp-down periods, which equate to a total packet time of approximately 650 ms. Evaluating this, 1,000,000 ms/650 ms = 1,538 packets/second. Assuming an increasing number of beacons in the RF field of the central device and an even distribution of peripherals across all three of the advertising channels, the maximum throughput is 769 beacons. This maximum beacon count occurs because of increased collisions as the number of beacons exceeds 769. Figure 29 is a chart of the values shown here evaluated in SciLab.

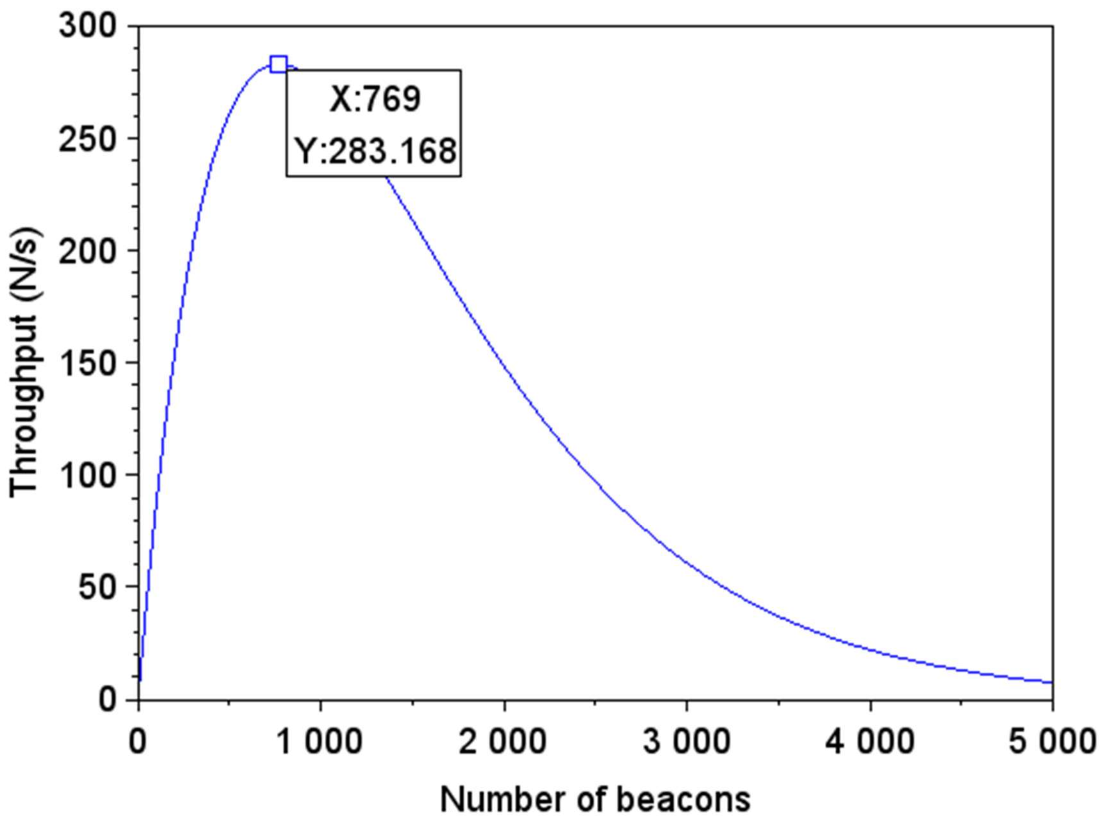

Figure 30 – BLE Throughput

When the beacon interval is included in the formula, this variable drives the results. As a central's beacon channels (37, 38, and 39) reach the optimal capacity in Figure 30, there is a marked increase in beacon collisions. This increased collision rate, in turn, causes delays in the capture of beacons by the central. Each beacon is sent with a randomization schema that intends to overcome collisions. As shown in Figure 30, a beacon interval of 0.25 s quickly starts affecting the overall time of tag detection. As the interval period increases to 1 second, the number of tags a central receives can increase, and the time to detect peripherals decreases. For longer intervals (e.g., 5 s, as indicated in Figure 30), the capture rate stays consistent beyond 10,000 tags in the area of the central.

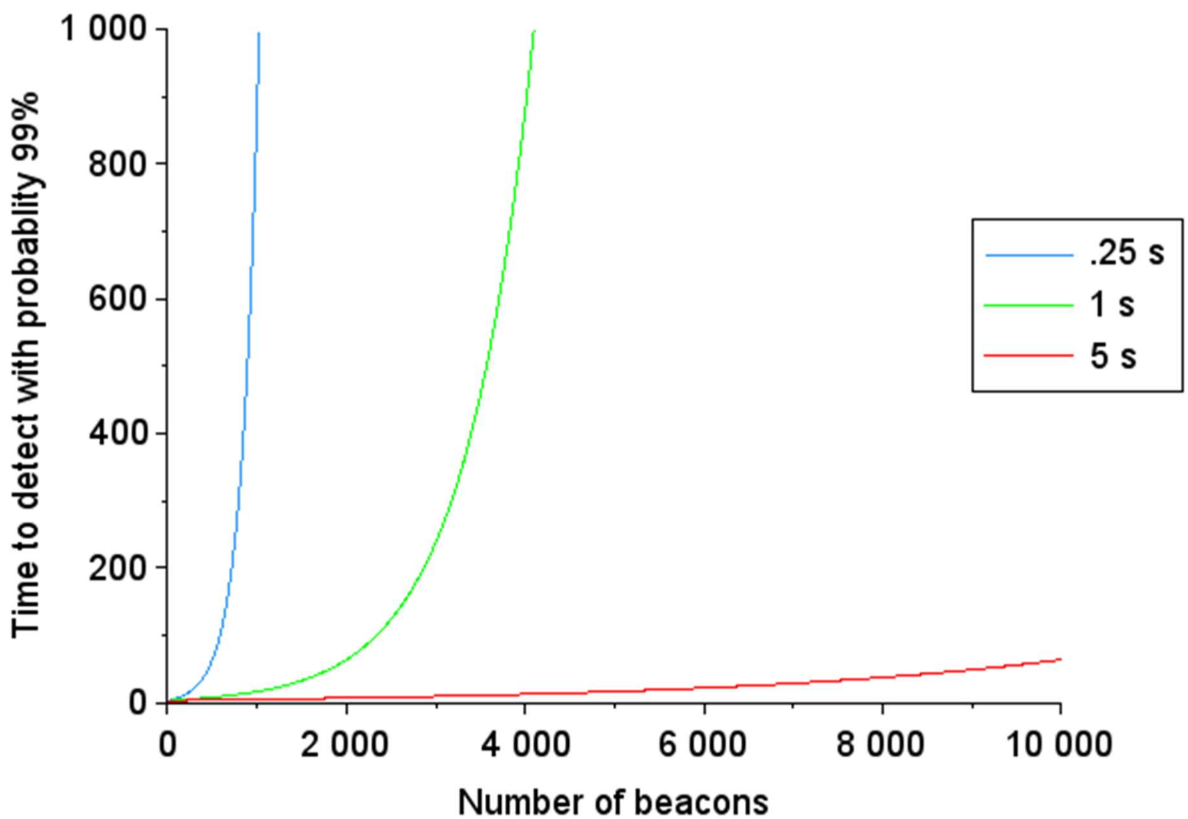

Figure 31 - Interval Impact on Number of Beacons v. Time

RF Reading Range

Regarding the requirements, Bluetooth peripherals can beacon information up to 100 m in extreme environments, but typically, the beacons reach 30 to 40 m. A unidirectional link budget is illustrated in the following formula:

$$P_r = P_t + G_t - CL_t - P_L - F_M + G_r - CL_r$$

$$P_r = power\ at\ the\ receiver$$

$$P_t = power\ output\ of\ the\ transmitter$$

$$G_t = gain\ of\ the\ transmit\ antenna$$

$$CL_t = cable\ loss - transmit\ cable$$

$$P_L = path\ Loss\ (Friis\ Formula)$$

$$F_M = fade\ margin\ (includes\ all\ forms\ of\ fading)$$

$$G_r = gain\ of\ receiver\ antenna$$

$$CL_r = cable\ loss - receiver\ cable$$

$$Friis\ Formula = P_L = 20log_{10}\left(\frac{4\pi D}{\lambda}\right)$$

$$Wavelength\ \lambda = \frac{v}{f}$$

Taking the Nordic Semiconductor nRF52840 BLE chipset as an example (See appendix B), the following values are considered in the link budget: $P_t = 0\ dBm, G_t = 0\ dBi, P_r =$ $, -95\ dBm@\ 1MBPS\ (minimum),\ G_r = 10\ dBi, CL_t = 0d\ Bm, CL_r = 1\ dB, F_M = 2\ dB$. The frequency is 2,426 MHz (Channel 38). D = 10 M according to requirements.

Therefore, $\lambda = \frac{299\ 792\ 458}{242600000} = 0.12357\ m.$ Given λ, free space loss is calculated as = $20log_{10}\left(\frac{4\pi 10}{0.12357}\right) = 60.15\ dB.$ Therefore the beacon link budget from a peripheral to a central, where both are based on the nRF52840, is:

$$-53.15\ dBm = 0 + 0 - 0 - 60.15 - 2 + 10 - 1$$

With the minimum requirement at the receiver of -95 dBm, the signal-to-noise ratio is 41.85 dB, indicating the signal is exceptional at the 10-m range from the central.

Bluetooth 5.1 supports Angle of Arrival (AoA) for RTLS solutions. These RTLS solutions include a phased array antenna system that develops a vector angle and a distance based on the received signal strength indicator (RSSI), which measures the RF energy recognized at the receive antenna. Maus (Maus et al., 2022) illustrate the shift of phase based on the angle in Figure 31.

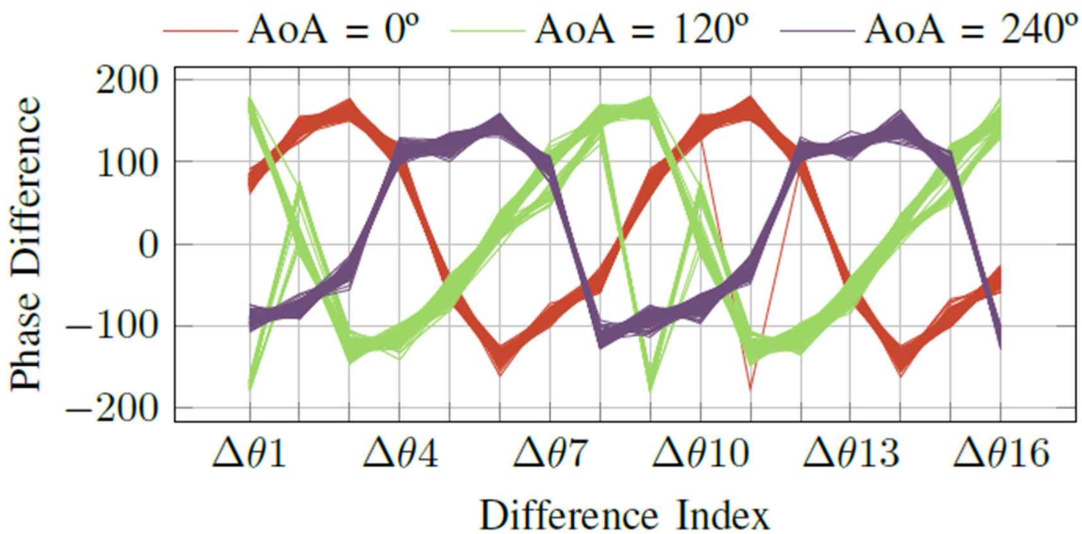

Figure 32 - Phase Shift at Angles in Phased Array RTLS System

Note: Taken from Paulino, N., Pessoa, L. M., Branquinho, A., & Goncalves, E. (2022). Design and Experimental Evaluation of a Bluetooth 5.1 Antenna Array for Angle-of-Arrival Estimation. 2022 13th International Symposium on Communication Systems, Networks and Digital Signal Processing, CSNDSP 2022, 627. https://doi.org/10.1109/CSNDSP54353.2022.9907908

Isolation at Mantrap

Having reviewed Bluetooth system capacity, link budget, and RTLS, the next topic is isolation between adjacent chokepoints. Osama Ata (2017) performed a series of tests to evaluate signal loss through structural walls. In that study, the researcher found that interior gypsum walls with an air gap provided 8dB of loss while interior brick walls provided 14.4 dB loss, both at 2.447 GHz. With a signal-to-noise ratio of more than 40 dB, these losses are insignificant enough to draw definitive conclusions about the correct chokepoint. Reducing the gain of the receiver antenna of the central to 3 dBi and reducing the output power of the peripheral to -20 dBm would change the link budget to a value of -80.15 dBm.

$$-80.15\ dBm = -20 + 0 - 0 - 60.15 - 2 + 3 - 1$$

Adding in the loss of a wall (gypsum or concrete) would then be enough to prevent communications through the walls and allow for differentiation between chokepoints. The reduced power may, however, jeopardize the BLE AoA solution.

Tamper, Security, Resilience, Encoding, and Printing

Tamper, security, and resilience are the next topic. As defined earlier, resilience in this application is to continue operational behaviors without network connectivity. BLE beacons (peripherals) can be programmed to broadcast a string of information; therefore, during a pairing process, this can be programmed into the tag's memory through a phone or tablet. In this case, there is no human-readable label, but a small label maker could be used to perform that action. BLE also supports security schemas to prevent adjusting the programming of the tag. Tamper can be addressed by applying clips or adhesives that cannot be removed from the bag without causing apparent damage. BLE tags cannot be printed.

IoT Device Cost per Bag

Depending on the feature sets and enclosure, a BLE beacon costs $5 to $10. Because there is a need for a unique attachment method that indicates tampering, the value of $10 is used for this application. Several assumptions need to be made. Because the device needs to be small, a CR2032 coin cell battery is assumed for the power source. A Nordic nRF52840 chipset is assumed and operating at 0 dBm on PHY 1 (1 MBPS). It is assumed that devices stop beaconing when disassociated from a bag. The expected lifespan of a bag is 92 days which includes one day for preparation, one day for transportation, and 90 days in "teller trash." Teller trash consists of bags kept for 90 days after reconciliation is complete, and a reasonable waiting period has elapsed to uncover any inconsistencies in the bag contents. It is assumed that the beacon is reissued after it is removed and ready for reuse.

Given the assumptions, the CR2032 is a 3V 255mAh battery. The energy consumption of an nRF52840 module is 3.16 µA when idle, 6.4 mA when transmitting, and 6.26 mA for receiving operation. Given that beacon messages are 650 µs in duration and the receiver listens for 60 µs after each beacon, the overall cycle is approximately 4.31 ms in duration for transmissions on the three beacon channels, as indicated in Figure 32 from Nordic Semiconductor.

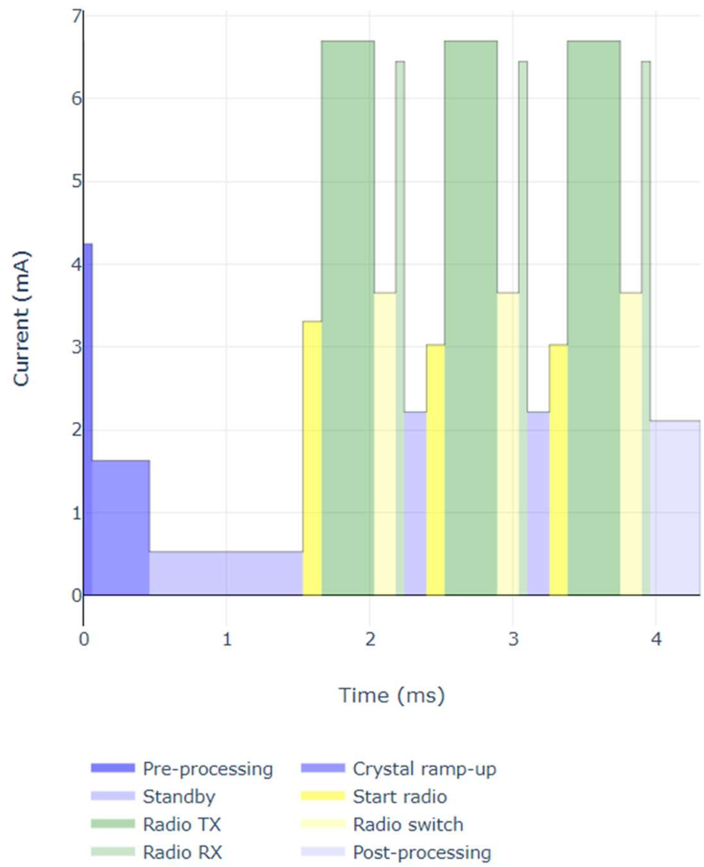

Figure 33 - Bluetooth LE Power Profile

Note: Taken from Nordic. (n.d.). Online Power Profiler for Bluetooth LE.

https://devzone.nordicsemi.com/power/w/opp/2/online-power-profiler-for-bluetooth-le

Assuming that the beacon interval is 1000 ms, the idle time is 996 ms. The 4.31 ms is then divided into Transmit state 1.950 ms (650 µs*3 transmissions), Radio Receive: 180µs (60 µs*3 reception periods), Switching/pre & post processing, standby and crystal warm-up of 2.18ms. Therefore, the device is in the following states: 99.6% - standby, 0.195% - transmitting, 0.018% - receiving, and 0.218% - remaining activities. To formulate the current utilization, the following formula applies:

$$Standby\ Current * \% + TX\ Current * \% + RX\ Current * \% + Other\ Current * \%$$

$$3.16\ \mu a * 99.6\% + 6400\ \mu a * 0.195\% + 6260\ \mu a * 0.018\% + 2100\ \mu a * 0.218\%$$

$$= 21.233\ \mu a$$

$$Then: \quad \frac{255{,}000\ \mu ah\ (battery)}{21.233\ \mu a} = 12{,}013\ hrs = 500\ days = 1.37\ years$$

Given a battery life of ~500 days and a reuse rate of 92 days, 500 days/92 days = ~5 bags per tag per battery. Assuming 10 years of useful life, eight batteries are required at ~ $0.34 (Mouser) each. $10 tag+(8*.34) = $12.72. Over 10 years, the tag has been used on approximately 40 bags (3,650 days/92 days). Therefore, the cost per tag/bag is $12.72/40 =~$0.32/bag. Note that this is a best-case scenario for battery utilization. Temperature, battery leakage, and additional circuitry were not included. Consumption for pairing and programming the tag with the traceability was also not included, although this procedure would be conducted for a few seconds every 92 days.

Passive Bluetooth Low Energy

Technology Overview

An emerging technology in BLE is the passive beacon label. Today, one company controls the intellectual property of this technology. That company is Wiliot, located in Caesarea, Israel. Wiliot utilized a form of power harvesting from local area transmitters to passive beacons. Wiliot and its partners do not distribute information about how the system works. Therefore, investigating this technology relies on a patent review and anecdotal testing of a Wiliot development kit.

According to a Wiliot patent for their capacitor technology, Wiliot engineers have developed an on-chip capacitor that allows energy storage to operate the device. This capacitor is unique in its small size, yet it stores enough energy for the device (the brand is “Pixel”) to broadcast a BLE beacon (Elboim & Yehezkely, 2022).

In an additional patent, Wiliot describes the system in detail as a continuous wave transmitter broadcasting in an area where energy-harvesting transponders receive the RF energy from the continuous wave transmitter. The energy harvesting transponder collects the energy through a harvesting component and stores the energy in the aforementioned capacitive reservoir. Then, according to a timing behavior, discharges the capacitor into a BLE transmitter that develops a BLE beacon backscatter Gaussian Frequency Shift Keying (GFSK) transmission (Ziv & Domb, 2019), as seen in Figure 33.

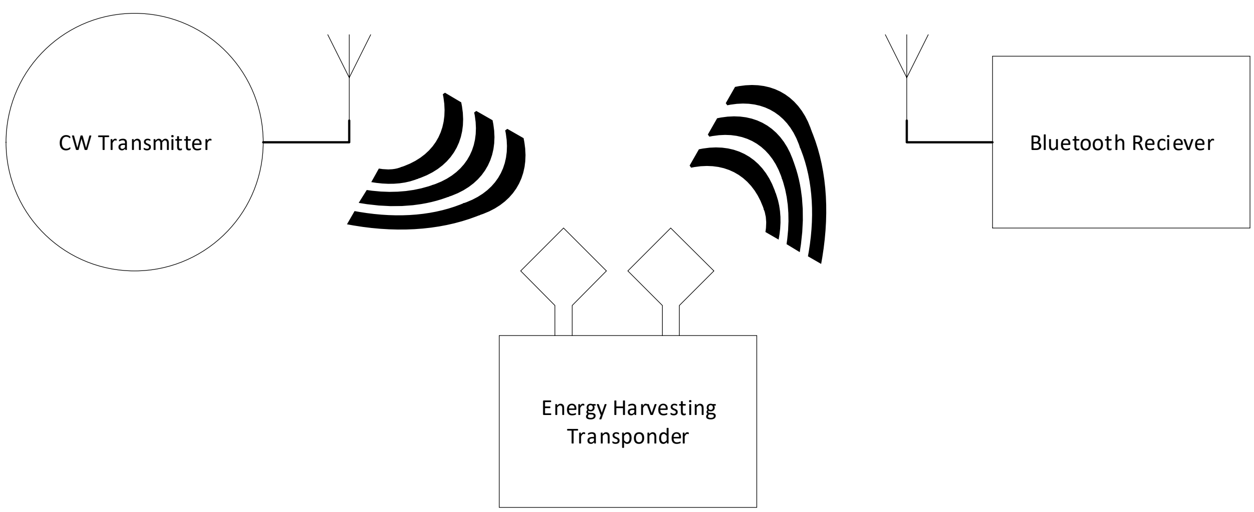

Figure 34 - Wiliot Methodology

Each Pixel sends a beacon on an interval determined by its settings and proximity to the area transmitter. A BLE gateway gathers the beacons and forwards them to the Wiliot server for processing. An area transmitter may also serve as a BLE gateway. If the passive RFID tags are used with a Wiliot phone application, a phone may operate as an area transmitter and a BLE gateway. Area transmitters may be single-band or dual-band. Single-band area transmitters broadcast on channels 37, 38, and 39 at a 1.3% duty cycle and an additional channel at a 55% duty cycle. The additional channel changes each time the area transmitter is rebooted. During the initial testing period, the area transmitter was broadcasting on channel 10. Dual-band area transmitters also broadcast in the 900 MHz frequency band, hopping across 917.193750 MHz to 918.768750 MHz.

Figures 34 and 35 indicate the RF transmission envelope for the area transmitter on a real-time spectrum analyzer representing BLE channels 37 and 39. There is a consistent transmission on these channels filled with data packets made up of Hex A, which in binary is 10; therefore, the signal is simply alternating from 1 to 0 and back in the data portion of the frame. Figure 36 shows the chip timing for these transmissions. This chip is consistent with BLE transmissions.

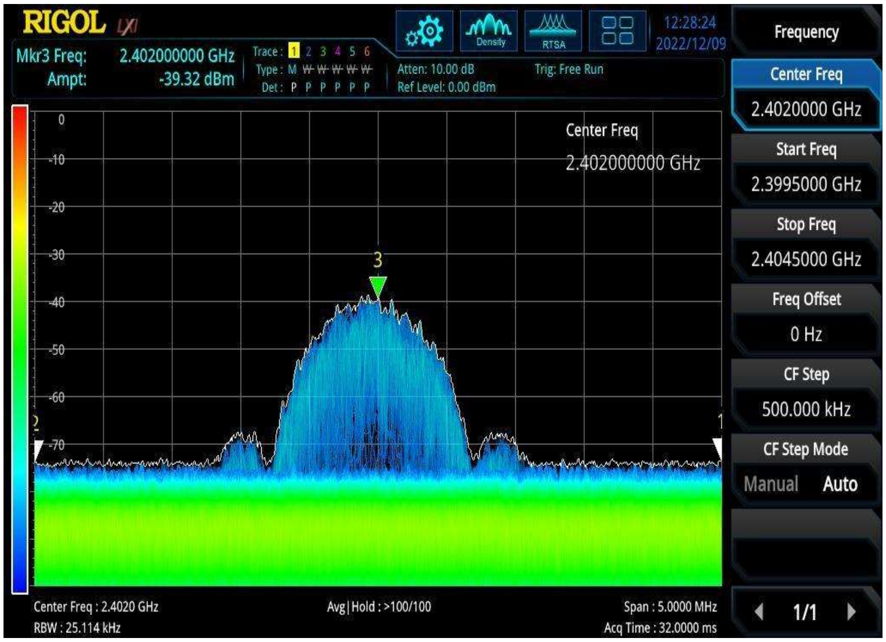

Figure 35 – Channel 37 Area Transmitter Broadcast

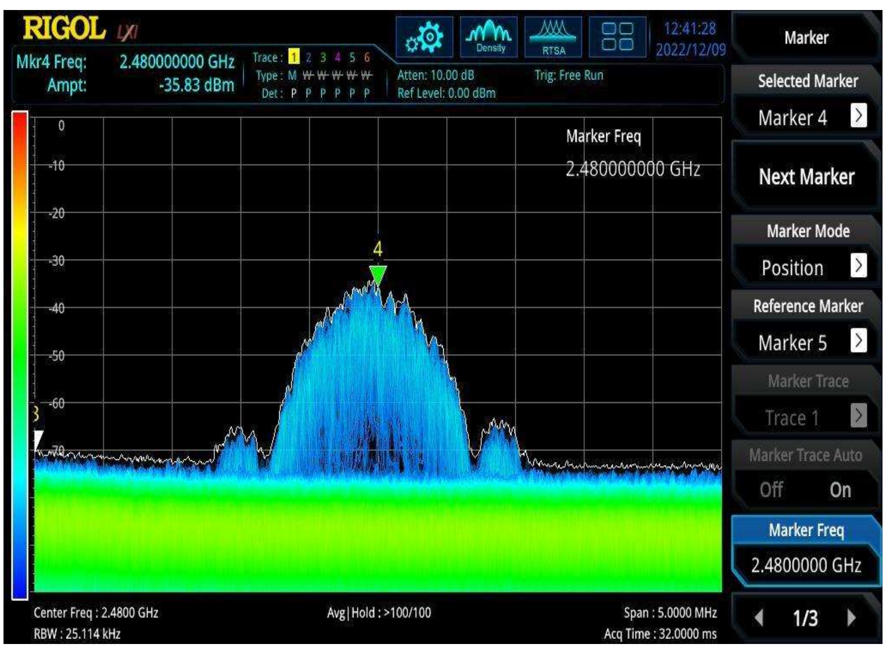

Figure 36 - Channel 39 Area Transmitter Broadcast

Figure 37 - Channel 38 Area Transmitter Broadcast and Chip Timing

These transmissions also alternate in power with three power states on the three broadcast channels (37, 38, 39). The low state recorded below is -34.5 dBm on Channel 37, the mid-state value is -32.5 dBm (+2 dB increase) on Channel 38, and the highest power state is -30 dBm (+2.5 dB increase) on Channel 39. These values were taken from an Ellysis BLE test device that measures transmission power in 0.5 dB steps. These steps may vary slightly. Of note, however, is the cyclic nature of the transmission power that appears consistent, as seen in Figure 37.

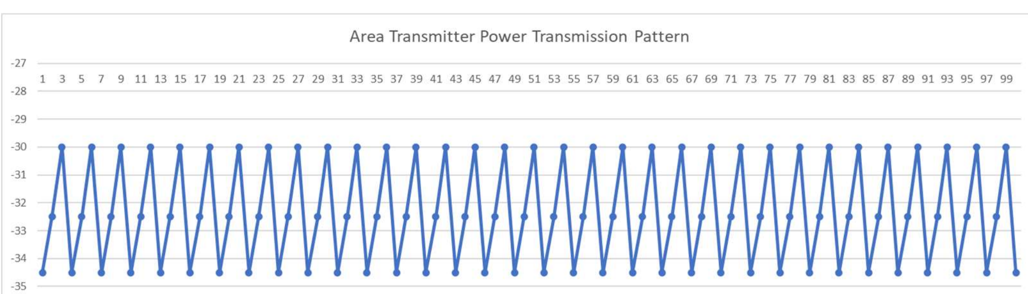

Figure 38 - Area Transmitter Power Cycle

Figure 38 shows a more consistent signal at approximately a 55% duty cycle on BLE channel 10. These signals appear to be transmissions of 47 ms at a logic high and 37 ms at a logic low state, as seen in Figure 39. This transmission is not compliant with BLE protocols. The purpose of this channel appears to be to provide significant energy to the Pixels in the area of the transmitter.

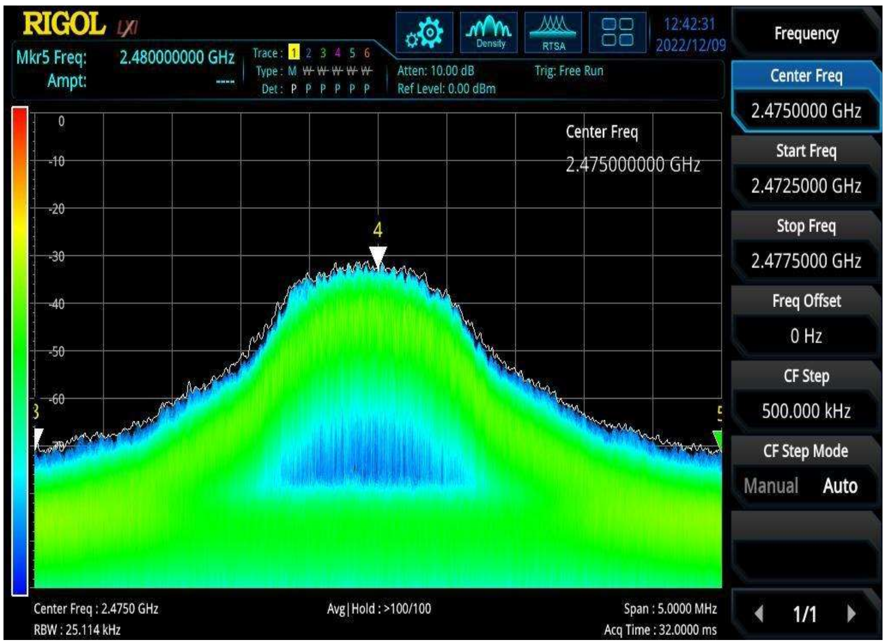

Figure 39 - Channel 10 Area Transmitter Broadcast

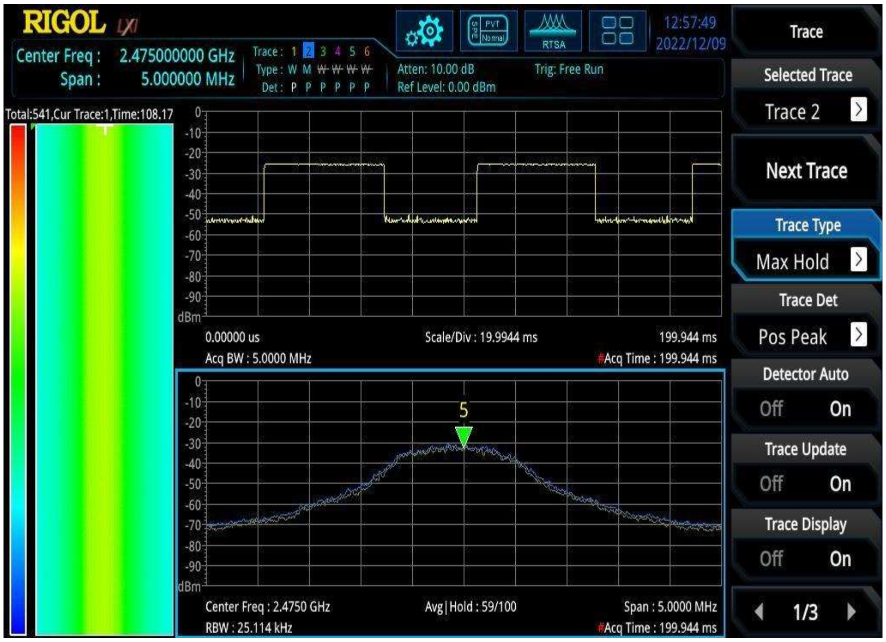

Figure 40 - Channel 10 Area Transmitter and Chip Timing

As previously mentioned, dual-band area transmitters also broadcast within the 900 MHz ISM band. These transmissions are frequency hopping across a band from 917.19375 MHz to 918.768750 MHz. Based on the spectrum analyzer, there appear to be 50 channels in this band approximately 31.5 kHz apart. See Figures 40 and 41 for the minimum and maximum frequencies and the channel hopping behavior. It is believed that these transmissions are also only intended to be RF energy harvesting transmissions for the Pixel devices.

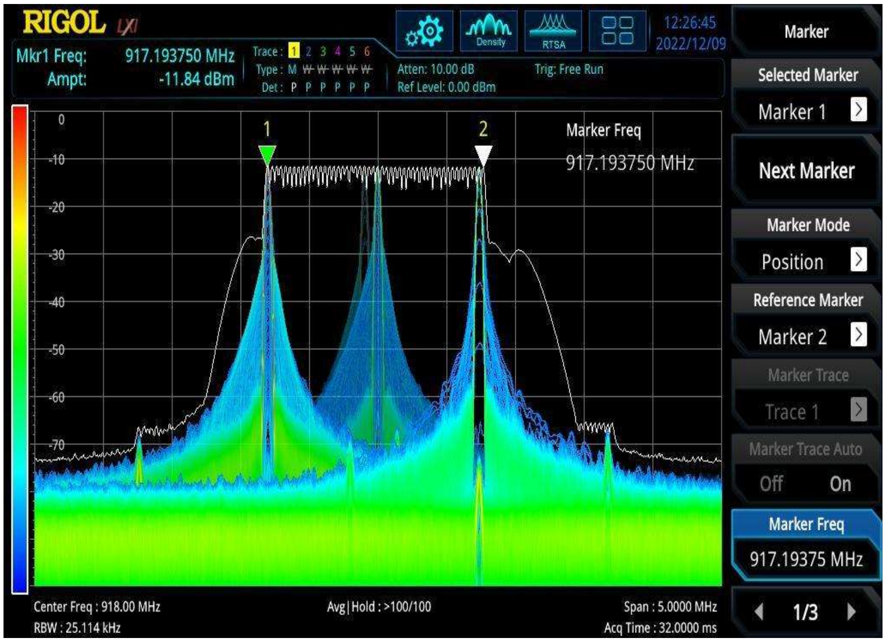

Figure 41 - Image of 900 MHz Low End Area Transmitter

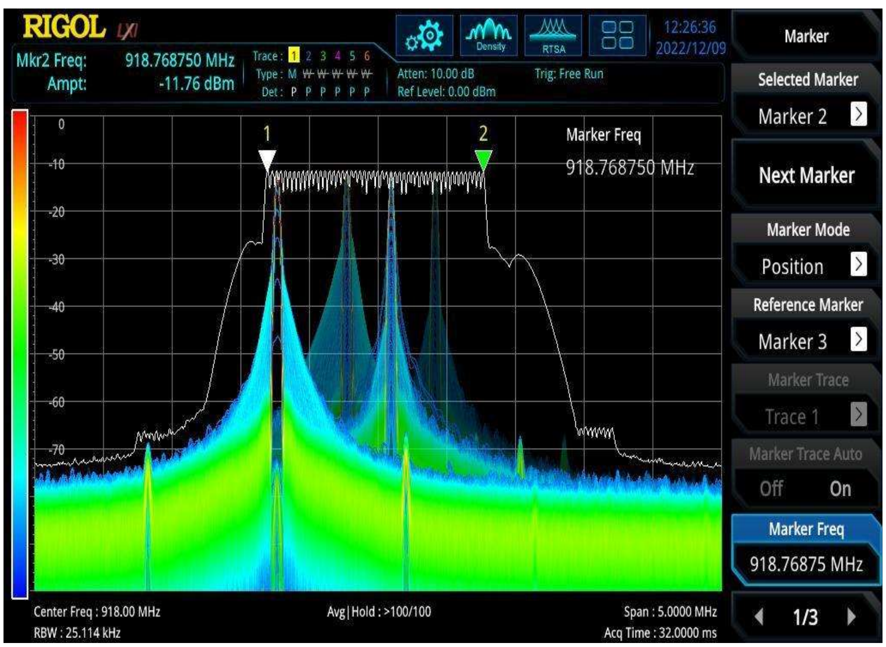

Figure 42 - Image of Frequency High-End Area Transmitter

An analysis of an area transmitter in an anechoic chamber illustrates the horizontal RF propagation pattern at both the 2.4 GHz band and the 900 MHz band. The area transmitter was placed on a battery-powered rotational table for this investigation. The receiver antenna was placed on the horizontal plane of the area transmitter to capture the power levels from a single point as the area transmitter rotated 360°. The distance to the area transmitter was measured to ensure consistency as the device rotated. The test equipment used to capture the power settings was a spectrum analyzer with a power logging function. During initial testing, the spectrum analyzer captured RF signals at different points in the power generation cycle. To overcome this, the device was rotated four times to capture multiple power readings at each radial position. Figure 42 is the test configuration. Figure 43 represents the capture at 2.4 GHz which is illustrated by a horizontal propagation scatter polar plot.

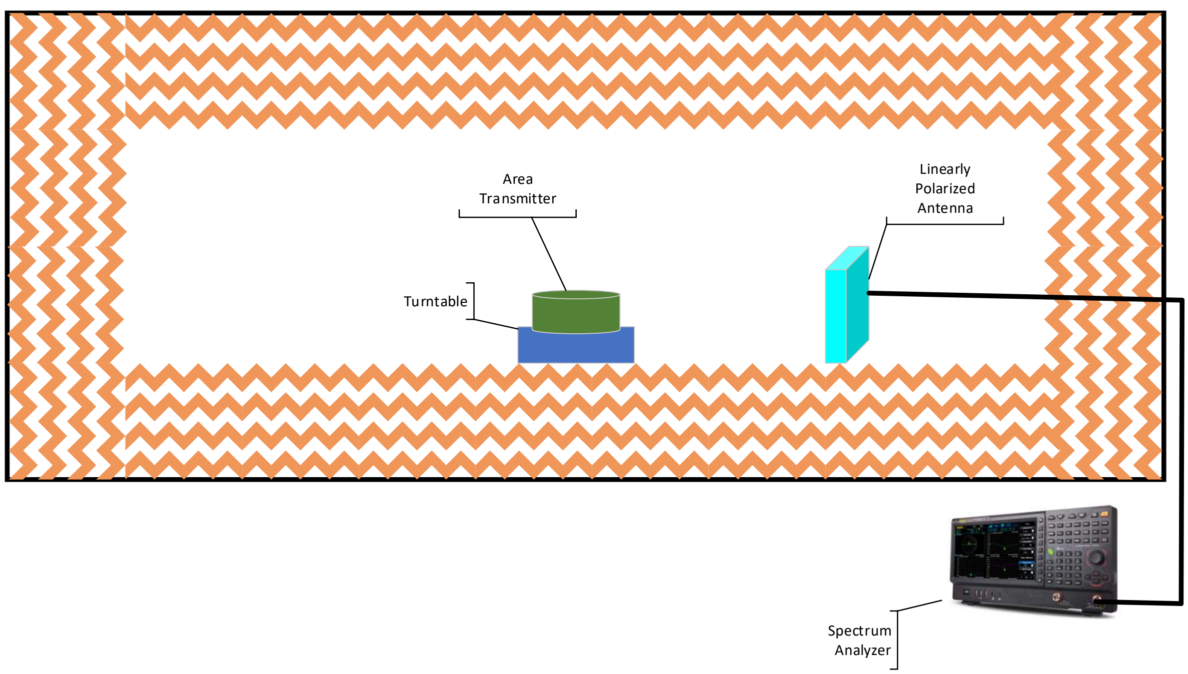

Figure 43 - Rotational Test Configuration for Area Transmitters in Anechoic Chamber

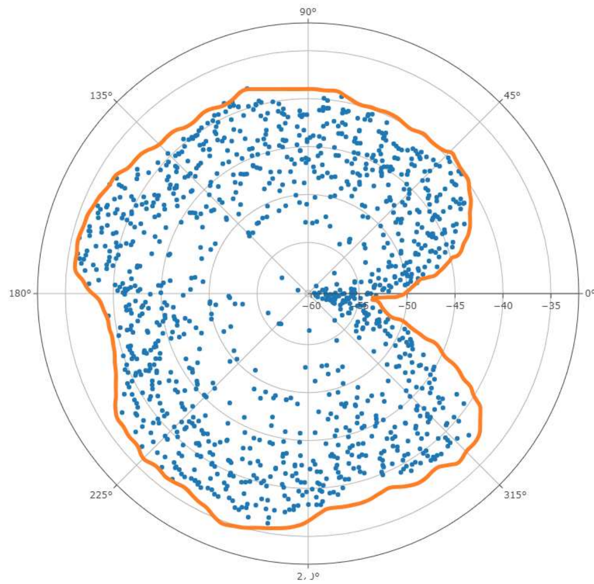

Figure 44 - Horizontal Propagation Pattern of Dual Band Area Transmitter at 2.4 GHz

The 900 MHz broadcast from the area transmitter frequency hops across a 1.535 MHz band on 50 channels, with each having 31.5 kHz separation (refer to Figures 40 and 41 above). The transmission interval is 526 µs.

The single band area transmitter has a propagation pattern, as indicated in Figure 44, illustrating a bidirectional waveform with a null on the right side.

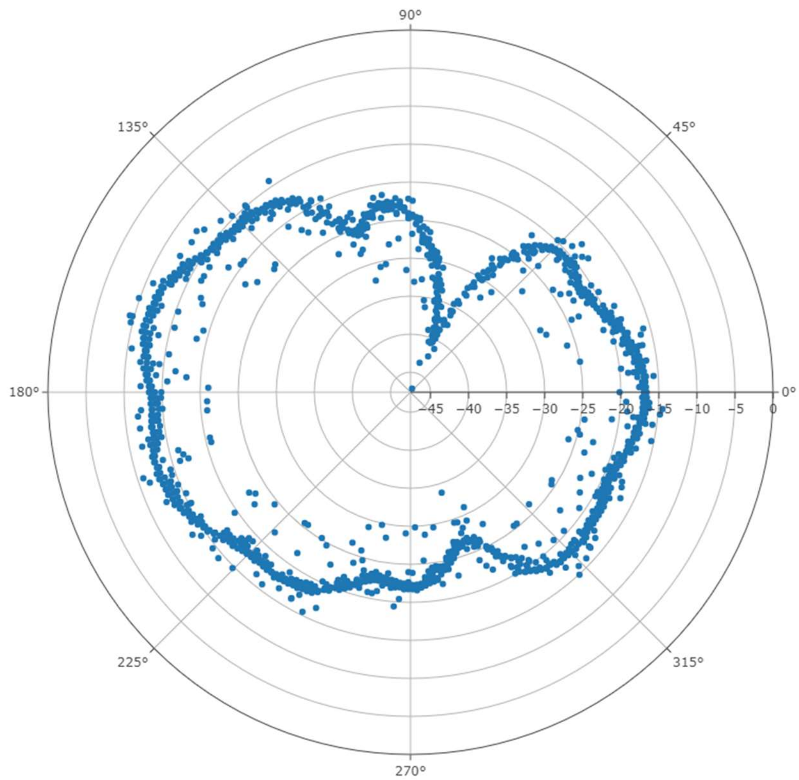

Figure 45 - Single Band Area Transmitter Horizontal Propagation Pattern

IoT Device Density

The 2.4 GHz broadcast from the area transmitter on channels 37, 38, and 39 is approximately 430 uS in duration, as shown in Figure 36. On channel 10, the cycle is significantly longer at approximately 50 ms with an interval of 40 ms. as shown in Figure 39. In a comparison of Figure 36 and Figure 39, note the congestion of channel 10 in the waterfall display on the left side of the real-time spectrum analyzer display.

Since the Wiliot Pixels beacon, according to the Bluetooth specification, much of the capacity discussion has already been addressed under the previous technology discussion. In testing the Pixels, the maximum beacon rate of the area transmitter on channels 37, 38, and 39 is

10 beacons per second or an interval of 0.1 s. This beacon is assumed to be developing energy for the Pixels. This transmission reduces the channel capacity by 1.3%, which minimizes the capacity for beacons from Pixels.

At 1.4 M, the dual-band tag reported 1,244 times over 420 s, equating to a 0.34-s beacon interval. As the Pixel moved away from the area transmitter, the transmission rate reduced significantly to only 38 beacons over 480 s or ~ 12.6 s between beacons. The only area of concern is when more than 769 Pixels are within 1.4 M of the area transmitter, which could swamp the channel at a higher beacon rate. (Refer back to Figures 29 & 30.) This scenario is unlikely in this use case.

RF Reading Range

The RF range of the Pixels is approximately 10 m, according to the device specifications. In testing, the reading range of a was approximately 10 ft (3 M) but was intermittent. The height of the area transmitter seemed to affect the reading range. The test configuration is indicated in Figure 45.

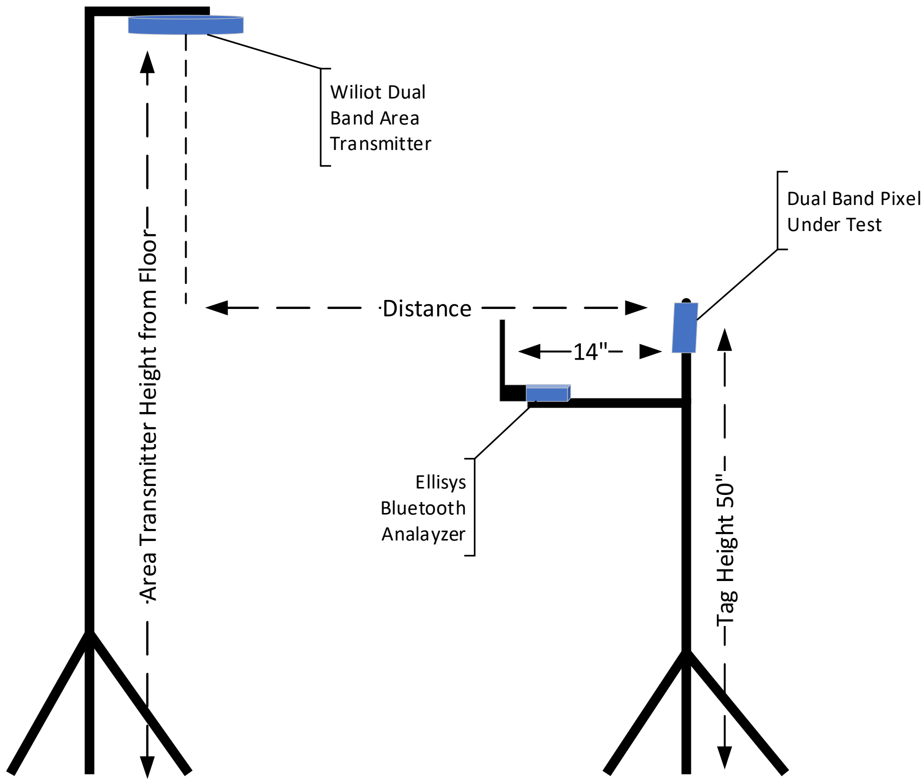

Figure 46 - Wiliot Test Configuration

The initial testing of the Pixel was done with the area transmitter at 94 inches (2.4 M). The Pixel stopped responding at 8 ft (2.4 M). The height of the area transmitter was lowered to 84 and 76 inches, and the Pixels responded at 10 ft (3 M). Figure 46 illustrates the range testing results.

Figure 47 - Range Testing Results

Note that all transmissions from Pixels were on channel 37. Also of interest is that the transmission levels of the Pixel changed with each test. The best transmission range with the area transmitter at 94 inches high was at a 5 ft distance. The transmission energy received at 9 ft and the area transmitter at 76 inches yielded the highest RSSI. Also of note is that there were no responses from the Pixel at 6 or 8-ft distance, as seen in Figures 47 and 48.

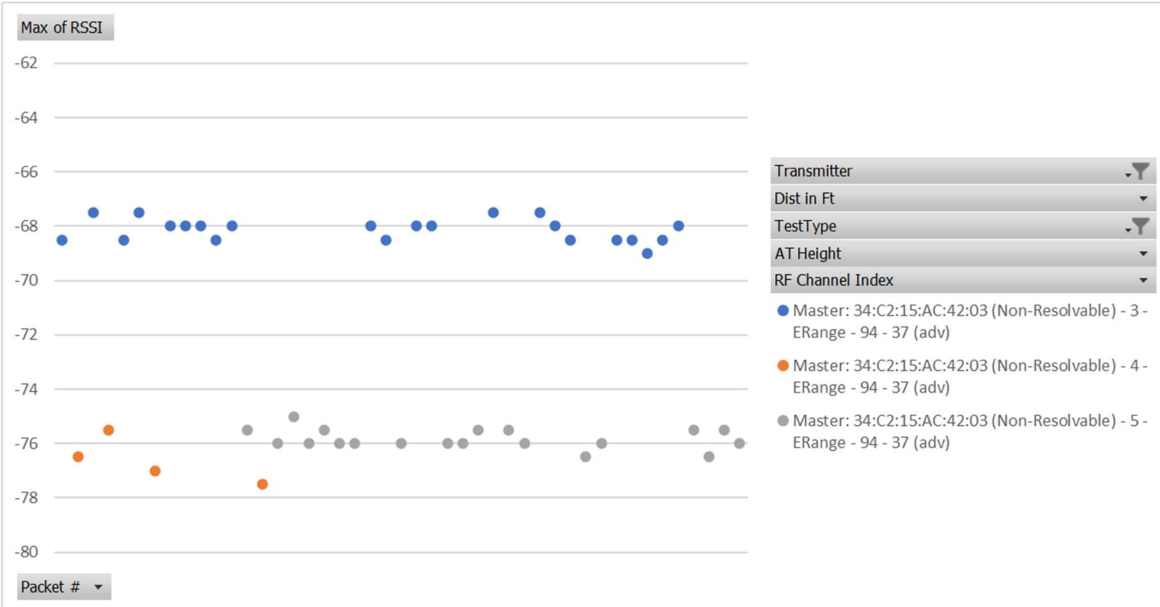

Figure 48 - RSSI at Distance Received by Ellisys BLE Analyzer

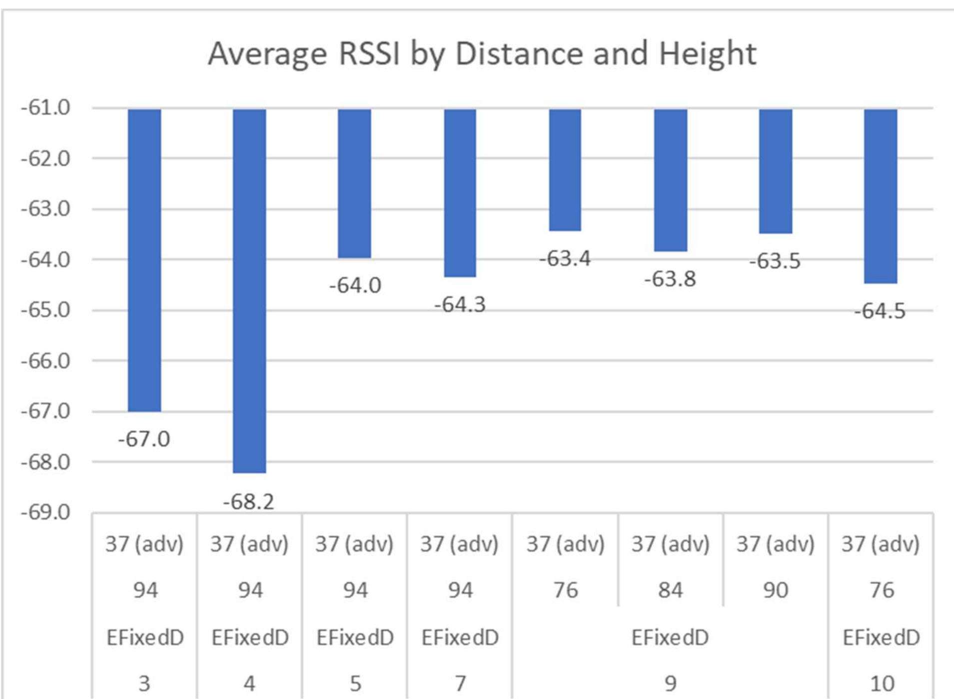

Figure 49 - Pixel RF Transmissions (37, 38, and 39)

The distance had the most effect when addressing the number of transmissions at each distance and height. Again, note that there were no received transmissions at 6 or 8-ft distances, as seen in Figure 49.

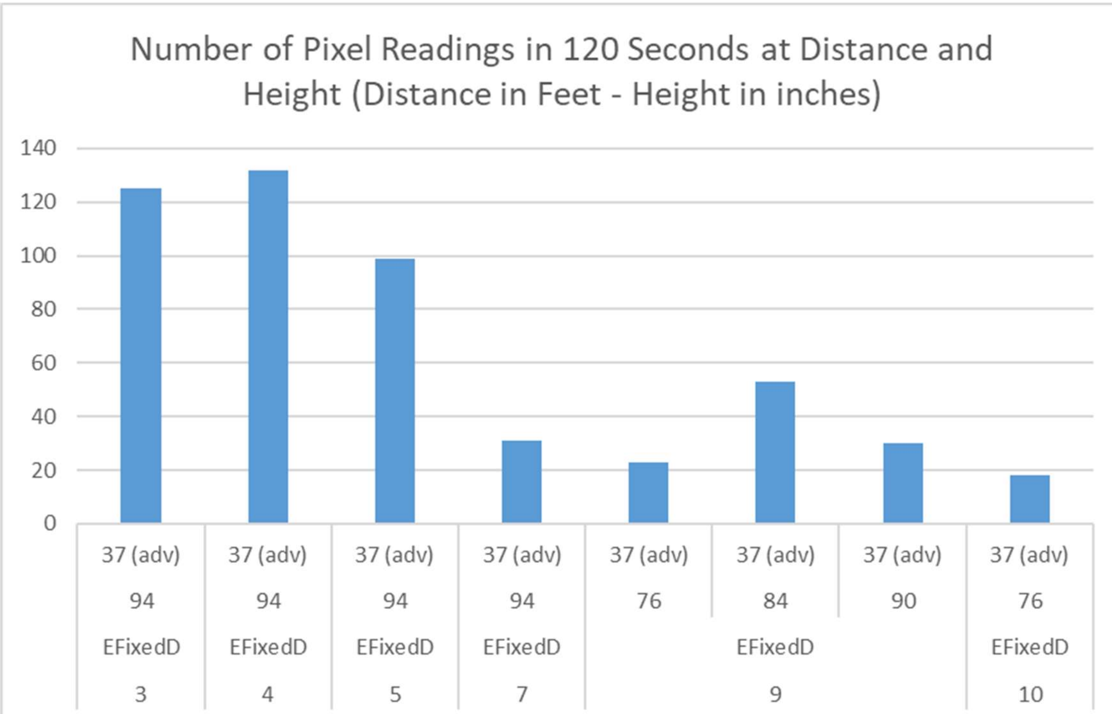

Figure 50 - Pixel RF Transmissions by Distance and Height

In another evaluation of the Wiliot system, two Pixels were placed in an anechoic chamber, and an area transmitter was placed horizontally to the Pixels at various distances. An Ellysis Bluetooth Analyzer was kept at the same distance from the Pixels (27 inches). The area transmitter was moved away from the Pixels at 7-in. intervals until the Pixels no longer responded. See Figure 50 for the test configuration.

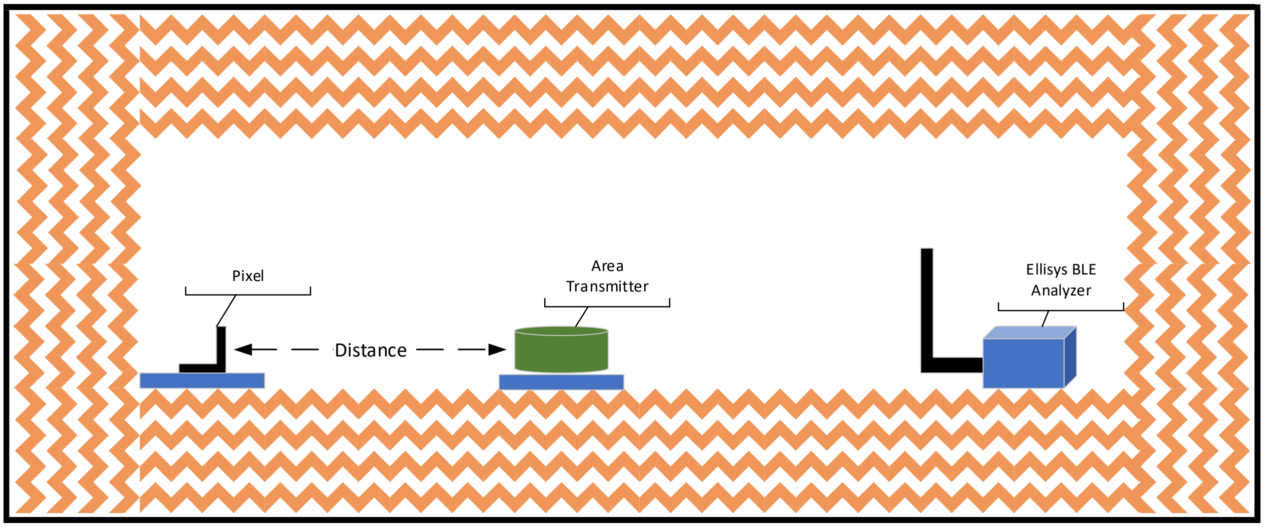

Figure 51 - Pixel Response Test in Anechoic Chamber

The results indicated that a combination of a dual-band pixel and a dual-band area transmitter performed the best. As the Pixel to area transmitter distance increases, the number of transmissions from the pixel decreases. At the shortest distance (7 inches) with a dual-band area transmitter, the 900 MHz transmission appears to apply too much power, presumably swamping the Pixel's RF front end. There is a much better response at 7 inches with a single-band area transmitter and a dual-band Pixel. See Figure 51 for the results.

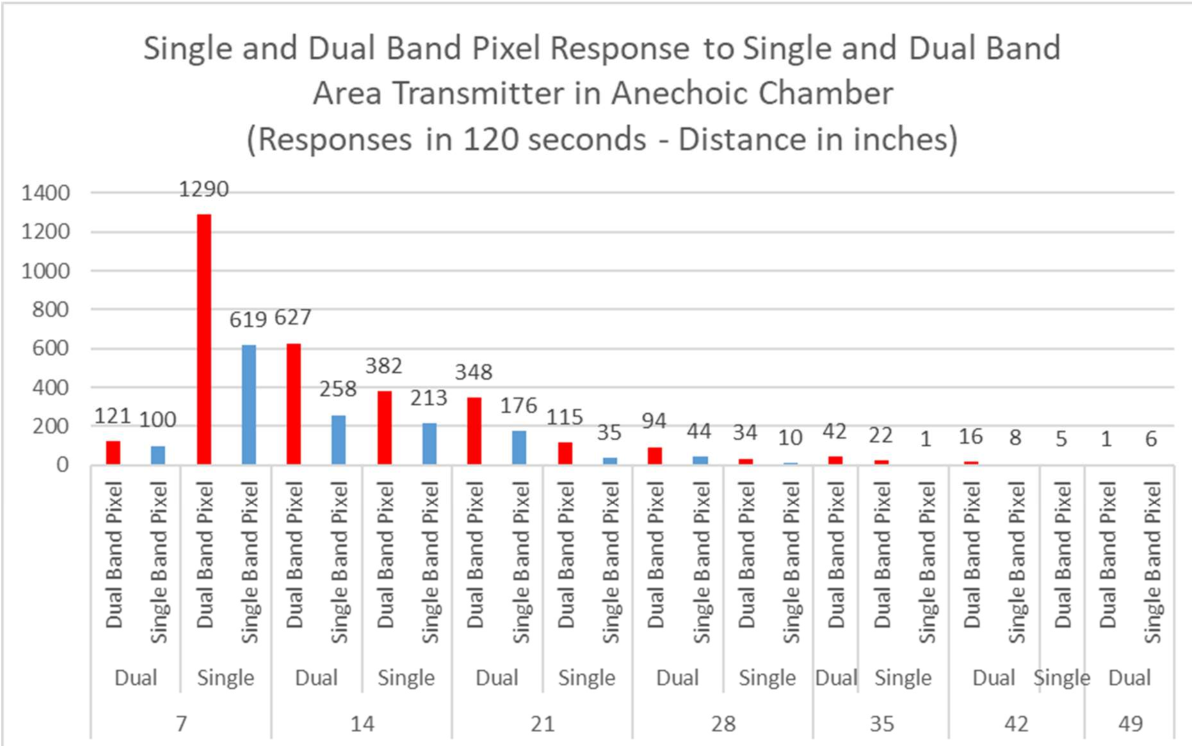

Figure 52 - Pixel Response Testing

The link budget for a single band pixel and single band area transmitter sets the baseline for a Wiliot system. The following calculations assume a reasonable behavior of 2 beacons per second from the Pixel and 1 watt of energy at 14 inches from the single band area transmitter.

Calculating $\lambda = \frac{299\,792\,458}{242600000} = 0.12357\ meters$. Given λ, the free space loss at 14 inches (0.3556 M) is calculated as $= 20log_{10}\left(\frac{4\pi 0.3556}{0.12357}\right) = 31.17\ dB$. Considering the maximum power transmitted by the area transmitter is +30 dBm, the power on the Pixel, in this case, is 30 dBm-(-31.17 dBm) = -1.17 dBm. This is the energy harvesting path.

The return path from the Pixel to the Ellisys BLE analyzer is dependent on the RF energy from the area transmitter, but the Pixel stores energy until it has enough to trigger a transmission.

Therefore, the return path is pseudo-independent. The RF energy determines the Pixel beacon rate from the area transmitter, but the energy developed by the Pixel is reasonably consistent because of the power storage and beacon triggering mechanism. The Pixel does not transmit unless it has enough stored energy.

Given this constraint, the Pixel's transmission power is calculated from previous testing (Figure 26), where the average received power was ~ -68 at 1.44 M (1.44 M is the hypotenuse of the right triangle developed by .9144 M (36") distance and 1.117 M (44") height difference). The free space loss is $= 20log_{10}\left(\frac{4\pi 0.3556}{0.12357}\right) = 31.17\ dB$. Given the energy received at the analyzer with a directly connected unity gain antenna, the energy from the Pixel is approximately -68 dBm – (-43.31 dB) = - 15 dBm or 0.03 mW.

For the dual band tag and area transmitter, the behavior of the Pixel is approximately double the number of beacons. The addition of the 900 MHz signal tends to illustrate an increase of 6 dB. This is derived by using the values from Figure 30 for a single-band Pixel/single-band area transmitter at 7 inches and comparing it to a dual-band Pixel/dual-band area transmitter at 14 inches with a nearly equivalent beacon rate. The free space loss of single/single combination is $= 20log_{10}\left(\frac{4\pi 0.1778}{0.12357}\right) = 25.14\ dBm$ while the free space loss of the double/double combination is $= 20log_{10}\left(\frac{4\pi 0.3556}{0.12357}\right) = 31.17\ dB$. The difference is approximately 6dB. Assuming this, the power on the Pixel is approximately +5d Bm (-1.17 dBm from earlier single band harvesting path discussion added to 6 dBm).

The parameters for passive BLE tags fall into the same constraints as the aforementioned BLE beacon technology. However, because the area transmitter consumes 1.3% of the available bandwidth, the channel's capacity also reduces slightly. The beacon rate is variable and depends on the tag's proximity to the area transmitter and the capture of the beacon at the gateway creating several variables in the capacity discussion. The maximum reading range of the Pixel appears to be approximately 10 ft (3 m).

Isolation at Mantrap

Osama Ata's (Ata, 2017) path loss through materials research is applied with interior gypsum walls with an air gap providing 8 dB of loss and an interior brick wall providing 14.4 dB loss, both at 2.447 GHz. The resulting link budget below indicates enough loss for proper isolation between adjacent rooms.

$$-130.15\ dBm = -70 + 0 - 0 - 60.15 - 2 + 3 - 1$$

Tamper, Security, Resilience, Encoding, Printing

Security with the Wiliot system is very good and proprietary to Wiliot. The messages from the Pixel are encrypted and forwarded to a Wiliot cloud server service that decrypts the messages. The Wiliot system is closed, where Pixels can only communicate with a single cloud service. Once the information is gathered in the cloud, data is exchanged with business servers at the Wiliot customer location.

At the time of this study, only one company is making an option for printing on the surface of Wiliot Pixels. Sato, a leading printer company for the RFID market, is in the process of designing a printer that prints human-readable information on the front of the Pixel, associates an asset to the Pixel, tests the Pixel for proper operations, and updates the centralized Wiliot database of the association and the activation of a Pixel. The Pixel does not have on-device memory that can be programmed.

Because of the lack of onboard memory, the Pixel cannot support a wireless level of resilience when there is not an internet connection; however, if there is printing on the surface of the Pixel, it may still allow for some level of resiliency by human sorting and machine sorting by a barcode.

IoT Device Cost per Bag

Wiliot Pixels are single-use disposable IoT devices that cost between $0.10 to $0.75 each. The price is affected by the quantity of the product purchased and the single or dual-frequency band wireless harvesting option. Wiliot has released a battery-assisted tag that can beacon without an area transmitter. The battery is printed and expected to beacon information for two years. The cost for the battery-assisted Pixel is approximately $2 each. The single-band Pixel cannot work for this use case.

Passive RFID

Technology Overview

Passive RFID tags require an interrogator (also called a reader) to inventory, read, and write memory locations within the tag. When outside of the reading range of a reader, the tag is idle and has no energy from which to operate. A tag within the read range of a reader must harvest enough energy from the reader to respond to the reader's commands. The amount of required energy varies by tag antenna design and the corresponding RFID chip specifications.

The response from the tag is called “backscatter,” which means the RFID tag utilizes the RF energy from the reader to encode and respond to the reflection of that energy back to the reader. Figure 52 illustrates the communications for an inventory cycle.

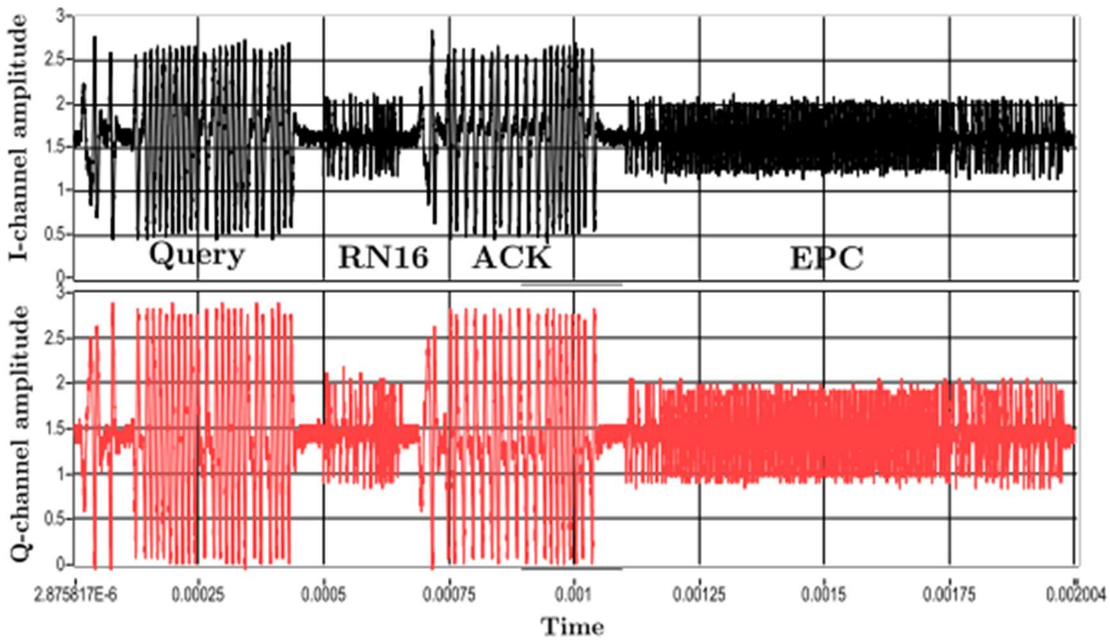

Figure 53 - RFID Inventory Cycle

Note: *Borisenko, A., Bolic, M., & Rostamian, M. (2013). Intercepting UHF RFID signals through synchronous detection. Eurasip Journal on Wireless Communications and Networking, 2013(1), 6.* [*https://doi.org/10.1186/1687-1499-2013-214*](https://doi.org/10.1186/1687-1499-2013-214)

RFID tags have three prominent memory locations, tag identification (TID), electronic product code (EPC), and user memory. The TID is permanent and not changeable. The GS1 standards body issues TIDs to chip manufacturers. These are written to the chip during the manufacturing process. The EPC memory is user configurable and varies in size based on the chip manufacturer. EPC is where a manufacturer can store a part or stock number to quickly inventory products in a warehouse. EPC is not limited to stock numbers but may be used for any customer-specific storage, such as serial numbers, unique identifiers, and asset identifiers (e.g., a vehicle license plate).

The resilience requirement above requires the basic manifest information to be stored within the IoT traceability device. In the case of RFID, this requirement demands a large EPC memory area of the tag. The manifest information stored on the tag comprises the BagID and the endpoint of the bag. The BagID is the same value as the barcode on the bag. The endpoint is the identifier of the final destination for the bag. The final destination of a deposit bag from a customer is the customer's bank. The final destination of a change order is the customer location.

According to the GS-1 specification, the BagID could also be referred to as the SSCC and the endpoint as the GLN (GS-1, 2020). The GS-1 specification does not identify a maximum number of characters for the SSCC. Still, from observation and database analysis, the United States Postal Service uses the longest SSCC, composed of 30 characters. The SSCC may contain letters, numbers, and a small number of special characters (e.g., period, dash, comma). Given these requirements, 7-bit ASCII may be used. Given 7-bit ASCII and the maximum BagID/SSCC of 30 characters, the memory required for this field is 210 bits of data. Table 19 contains the definition of alphanumeric characters with 7-bit ASCII (Montante, n.d.).

Table 19 - 7 Bit ASCII Table

Decimal	**Hex**	**ASCII**	**Decimal**	**Hex**	**ASCII**	**Decimal**	**Hex**	**ASCII**	**Decimal**	**Hex**	**ASCII**
0	00	*Ctrl*- @	32	20	sp	64	40	@	96	60	`
1	01	*Ctrl*- A	33	21	!	65	41	A	97	61	a
2	02	*Ctrl*- B	34	22	"	66	42	B	98	62	b
3	03	*Ctrl*- C	35	23	#	67	43	C	99	63	c
4	04	*Ctrl*- D	36	24	$	68	44	D	100	64	d
5	05	*Ctrl*- E	37	25	%	69	45	E	101	65	e
6	06	*Ctrl*- F	38	26	&	70	46	F	102	66	f
7	07	*Ctrl*- G	39	27	'	71	47	G	103	67	g
8	08	*Ctrl*- H	40	28	(	72	48	H	104	68	h
9	09	*Ctrl*- I	41	29	)	73	49	I	105	69	i
10	0a	*Ctrl*- J	42	2a	*	74	4a	J	106	6a	j
11	0b	*Ctrl*- K	43	2b	+	75	4b	K	107	6b	k
12	0c	*Ctrl*- L	44	2c	,	76	4c	L	108	6c	l
13	0d	*Ctrl*- M	45	2d	-	77	4d	M	109	6d	m
14	0e	*Ctrl*- N	46	2e	.	78	4e	N	110	6e	n
15	0f	*Ctrl*- O	47	2f	/	79	4f	O	111	6f	o
16	10	*Ctrl*- P	48	30	0	80	50	P	112	70	p
17	11	*Ctrl*- Q	49	31	1	81	51	Q	113	71	q
18	12	*Ctrl*- R	50	32	2	82	52	R	114	72	r
19	13	*Ctrl*- S	51	33	3	83	53	S	115	73	s
20	14	*Ctrl*- T	52	34	4	84	54	T	116	74	t
21	15	*Ctrl*- U	53	35	5	85	55	U	117	75	u
22	16	*Ctrl*- V	54	36	6	86	56	V	118	76	v
23	17	*Ctrl*- W	55	37	7	87	57	W	119	77	w
24	18	*Ctrl*- X	56	38	8	88	58	X	120	78	x
25	19	*Ctrl*- Y	57	39	9	89	59	Y	121	79	y
26	1a	*Ctrl*- Z	58	3a	:	90	5a	Z	122	7a	z
27	1b	*Ctrl*- [	59	3b	;	91	5b	[	123	7b	{
28	1c	*Ctrl*- \	60	3c	<	92	5c	\	124	7c	|
29	1d	*Ctrl*-]	61	3d	=	93	5d	]	125	7d	}
30	1e	*Ctrl*- ^	62	3e	>	94	5e	^	126	7e	~
31	1f	*Ctrl*- _	63	3f	?	95	5f	_	127	7f	del

According to the U.S. Guide for Cash Visibility Standards, the endpoint/GLN comprises up to fifteen alphanumeric characters (GS-1, 2020). This adds an additional 105 bits to the EPC storage requirements. Adding a single-character ASCII delimiter of an “:” symbol (7 bits), the total bits required for the EPC memory is 329 bits. Adding CRC-16 error detection, the total is 345 bits/50 characters, as seen in Figure 53.

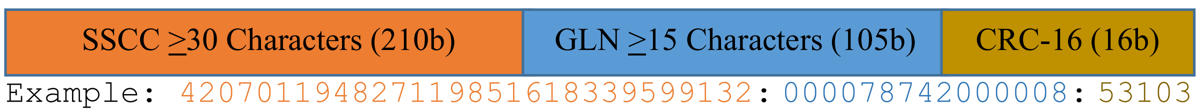

Figure 54 - EPC Memory Allocation and Size Requirements

At the core of the behavior of every RFID tag is the silicone chipset. Each chip has a set of unique characteristics, including its read sensitivity, EPC, and User memory capacity, and has a unique TID header. The read sensitivity affects the link budget significantly. The better the tag's sensitivity, the longer the tag read range is from the reader. Because of the large EPC memory requirement, only a few RFID chipsets can meet the system's requirements. Table 4 represents the list of UHF RFID EPC-Gen2 chipsets on the market. The highlighted chipsets represent the chips with the memory characteristics required for application into the cash visibility system. See Table 20 for a list of available RFID chips.

Table 20 - Available RFID Chips with Features

RFID Chip	Receive Sensitivity	EPC Memory	User Memory	TID Prefix
Alien Higgs 3	-20dBm	96-bit	512-bit	E200 3412
Alien Higgs 9	-22.5dBm	96/496-bit	Up to 688-bit	E280 3821
Alien Higgs 4	-20.5dBm	128-bit	128-bit	E200 3414
Alien Higgs EC	-22.5dBm	128-bit	128-bit	E200 3811
Impinj Monza 4D	-19.5dBm	128-bit	32-bit	E280 1100
Impinj Monza 4i	-19.5dBm	256-bit	480-bit	E280 1114
Impinj Monza 4QT	-19.5dBm	128-bit	512-bit	E280 1105
Impinj Monza 5	-17.8dBm	128-bit	32-bit	E280 1130
Impinj Monza R6-B	-22.1dBm	96-bit	0	E280 1171
Impinj Monza R6	-22.1dBm	96-bit	0	E280 1160
Impinj Monza R6-A	-22.1dBm	96-bit	0	E280 1171
Impinj Monza R6P	-22.1dBm	96/128-bit	64/32-bit	E280 1170
Impinj Monza M730	-24dBm	128-bit	0	E280 1191
Impinj Monza M750	-24dBm	96-bit	32-bit	E280 1190
Impinj Monza M770	-24dBm	128-bit	32-bit	E280 11A0
Impinj Monza M775	-24dBm	128-bit	32-bit	New
Impinj Monza M780	-23.5dBm	496-bit	128-bit	New
Impinj Monza M781	-23.5dBm	128-bit	512-bit	New
Impinj Monza 4E	-19.5dBm	Up to 496-bit	128-bit	E280 110C
NXP G3iM	17.5dBm	256-bit	512-bit	E280 680A
NXP UCODE 7	-20dBm	128-bit	0	E280 6810
NXP UCODE 7+	-19dBm	448-bit	2K-bit	E280 6D92
NXP UCODE 7XM 1K	-19dBm	448-bit	1K-bit	E280 6D12
NXP UCODE 7XM 2K	-19dBm	448-bit	2K-bit	E280 6F12
NXP UCODE 8	-23dBm	128-bit	0	E280 6894
NXP UCODE 8M	-23dBm	128-bit	0	E280 6895
NXP UCODE 9	-20dBm	96-bit	0	E280 6995
NXP UCODE DNA	-19dBm	224-bit	3K-bit	E2C0 6892
NXP UCODE G2iM	-17.5dBm	256-bit	320/640-bit	E200 680A
NXP UCODE G2iM+	-17.5dBm	448-bit	512-bit	E200 680B
NXP UCODE G2il	-17.5dBm	128-bit	0	E200 6806
NXP UCODE G2il+	-17.5dBm	128-bit	0	E200 6807

Beyond the chipset, the tag consists of an inlay, label material, and adhesives. The inlay contains the chosen chipset and an antenna. Depending on the RFID tag's intended use, the inlay antenna can improve or degrade the tag's behavior. In this use case, the tag design is also constrained by the information to be printed on the surface of the RFID label material. The size of the overall tag should be no greater than 4 inches wide and 2 inches tall. The armored couriers recommend the smallest possible tag to reduce bag tampering (e.g., a person cutting the bag to remove some cash and then resealing it with the RFID tag).

RFID inlays come in a variety of sizes and shapes. When RFID antennas are designed, a great deal of testing is done to ensure the tag performs well in various applications. RFID tags may also be affected by the surface on which they are applied. A tag may slightly change frequencies when applied to glass, rubber, plastic, or paper. Unique tags are created for placement on metal objects. For cash visibility, RFID tags are applied to a plastic cash bag.

IoT Device Density

The first element of passive RFID is the PIE (pulse-interval encoding) method which is an asymmetrical binary transmission mechanism where the “0” symbol and the “1” symbol have different durations. The “0” symbol duration is equal to a “Tari.” A Tari is the reference interval for reader-to-tag signaling. The “1” symbol is between 1.5 and 2.0 Tari in duration. See Figure 54 from the GS-1 EPC Gen-2 standard (GS-1, 2018). The difference in the length of the “0” and “1” prevent the accurate measurement of an exact data rate, so data rates are discussed as “effective data rates.”

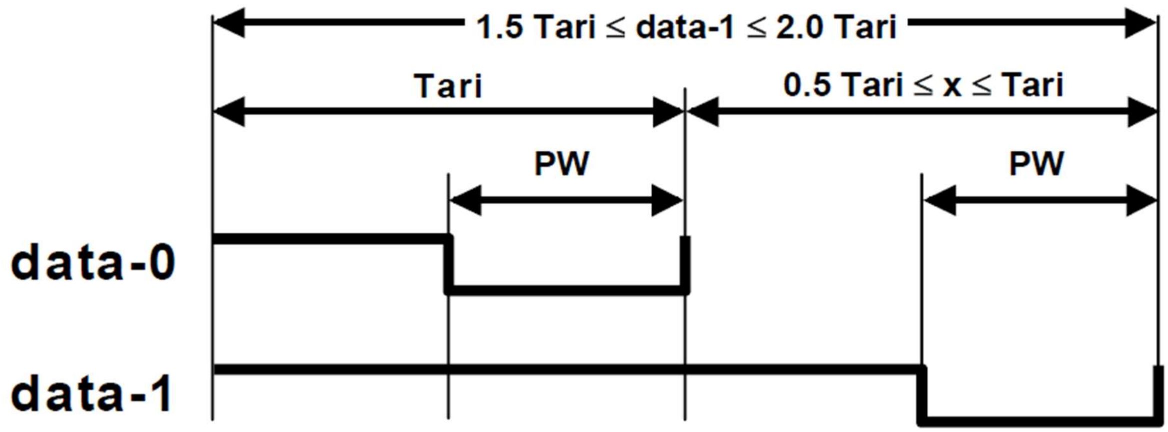

Figure 55 - PIE Methodology

Note: Taken from GS-1. (2018). EPC™ RFID Protocols Generation-2 UHF RFID Standard.pdf, 22.

In addition, a Tari may range from 6.25 µs to 25 µs in duration. As in most communications methodologies, reducing the symbol rate also reduces the RF range of the signal because the bit error rate (BER) increases. The choice of the Tari affects the number of timeslots for tags to respond to reader commands. A minimum Tari of 6.25 µs increases system capacity but also reduces RF range.

An important note to consider in the explanation is that RFID tags are required to operate at all Tari values and can, therefore, communicate with one reader using a very high-speed symbol rate and a different reader in another area at a lower speed symbol rate. This flexibility of the tags allows for a wide range of uses for the same tag. For instance, a tag is printed, tested, and encoded in an RFID printer (short range, low power, high speed), attached to an item, and tested with a handheld (mid-range, mid power, low speed), taken through an RFID portal/chokepoint (mid-range, high power, high speed), and then read in a large area using an RTLS reader (long range, high power, low speed).

Having discussed reader-to-tag communications, tag-to-reader communications also have constraints for behavior and modes of communication. RFID tags respond to interrogations from readers with either ASK (amplitude shift keying) or PSK (phase shift keying). All readers are required to be able to demodulate both. This backscatter, synchronized by the reader, has a clocking mechanism called “Backscatter Link Frequency,” or BLF. This clocking has two modes: FM0 and Miller Modulated Subcarrier (MMS).

For both techniques, the range is from 40 kbps to 640 kbps. Typically, FM0 is operated at a higher BLF. MMS intends to be more robust communications than FM0 and increases the number of symbols required to indicate a 1 or 0. MMS requires two, four, or eight times the symbols, increasing the baseband robustness with each increasing step, but conversely decreases the channel bandwidth by half, quarter, or eighth, respectively (GS-1, 2018). FM0 modulation symbols and sequences are illustrated in Figure 55, and MMS modulation sequences are illustrated in Figure 56.

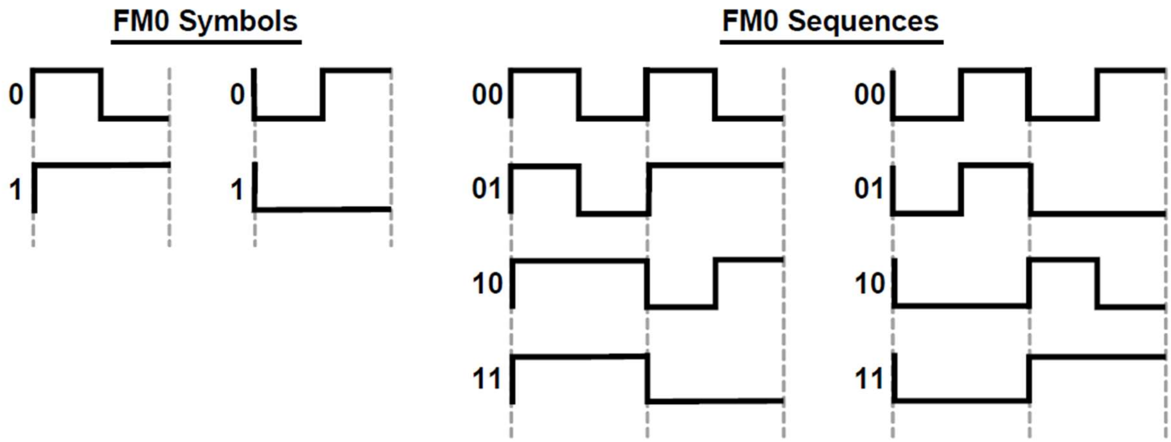

Figure 56 - FM0 Symbols and Sequences

Note: Taken from GS-1. (2018). EPCTM RFID Protocols Generation-2 UHF RFID Standard.pdf, 28.

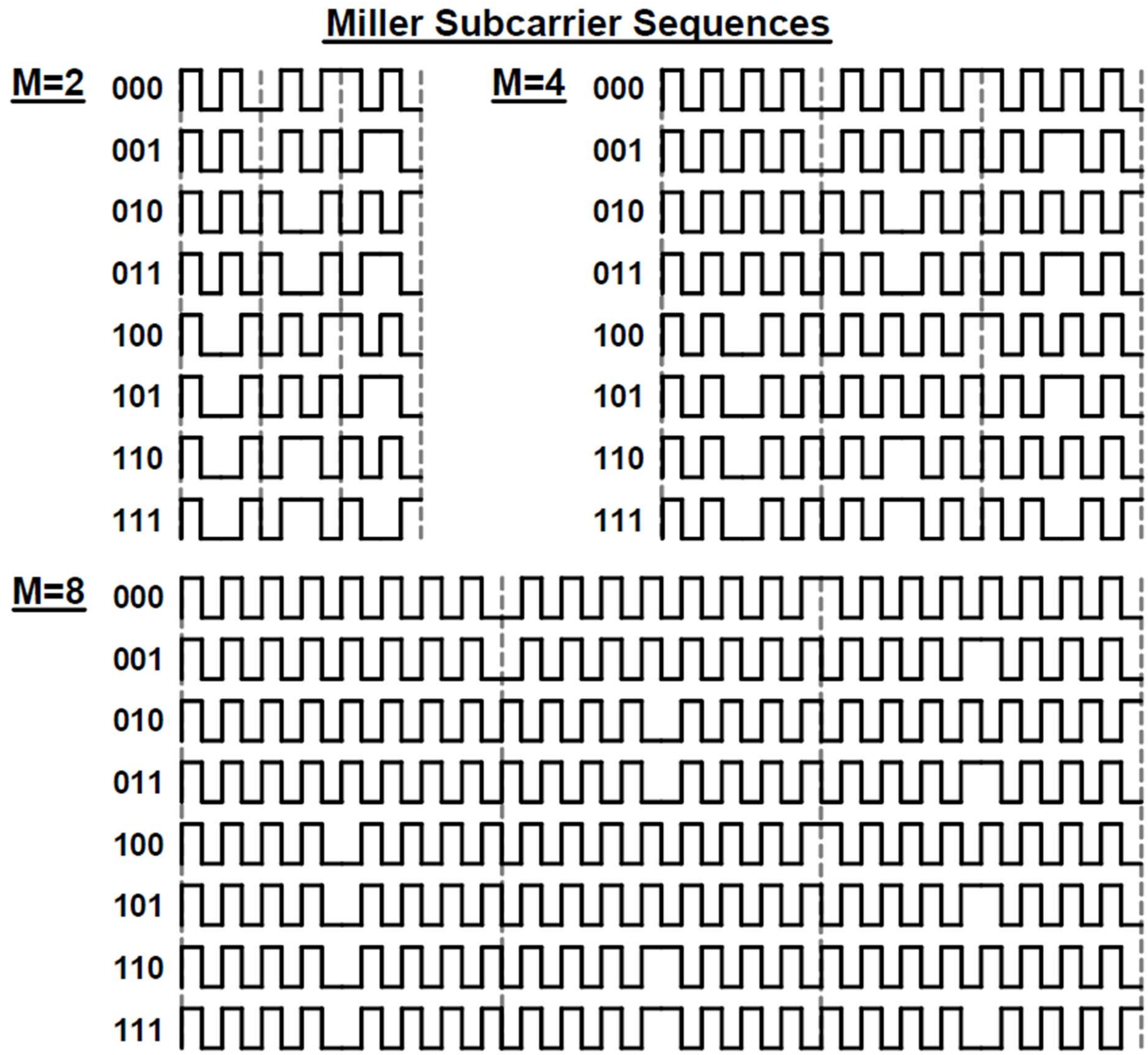

Figure 57 - Miller Modulated Subcarrier Sequences

Note: Taken from GS-1. (2018). EPCTM RFID Protocols Generation-2 UHF RFID Standard.pdf, 30.

A typical transaction, and the transaction applicable to cash traceability, is the inventory command. This command elicits a response from tags in the area receiving enough RF energy to activate and process the command. The response is an RN16 (a 16-bit random or pseudo-random number) that the reader acknowledges. The acknowledgment from the reader elicits a response from the tag, including the data stored in the EPC memory location of the tag. The reader responds with an Req_RN (contains the same RN16), and the tag responds with its handle. The reader responds by verifying the handle, and the communication is completed for that round of the inventory command, as seen in Figure 57.

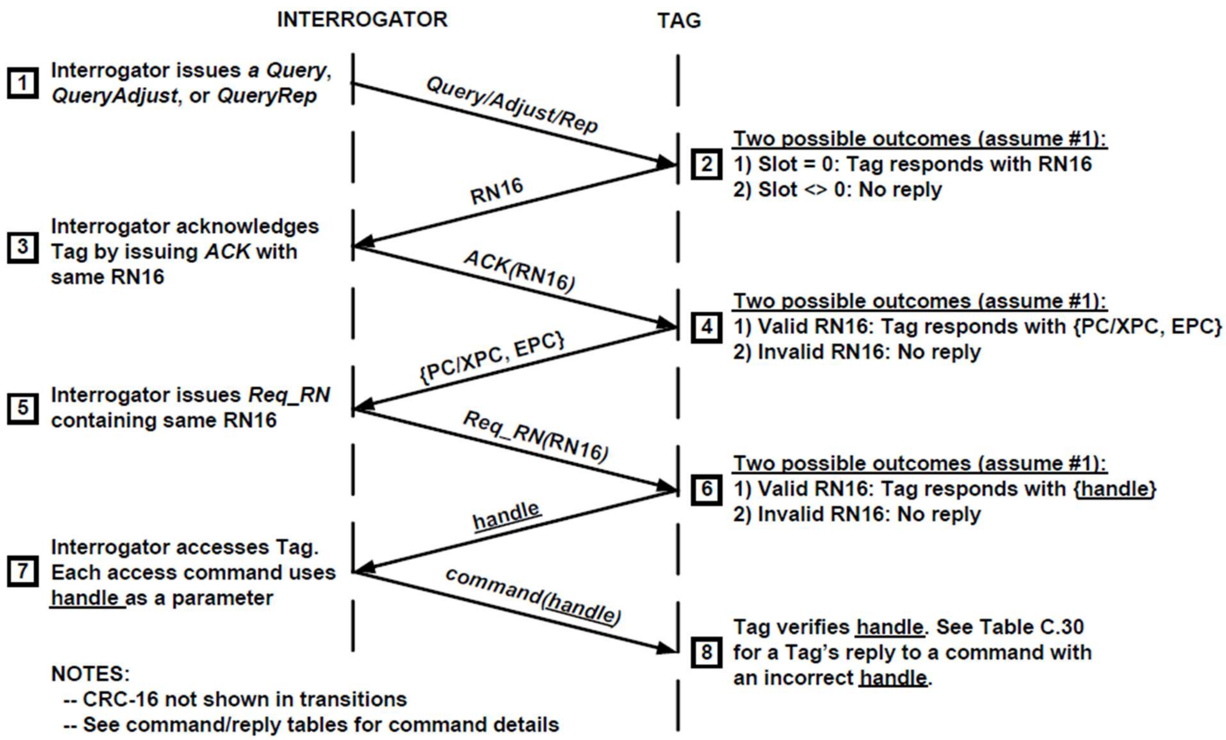

Figure 58 - Reader-Tag Interaction

Note: Taken from GS-1. (2018). EPCTM RFID Protocols Generation-2 UHF RFID Standard.pdf, 142.

Passive RFID systems typically operate with monostatic antennas, meaning that a single antenna is used to transmit a carrier wave (CW) and commands and receive responses from RFID tags. The RFID tag requires CW from the transmitter to harvest power and modulate the backscatter signal to the reader. Figure 58 illustrates the inventory cycle from 26 regarding time and RF usage. Note that the reader maintains CW throughout the entire process, only modulating with commands and responses as necessary for tag interaction.

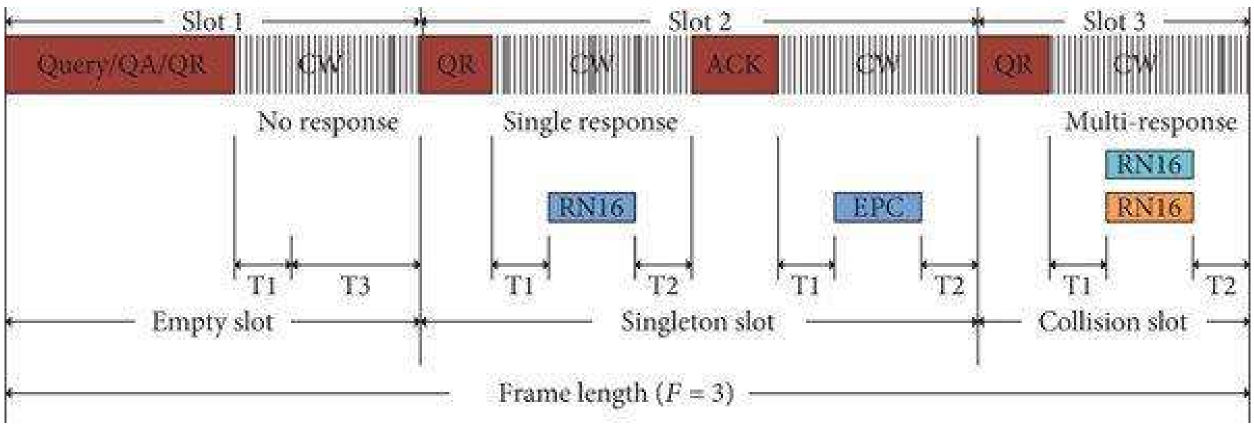

Figure 59 - Reader-Tag Inventory Cycle

Note: Taken from Qian, H. (2021). Research on RFID Anticollision Algorithms in Industrial Internet of Things. Wireless Communications and Mobile Computing, 2021, 3. https://doi.org/10.1155/2021/6883591

The CW transmission of the reader also behaves like a self-jamming signal that challenges the reader's receiver to pick up the response from the tag. The extent to which the RFID reader can employ a self-jamming mitigation system determines the overall sensitivity of the RFID reader. A self-jamming controller (SJC) circuit eliminates the jamming signal from the reader transmission leaving only the received signal from the RFID tag for demodulation. Figure 59 shows a typical SJC that inductively couples the transmission signal from the transmitter, identifies the RSSI (received signal strength indicatory) level, and inverts the polarity of the signal to cancel out the transmission jamming signal from the received signal (Zhonghua & Yanfeng, 2019).

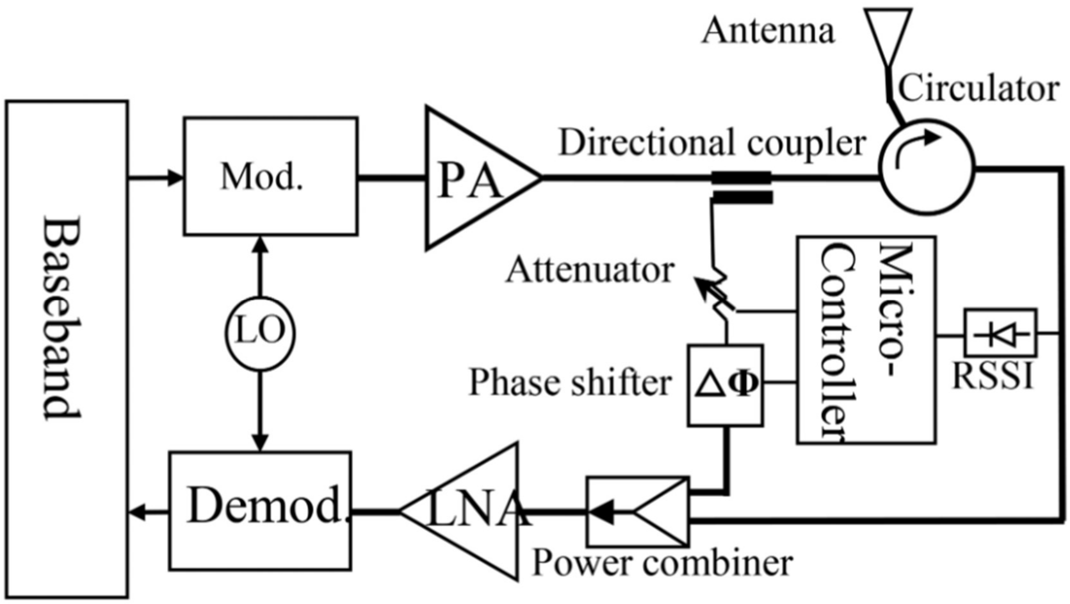

Figure 60 - SJC Circuit Diagram

Note: Taken from Zhonghua, M., & Yanfeng, J. (2019). Carrier extraction cancellation circuit in RFID reader for improving the Tx-To-Rx isolation. IET Circuits, Devices and Systems, 13(5), 623. [*https://doi.org/10.1049/iet-cds.2018.5317*](https://doi.org/10.1049/iet-cds.2018.5317)

Because of the number of options for timing and the variety of modes in Passive RFID (for a Zebra FX9600, there are 40 combinations for FCC readers [Zebra, 2022]), the published maximum reading rates for several RFID manufacturers were compiled from each manufacturer website in Table 21.

Table 21 - Maximum RFID Tag Read Rates by Manufacturer

Manufacturer	Device	Maximum tags/second
Zebra	RFD8500	900
Zebra	FX9600	1250
Impinj	RFR901	1300
Impinj	R-700	1250
Janam	X2C	700

Impinj compares reader modes to reading rate and receiver sensitivity in Figures 60 and 61. Each mode has a specific application based on the type of installation and the expected quantity of RFID tags. The maximum throughput option is based on the FM0 mode. Dense reader mode is adopted when multiple readers are in the same RF field, increasing the MMS value. The AutoSet options are proprietary Impinj reader modes.

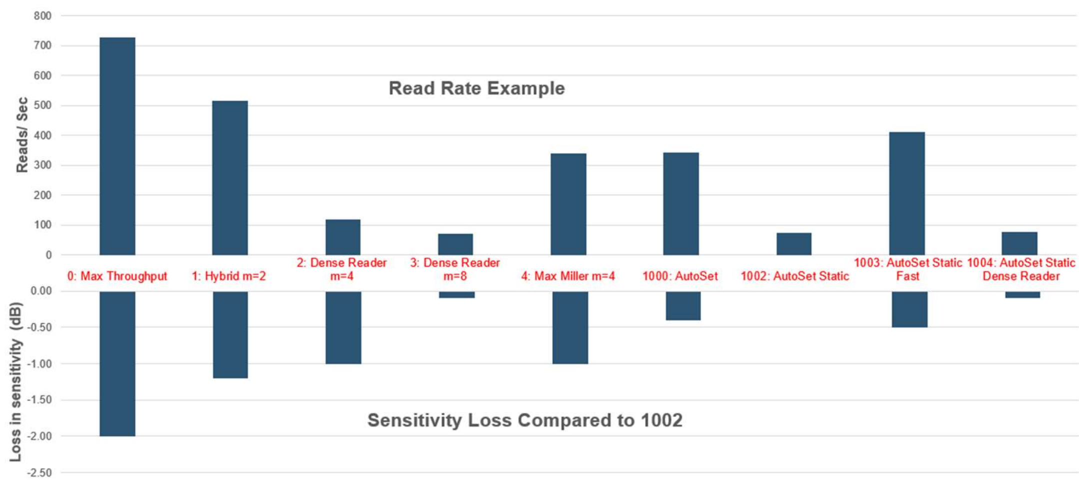

Figure 61 - Impinj Reader Mode Reads/Sec v. Loss in Sensitivity

Note: Taken from Skinner, J. (2022). Reader Modes (RF Modes) Made Easy. [*https://support.impinj.com/hc/en-us/articles/360000046899-Reader-Modes-RF-Modes-Made-Easy*](https://support.impinj.com/hc/en-us/articles/360000046899-Reader-Modes-RF-Modes-Made-Easy)

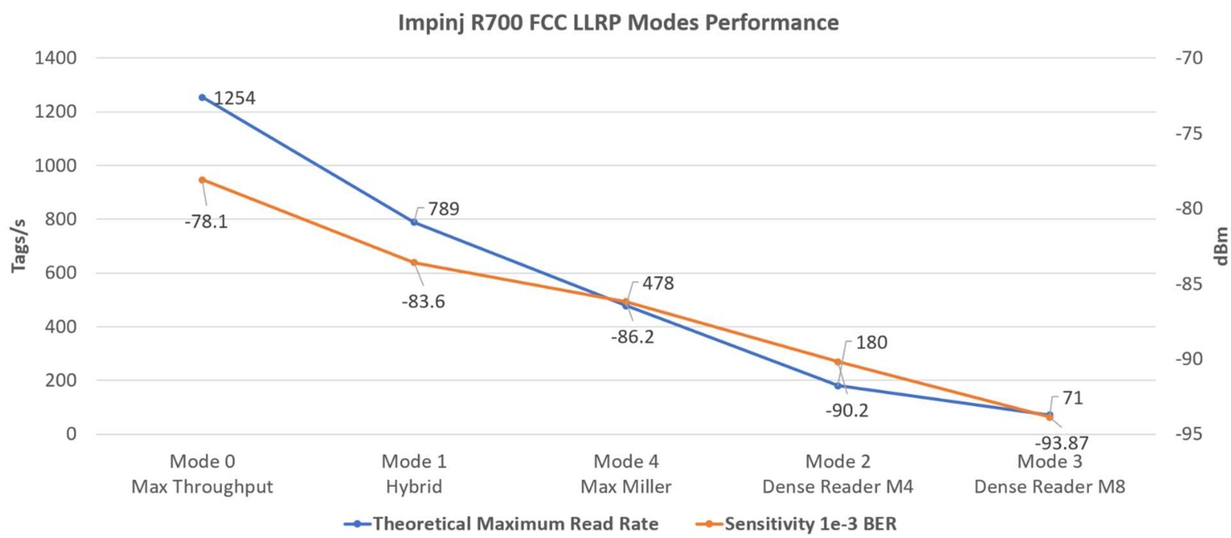

Figure 62 - Impinj R700 Reader Modes Theoretical Maximum by Mode

Note: Taken from Donley, A. (2022). Impinj R700 Reader Modes (RF Modes). https://support.impinj.com/hc/en-us/articles/1500003045181-Impinj-R700-Reader-Modes-RF-Modes-

RF Reading Range

There are several ways to read RFID tags, including handheld readers, fixed location readers, and real-time location system readers (RTLS). Each type of reader has constraints or specific behaviors.

A handheld reader generally has a small directional antenna and limited RF power. They are typically battery-powered and connected to a computing device by Bluetooth or Wi-Fi. These are most commonly used in warehouses or truck gate entry/exit lanes for inventory purposes. The battery life for a handheld reader is typically 8 to 10 hr.

Fixed readers are often powered by power-over-ethernet (POE) or power supplies. Some readers can share power by connecting them in series (daisy chaining). Fixed readers are placed at chokepoints where goods must pass while entering or leaving a facility. A fixed reader may also be mounted on vehicles for taking inventory in a warehouse or the contents of a truck. Fixed readers typically support one to eight antennas. Some fixed readers also support multiplexers, enabling the reader to work with up to 32 antennas.

RTLS readers comprise phased array antennas that can position an RFID tag within an area. Multiple RTLS readers in an area can work together to position an RFID tag within 1 m. RTLS systems are useful in tracking the location of people or assets in a given area.

The link budget for passive RFID must consider the transmitted energy from the reader to the tag, the energy consumed by the RFID tag, and the return backscatter energy to the reader as a complete cycle, as seen in Figure 62.

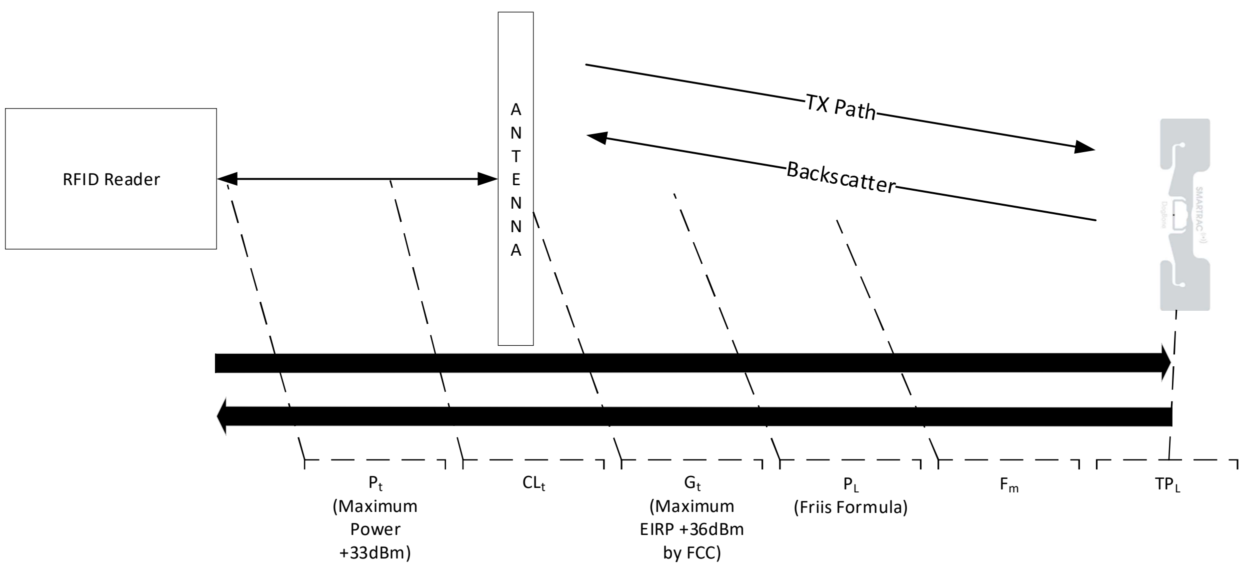

Figure 63 - RFID Link Budget Overview

Given the path above, the formula for the link budget calculation is the following:

$$P_r = P_t + 2G_t - 2CL_t - 2P_L - 2F_M - TP_L$$

$$P_r = power\ at\ the\ receiver$$

$$P_t = power\ output\ of\ the\ transmitter$$

$$G_t = gain\ of\ the\ transmit\ antenna$$

$$CL_t = cable\ loss - transmit\ cable$$

$$P_L = path\ Loss\ (Friis\ Formula)$$

$$F_M = fade\ margin\ (includes\ all\ forms\ of\ fading)$$

$$TP_L = energy\ consumed\ by\ the\ tag\ to\ power\ the\ chip\ and\ modulate\ backscatter$$

$$Friis\ Formula = P_L = 20log_{10}\left(\frac{4\pi D}{\lambda}\right)$$

$$Wavelength\ \lambda = \frac{v}{f}$$

Assuming the reader transmit power (P_t) is 30 dBm (or 1 watt), the antenna is a 6 dBi gain (G_t) linear antenna, the distance (D) is 5 m, and the RFID chip is an Impinj Monza 4E, the following formula would represent the link budget.

$$\lambda = \frac{299\ 792\ 458}{915000000} = .3276\ m$$

$$P_L = 20log_{10}\left(\frac{4\pi 5}{.3276}\right) = 45.66\ dB$$

$$P_r = 30 + 2(6) - 2(1) - 2(45.66) - 2(1) - 10 = -63.32\ dBm$$

It is also essential to consider the power on the tag (P_{tag}), which is the path from the interrogator to the tag. This is important because each tag has a required minimum signal to power the operations of the chip. This represents only the transmission path to the RFID tag. The following represents the formula for (P_{tag}).

$$(P_{tag}) = P_t + G_t - CL_t - P_L - F_M$$

In the previous example, the $\left(P_{tag}\right) = 30 + 6 - 1 - 45.66 - 1 = -11.66\ dBm$ which is above the $-19dBm$ required by the RFID chip.

In certain circumstances, it is easy to evaluate that a lower-powered reader (e.g., a handheld) may have difficulty at a distance of 5 m where $\left(P_{tag}\right) = 26 + 0 - 1 - 45.66 - 1 = -21.66\ dBm,$ which is insufficient power to activate the RFID tag. This use case would have a limit of $\left(P_{tag}\right) = 26 + 0 - 1 - x - 1 = -19\ dBm$, solving for x, the path loss formula should result in ~43 db. This indicates that the maximum distance for this link budget is approximately 3.7 m.

$$P_L = 20log_{10}\left(\frac{4\pi x}{.3276}\right) = 43\ dB\ where\ x = 3.68429\ m$$

Understanding the link budget, the focus turns to the channel's capacity. Within passive RFID, several configurations or modes can be applied to various reader/tag configurations. For the case of cash traceability, the assumption is made that readers are not overlapping, allowing the use of faster reading modes.

Isolation at Mantrap

During the ATC process mapping and discovery period, the researcher set up RFID equipment in the mantrap area to perform preliminary testing with a spectrum analyzer, readers, antennas, and tags. The testing yielded workable system settings for mantrap isolation.

Tamper, Security, Resilience, Encoding, Printing

An additional requirement is a need for tamper-evident tags. This requires the use of both adhesive and the proper label material. Cash bags are made of Category 4 LDPE plastic. The chosen adhesive should have reasonable gripping force (initial tack) from the moment it is placed on the bag and cure quickly to a sheer strength greater than the bag surface. The application temperature range of the tag should be 0 °C to 40 °C. The operational temperature range should be -40 °C to 80 °C. The tags should not fall off when exposed to extreme temperatures.

There are several means to illustrate attempted tampering with passive RFID tags. First, the adhesive used for the tag must be a quick tack permanent adhesive that supports a broad application and service temperature range. The adhesive should also have high shear strength. An example of a proper adhesive is Spinnaker BP-164 which is rubber based and has an application temperature of 4 °C and maintains a connection from -45.5 °C to 65.5 °C (Spinnaker, n.d.).

Second, if removal is attempted, the face stock material can be designed to shred. This type of paper clearly shows any attempt to remove the label after it has been applied.

Third, when the RFID tag is printed, the tag data can be locked in the tag memory, preventing reprogramming. In addition, during printing, the TID and EPC can be uploaded to the API service for validation. TIDs are programmed into the RFID during manufacturing and cannot be changed. When an RFID reader reads a tag within the system, the original TID and EPC must match to validate the original tag. A mismatch of TID to EPC indicates an attempt to replace the RFID tag by a person.

In addition, The EPC Gen 2 specification calls out security services for RFID tags. This function enables a challenge and authentication process based on a tag password stored in the tag memory. The tag enters the secure state following the receipt of the Req_RN from the reader. At this point, the reader must send an authentication command with the password before communications can continue.

Printing RFID tags is very common and is supported by several manufacturers like Zebra and Sato. RFID label printers are typically adapted from standard label printers by adding a small RFID programmer option. RFID label printers come in various sizes and shapes, from small, handheld printers to industrial printer-applicator machines.

IoT Device Cost per Bag

Generally speaking, RFID tag costs depend on several factors, including the materials used, the inlay, and the chosen chipset. Since the RFID label presented here is relatively basic, the cost of $0.05 to $0.09 is achievable in volume (greater than 1M tags per year).

Technology Decision

Breaking down the three options presented, Table 22 compares the three technical solutions and the requirements previously laid out.

Table 22 - Technology Comparison Against Requirements

	Requirement	Standard BLE	Passive BLE	Passive RFID
RF Reading Range	0.5 – 10 meters	Yes	No	Yes
IoT Device Density	2500 devices in a 5000 square foot area	No	No	Yes
Isolation between mantrap chokepoint	30 dBm	No	Yes	Yes
Tamper	Shows signs of tamper attempt	Yes	Yes	Yes
Security	Technology specific security	Yes	Yes	Yes
Resilience/Encoding	Storage in device memory for basic manifest information	No	No	Yes
Printing	Human readable bag routing information	No	Yes	Yes
IoT cost per bag	$0.05 - $0.09	No	No	Yes
Battery life	A passive device or reusable device w/5 year battery.	No	Yes Passive	Yes Passive

The technology that meets all the requirements is passive RFID. Since passive RFID is the chosen technology for cash traceability, several additional choices must be made based on the individual use cases.

RFID Tag Evaluation

Several RFID tags were evaluated from multiple suppliers to assess the behaviors of the RFID tags. Two different systems were utilized to evaluate RFID tags. The first system was a Voyantic Tagformance Pro RFID system. The second system used an Impinj R-700 reader sampling the RFID tag at the maximum read rate (Max Throughput -FM0).

Nine RFID tag combinations were tested for reading range, power on the tag, and responsiveness based on orientation. Four of those tags were chosen to be successful in this application (highlighted in blue in Table 23).

Table 23 - RFID Chipsets Tested

Provider	Inlay	Chipset
Brady Corporation	ALN-9630	Higgs 3
Avery Dennison	Dogbone	Monza 4E
Avery Dennison	AD Grille	UCode9
RR Donnelley	EOS-500 U7XM-2k (Hexbug)	UCode7XM2K
RR Donnelley	Boentag	0x995
Starport	Boentag	Higgs 9
Synometrix	ALN-9630	Higgs 9
Tageos	EOS-261	M730
LabID	Boentag	UCode7XM2K

The selected tags were tested with a Voyantic Tagformance Pro system to measure a series of performance metrics, including expected read range (Figure 63), read threshold (Figure 64), read backscatter (Figure 65), and tag read orientation (Figure 66).

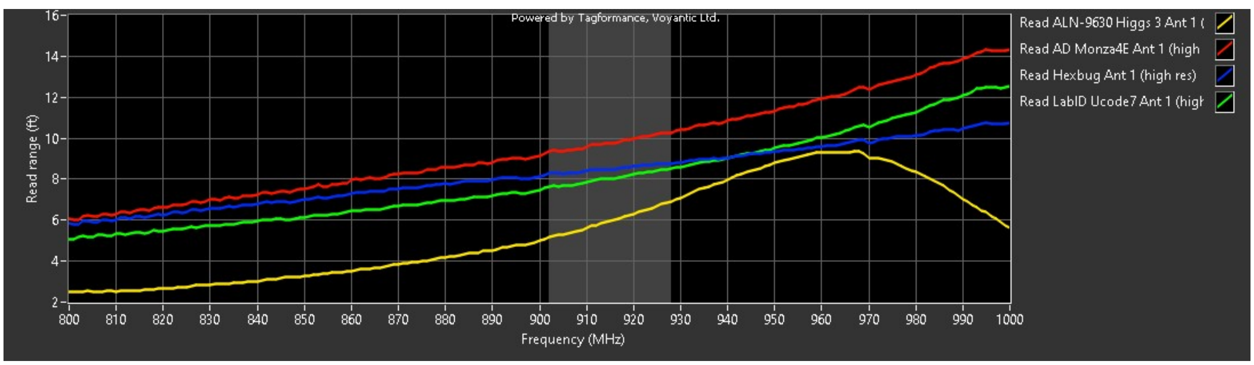

Figure 64 – Expected Read Range

Figure 63 illustrates the expected read range of the tag based on the frequency of the tag. The grey area from 902 – 928 MHz represents the FCC ISM frequency band used for RFID. In this example, the AD Monza4E tag has the greatest read range of approximately 10 ft from the reader antenna.

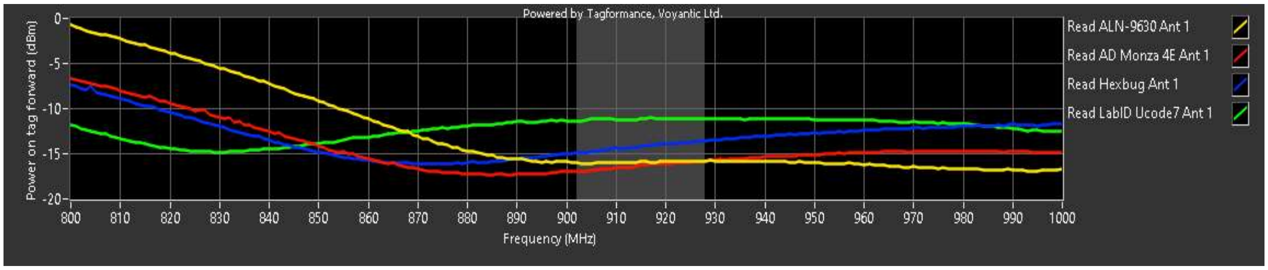

Figure 65 - Read Threshold

Figure 64 describes the amount of energy required on the surface of the tag to elicit a response from the RFID tag. In this case, within the 902 to 928 MHz range, the LabID UCode7 requires the power on the tag (about -11 dBm) to respond to reader commands.

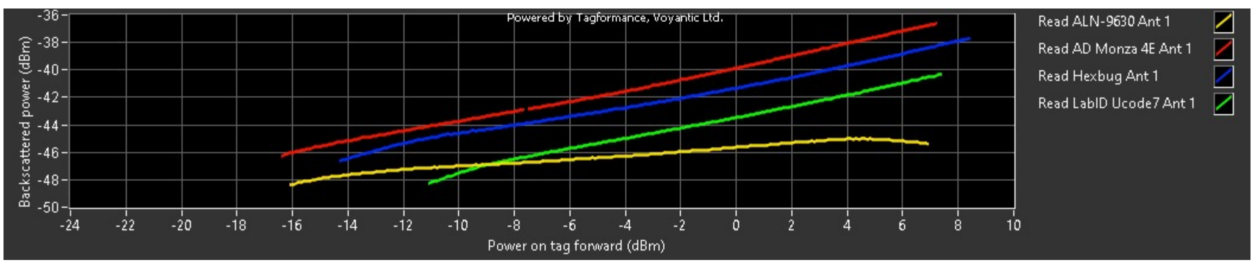

Figure 66 – Read Backscatter

Figure 65 compares the energy the reader places on the tag (horizontal axis) with the energy received from the tag. The ALN-9630 and the AD Monza 4E both respond with approximately -16 dBm power on the tag, but the AD Monza 4E tag responds with about +2 dB signal energy than the ALN-9630.

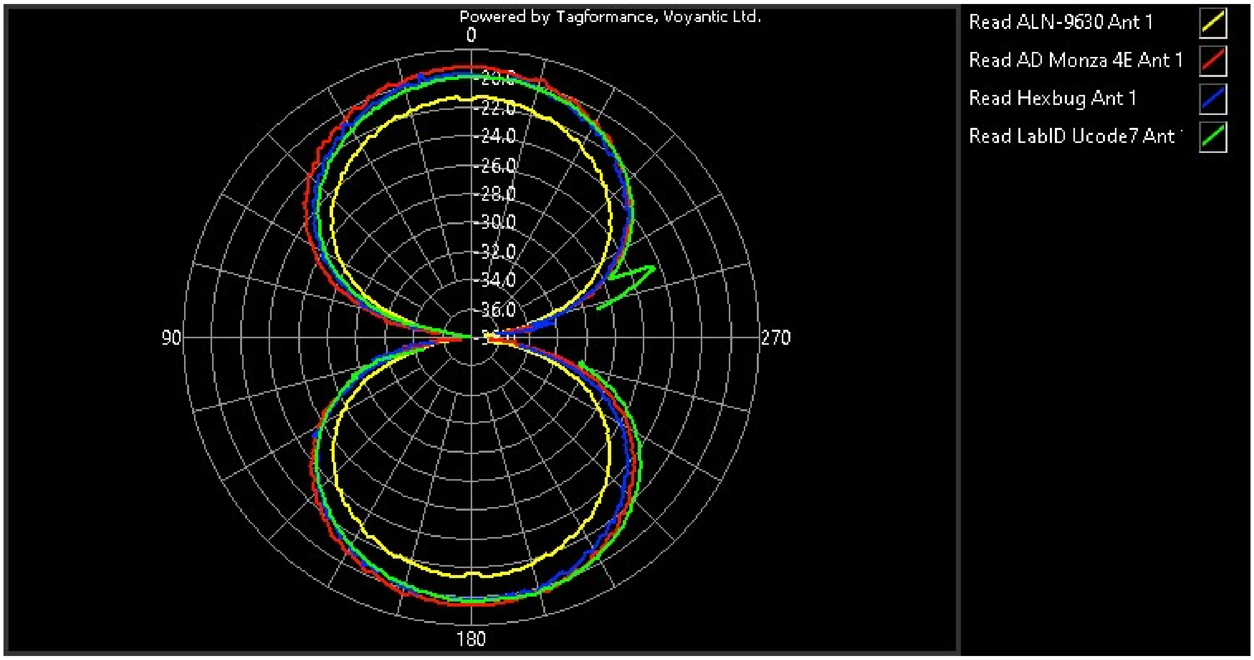

Figure 67 – Tag Read Orientation

The tag is rotated on a turntable during this test, and an RSSI reading is taken from the tag at each angle. All tags perform equally in this test, with the AD Monza 4E tag performing slightly better (stronger RSSI at the reader).

Throughout the testing, the goal was to have multiple candidates for use in the application. These four tags perform well in all use-case applications. From these tests, a set of tag requirements were gathered. The requirements also include physical items such as the physical dimensions, the required type of adhesive, and tamper-evident face stock. The tag requirements are listed in Table 24. These requirements were derived from use case testing and analysis by the Tagformance Pro system.

Table 24 - RFID Tag Attributes

Attribute	Description
Size	4 inches x 2 inches rectangular label, rounded corners
Face stock	Supports thermal transfer and direct thermal printing. Printing must maintain readability for 90 days
RFID Frequency	UHF - Prefer 860 – 960 MHz, minimum 902 – 928MHz
Inlay RF Parameters	Minimum Read sensitivity -19dBm, Minimum Write sensitivity - 16dBm. Read range 4M.
Chipset	Must contain EPC memory of at least 390bits. Suggested chipsets: Alien Higgs 3 with extended EPC, Impinj Monza 4E, NXP UCODE 7xm, NXP UCODE G2iM+. Other chipsets may be considered. User memory 600 bits.
Adhesive	Must aggressively bond to polyethylene plastic. Application temperature range + 10 to +40C. Maintains bond after 5 minutes to -40C to +60C. The minimum period of adhesion – 90 days.

CHAPTER 8

MODELING FUTURE STATE

The research's fundamental hypothesis is that adding an IoT technology into the cash movement ecosystem reduces costs, improves capacity, and provides visibility to all parties involved in the cash movement. The addition of IoT also brings with it the assumption of software interoperability between the entities (retailer, ATC, and bank), whom all have a vested interest in the timely and accurate movement of financial assets. Within the ecosystem, the customer can be the retailer or the bank, depending on the type of movement. For the change orders and deposits, the customer is the retailer. For ATM servicing and smart safes, the customer is the bank. The bank is also a customer for Federal Reserve Bank transactions.

Vision

The vision of the future of cash visibility is to have an interoperable and integrated system that 1) reduces operational costs for all parties involved, 2) increases the capacity of ATCs which improves profitability without adding personnel, 3) integrates the business systems of cash management organizations, 4) provide visibility to clients/customers that use ATC services of the status of transported goods, and 5) raise the level of awareness of operational status in real-time allowing all parties to make better decisions.

Reducing Operational Costs

Reducing operational costs is mostly about speeding up processes and behaviors. For instance, adding technology to the system should speed up the processes of picking up deposits, transferring bags from CIT to the vault, and sorting bags. These reductions in operational times reduce manpower costs by reducing the number of work hours and overtime for employees. RFID also allows for robotic sorting systems that shift sorting work from tellers by hand to automated systems.

Increasing Capacity

The observed ATC was at its operational capacity limit, and the branch was very sensitive to adding additional customers. Reducing staff work hours, in turn, increases capacity for the ATC. Transforming routes that chronically require overtime into manageable routes with available capacity allows the ATC to take on more business.

Integration and Interoperability

One of the keys to this solution is the addition of business systems connectivity between entities in the cash supply chain. For example, a retailer creates a deposit bag, which, in turn, prints an RFID label and notifies both the retailer’s bank and ATC that a bag is ready for pickup. This process populates the database of both the bank and the ATC systems. The databases then contain the deposit information, and the bag ID. RFID readers can then scan the bag's RFID tag at any point in the movement and updates provided to the retailer. Picking up the bag at the retailer is as easy as a quick RFID scan and visual inspection.

Visibility

Throughout this research, retailers consistently complain of the lack of understanding of where a deposit or change order is within the ATC. In a day where Amazon can tell us how many stops away our deliveries are, ATCs are quite the antithesis of Amazon. A deposit may appear in the retailer’s bank account in one day or five days without explanation. RFID can provide a very granular visibility of the location of every bag as it moves through the process. Additional visibility also provides a detailed history of every bag and each employee that has come into proximity with the bag. If a bag has signs of tampering, the investigation quickly pulls a complete bag record from the historical record.

Raising Operational Awareness

Operational awareness allows managers to visualize system behaviors in a new and exciting way. Operational scoreboards can inform processing teams about the status and quantity of bags in CIT, including route progress and compliance with operational limits (e.g., an armored vehicle carrying more cash than allowed). The researcher addresses many of these topics in greater detail in the following paragraphs.

API Integration

The future state of the entire industry is already moving toward an API integration between cash-handling industry elements. The Federal Reserve Bank has a Cash Advisory Council comprising businesses from a cross-section of the industry whose role is to develop the API standard. The API is an integral part of the future state of this research.

As previously mentioned, armored couriers and banks have no foreknowledge of customer deposits prepared for pick up by the ATC. This is overcome by contractual agreements between the retailers and ATCs, which spell out the exact days of the week and the time when couriers check for deposits. ATCs lack foreknowledge of the preparation of change orders by banks and, again, show up according to a preset schedule. This process is inefficient and can be addressed through an API application.

The future state relies on an API integration that provides foreknowledge of preparing bank change orders and deposits at customers. This foreknowledge creates manifests that are distributed to the actors in the cash movement. Since the manifest of any exchange is known, there is less reliance on human data entry, as seen in Figure 67.

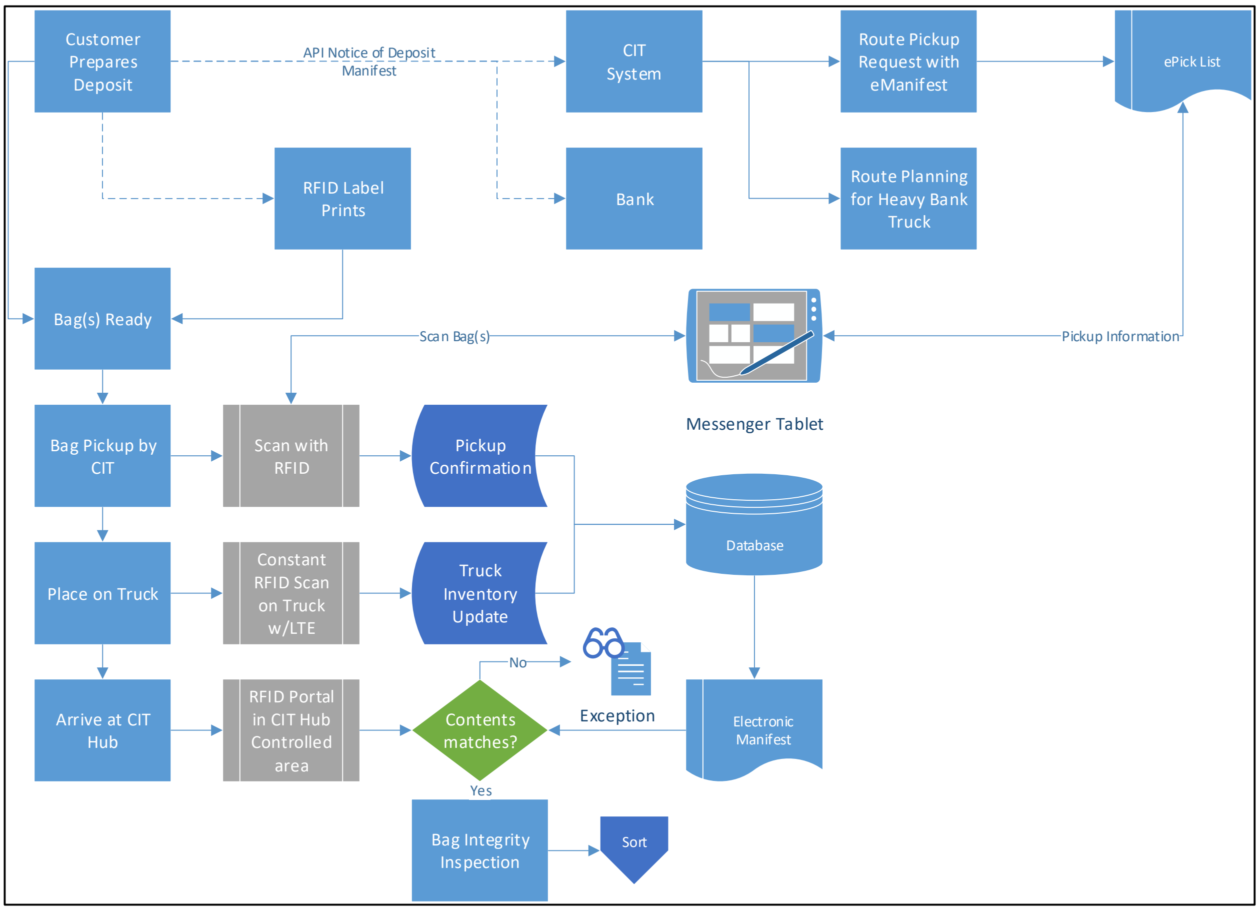

Figure 68 - Future State Flow Diagram

In addition to populating the shipment manifest, the foreknowledge of prepared cash bags enables more efficient route management for the armored vehicle. It removes stops where no retailer deposit bag or bank change order is ready for retrieval. In addition, the electronic manifest allows the messenger to retrieve the deposit and change order bags. In the current state, messengers must enter the final destination for each bag in a small handheld computer, opening the door to human error and customer dissatisfaction. In this future state, this requirement is removed, which in turn, eliminates the opportunity for human error.

RFID IoT Application

As the chosen methodology from the evaluation of technologies in Chapter 3, RFID enables real-time tracking of cash bags throughout the movement process, human identification of bags, and robotic sorting. RFID readers can be deployed in several locations to enhance traceability and speed up transactions. At the pickup point, the messenger has a handheld RFID reader connecting to the messenger's cellular-capable tablet to quickly scan and accept bags from customers and banks. Each armored vehicle has an RFID reader with a cellular data connection to accurately identify the contents of each vehicle. The transition area (mantrap) at the branch where the bags are transferred to the vault teller has an RFID reader with a network connection for information transfer. Inside the branch, RTLS systems would maintain the position of every bag within the facility. Security carts, totes, and bins would also have RFID readers to enable instantaneous inventory of each receptacle.

Each cash bag has an RFID tag label placed on the surface to serve two roles during transportation. First, the RFID tag has the EPC memory area encoded with the same bag ID represented on the bag's barcode. In addition, the final endpoint of the bag is encoded in the EPC memory. Each time the bag is inventoried at any location, these two pieces of primary routing information are read. Second, the RFID label is printed with human-readable text, becoming the bag's transaction slip (e.g., deposit, change order). Account numbers, the bag's value, routing information, and customer information are readable for human sorting. In addition to the human-readable information, a 2D barcode could also be printed on the bag for optical machine routing. Each bag has its own manifest readable by humans, RFID tags, and optical machine readers.

The bag label also becomes a source of interoperability between non-connected entities in the cash movement ecosystem. For instance, when competitors must exchange bags, the RFID tags can be scanned quickly by the receiving ATC messenger confirming the entire shipment.

Robotic Sorting

AmbiSort Robotics has a barcode-based package sorting system that shipping companies use to sort packages. With only the addition of RFID readers, the system can sort cash bags. The bin system has up to 66 bins for sorting. The robotics system can be used to sort incoming and outgoing cash bags. This sorting system can accurately sort bags without error. Bags that are not readable are sent to a reject bin for teller attention. The robotic system can sort bags at a rate of 10 per minute and can run 24 hours a day.

The robotic sorting system operations start in the morning with outbound bags by sorting them into route bins. When that operation is complete, the route bins can be stored, and bank bins placed in the machine. As incoming bags are gathered, the tellers put them in large bins and, when full, move the large bin to the robotic sorting machine. After inbound bags are sorted by endpoint banks and repackaging, the route bins are returned to the robotic sorting machine for final route sorting.

Future State Process

In the future state, the customer has an API integration with their bank and contracted ATC. The customer enters the change order, and both the bank and the ATC are notified. The change order is automatically queued in the ATC packing room. The packing room teller creates the bag, and an RFID label is automatically printed and encoded with the client's endpoint and bag ID. The bag is automatically assigned to a route for the next delivery day for that client. The finished change order is placed in a large bin. As the number of change orders increases, the large bin is placed in a robotic sorting machine. The robotic sorting machine can handle 45 routes and foreign courier change requests. ATM cash has the same path. The robotic sorting system uses RFID tags to look up the proper assigned route and puts the bags in the appropriate route bin. While sorting, the system keeps track of the manifest for each route bin. Any unrouteable or unreadable bags are placed in the reject bin for teller review. See Figure 68 for a graphical representation of the process.

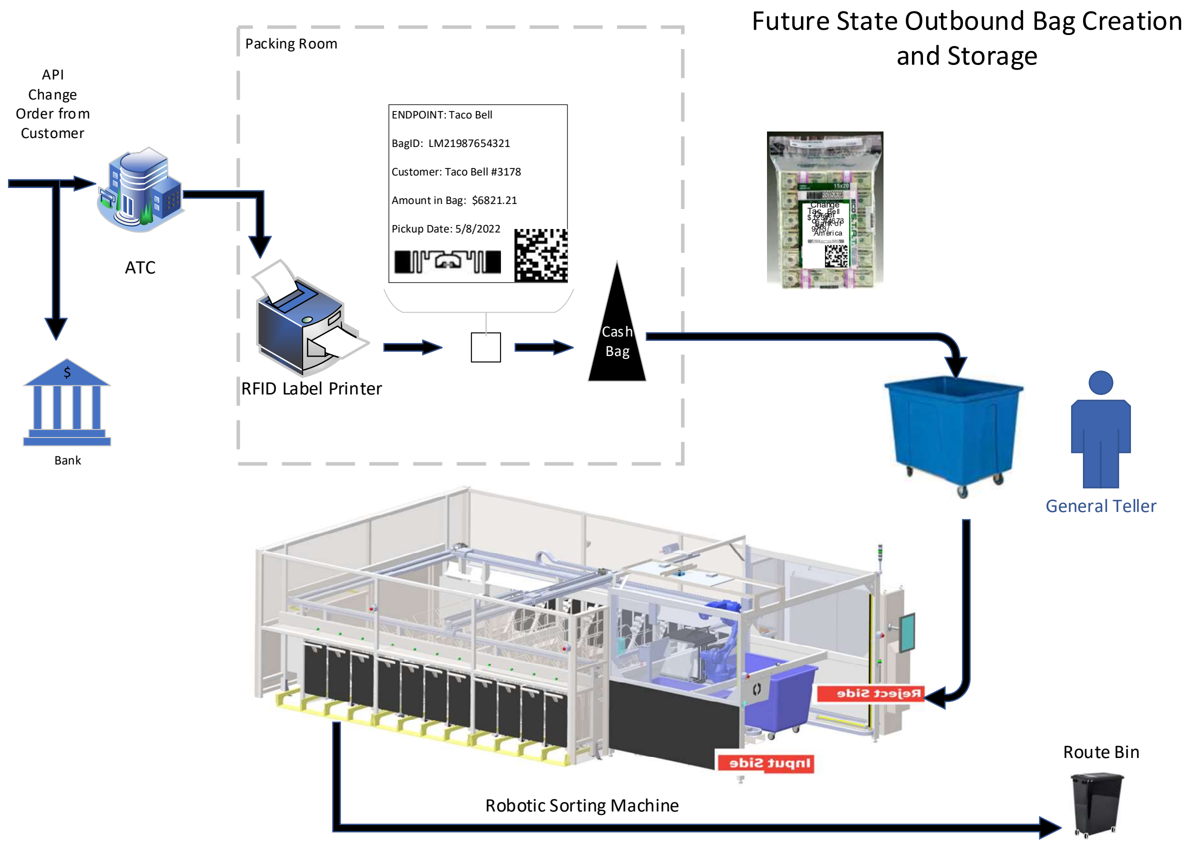

Figure 69 - Future State Outbound Bag Creation and Storage

When the messengers arrive at the branch in the morning, the appropriate route bin is pulled for the messenger. The RFID system detects the bin in the mantrap along with the accessories. The messenger also has an RFID badge. The bin, its contents, the accessories, and the messenger are all associated in the mantrap, as seen in Figure 69.

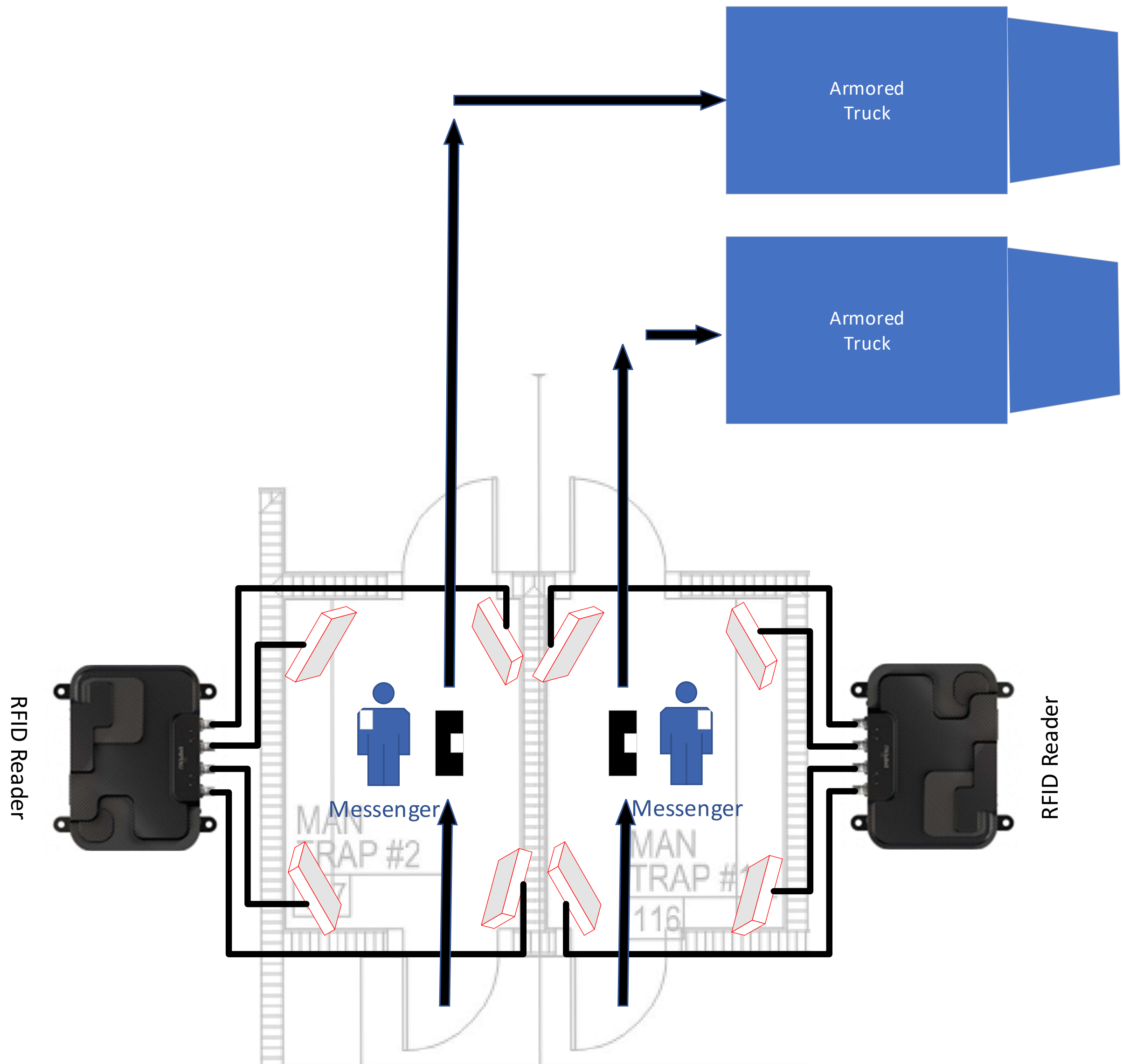

Figure 70 - RFID in the Mantraps

When the messenger reaches the truck, the truck RFID system validates the accessories, messenger, and bags as they are placed on the truck. Any inconsistency is identified as materials are placed in the vehicle. See Figure 70 for the vehicle mounted RFID system.

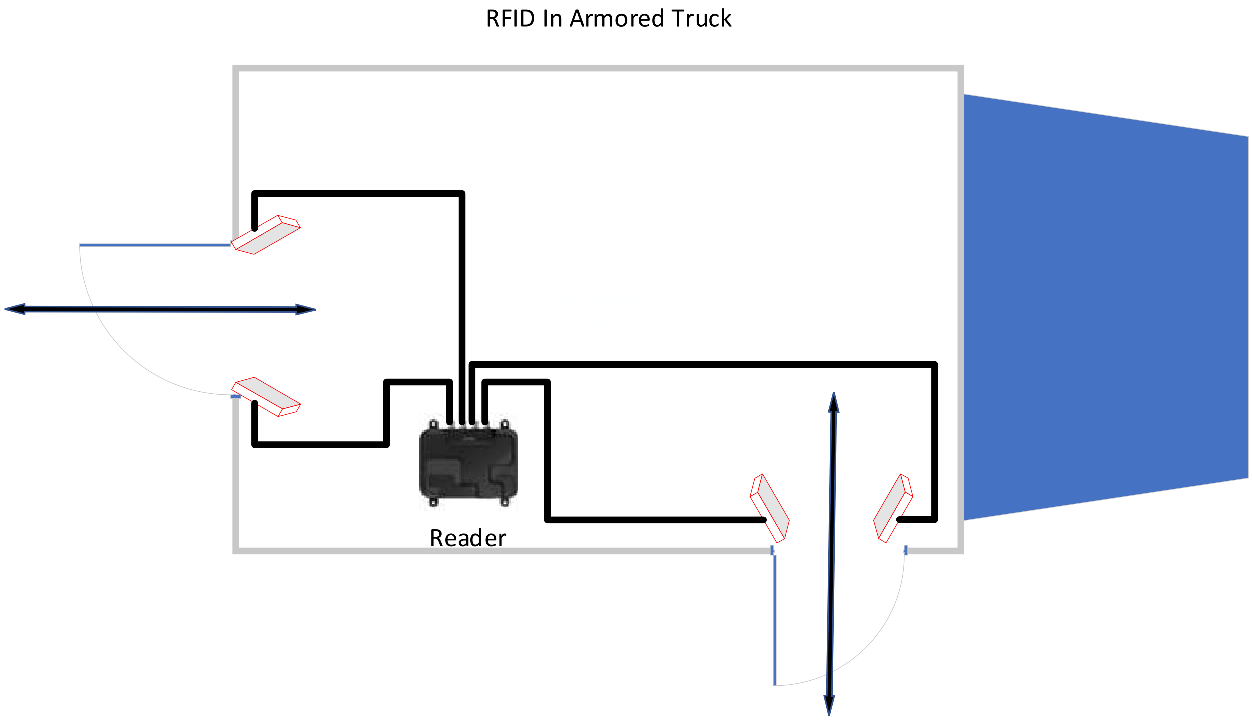

Figure 71 - RFID in Armored Truck

The exchanges are much faster during visits to banks, competitors, and retailers because the cash deposit bags are already in the handheld database. The messenger must only scan the bags and accept the lot in one touch. Bag drop-off is quicker because of RFID. In the future case, the armored truck crew does not stop at locations without a deposit.

When the truck returns to the branch after completing the route, the cash bags, accessories, and the messenger's RFID tag are detected leaving the vehicle and entering the mantrap. All items are registered automatically by the branch RFID system, and custody exchange is accomplished in just a few moments. The teller checks the manifest for the vehicle and the RFID read bags in the mantrap and assumes the custody transfer. The contents of the container are transferred to a large container and placed in the robotic sorting system.

In addition to the RFID in the mantrap and armored vehicle, a Real-Time Location System (RTLS) maintains the general location of all employees, accessories, carts, and cash bags within the branch area, including the armored truck CIT lanes, as seen in Figure 71. RTLS zones are indicated in pink-shaded circles.

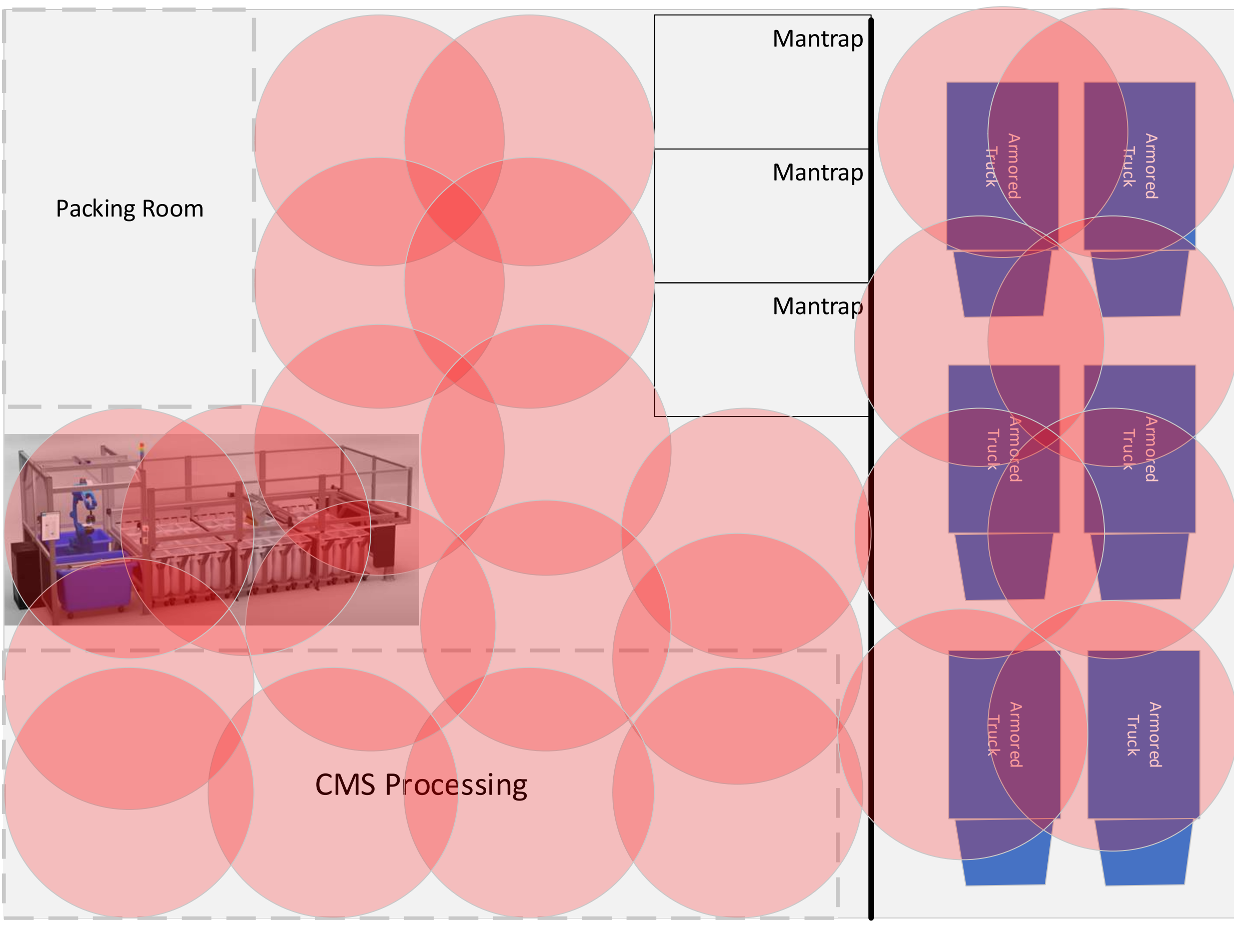

Figure 72 - RTLS Zones in Branch

Throughout the entire process, there is 100% visibility of every bag of cash from beginning to end. Customers (typically retailers) see the progress of their deposits and have Amazon-like estimates of when the armored courier team is arriving at their location.

Future State Simulation Model

The future state modifies some parameters in the simulation model. To avoid disturbing the current state parameters, a mode switch was placed in the model to operate in the current or future state. See Table 25 for parameter changes between the current and future state modes of simulation model changes. The changes in the model focus on changes that occur by adding API integration, RFID tags on bags, and RFID infrastructure at various locations within the cash movement process.

Table 25 - Model Changes

Current Processing Times Configuration	**Current Model Parameters**			
Parameter	value at retailer	value at bank	value at competitor	units
courier waits for bags and manager to be ready	uniform(0,10)	triangular(3,5,7)	triangular(3,5,7)	minutes
find bags in truck	triangular(20,30,60)	triangular(20,30,60)	triangular(20,30,60)	seconds
enter info of bag on phone or PDA	5	5	7	seconds
Future Processing Times Configuration	**Future Model Parameters**			
Parameter	value at retailer	value at bank	value at competitor	units
courier waits for bags and manager to be ready	uniform(0,2)	triangular(1,2,3)	triangular(1,2,3)	minutes
find bags in truck	triangular(3,4,5)	triangular(20,30,60)	triangular(20,30,60)	seconds
enter info of bag on phone or PDA	1	1	7	seconds
Current Branch Processing Times Configuration	**Current Model Parameters**			
submit, scan, and bag messenger belongings	uniform(1,2)	units		
one bag inspect and scan by vault teller	triangular(2,16,8)	minutes		
one bag preliminary sort by vault teller	triangular(2,16,9)	seconds		
one bag sort by sorting teller	uniform(15,30)	seconds		
paperwork and release	uniform(1,3)	seconds		
one bag overnight re-sort	uniform(15,30)	seconds		
issue keys, manuals, phone/PDA(s), radios, a manifest, and a detailed route sheet for that day to the messenger	uniform(1,2)	seconds		
load bag from branch to trolley	5	seconds		
move trolley from branch to truck	triangular(20,30,60)	seconds		
verify and accept bag to the electronic manifest on the phone/PDA	5	seconds		
one bag sort by early morning crew member	uniform(15,30)	seconds		
assign outbound change request bag to route or competitor	uniform(20,40)	seconds		
take bag to relevant rolling cabinet	triangular(15,30,45)	seconds		
register bag on inventory records	5	seconds		
Future Branch Processing Times Configuration	**Future Model Parameters**			
Parameter	value	units		
scan group of bags by RFID	triangular(5,10,15)	seconds		
transfer of custody between messenger and vault teller	triangular(1,3,5)	seconds		
move one bag from trolley to bin	2	seconds		
move bin trolley and place it in robotic sorter	uniform(1,3)	seconds		
sort one bag by robotic sorter	triangular(6,7,8)	seconds		
sort one bag by worker	triangular(1,2,3)	seconds		

Future State Model Data

The first area of the simulation model that was evaluated in the current state was the evaluation of the transfer of custody in the mantrap. Using the same methods, the model's output in future state mode yields a comparison of the total time spent in the mantrap in both modes. See Figure 72 for the future state box plot and Table 26 for a comparison of the mantrap time for both the current and future state.

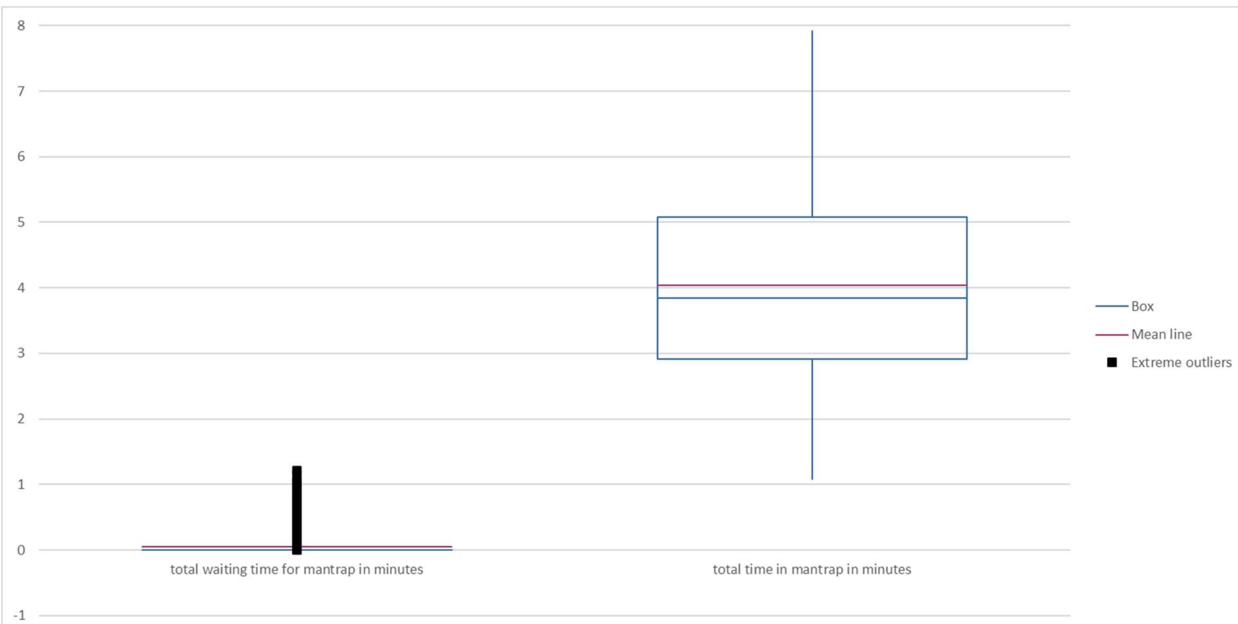

Figure 73 - Future State Time in Mantrap Box Plot

Table 26 – Comparison of Current and Future State in Mantrap

Current State	Count	Mean	Minimum	Lower whisker	Q1	Median	Q3	Upper whisker	Maximum
wait for mantrap	4400	2.9506	0.0000	0.0000	0.0000	0.0000	4.8051	11.9900	31.0113
time in mantrap	4400	12.969	5.3728	5.3728	10.535	12.6659	15.167	22.0390	23.3367
Future State	**Count**	**Mean**	**Minimum**	**Lower whisker**	**Q1**	**Median**	**Q3**	***Upper whisker***	***Maximum***
wait for mantrap	4400	0.0355	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	1.3244
time in mantrap	4400	2.9956	1.0274	1.0274	2.3976	2.9997	3.5922	4.9555	4.9555
Wait reduction		99%							
Trap reduction		77%							

The change in modes is significant, nearly eliminating waiting time for entering the mantrap (congestion) and reducing the time transferring inbound bags by 77%. Since the bags are detected automatically by the RFID system, a complete inventory of the bags within the mantrap can be verified against the electronic manifest of the vehicle. The custody transfer is entirely automatic, and any exception is immediately identified. The rolling bin used to bring the cash bags to the mantrap can be rolled directly to the sorting machine without human sorting.

The second area of investigation in the current state was the bags per truck. These values stay the same in the future state without further customer additions.

Next, teller utilization was explored. The most significant operational change in teller utilization is the addition of the robotic sorting of cash bags. The cash bags are loaded into a large sorting robotic cell and sorted into smaller mobile bins. In the future state, tellers have multiple roles and are called "general tellers." The teller utilization box chart from the simulation model is in Figure 73, and a comparison between the current and future state is in Table 27.

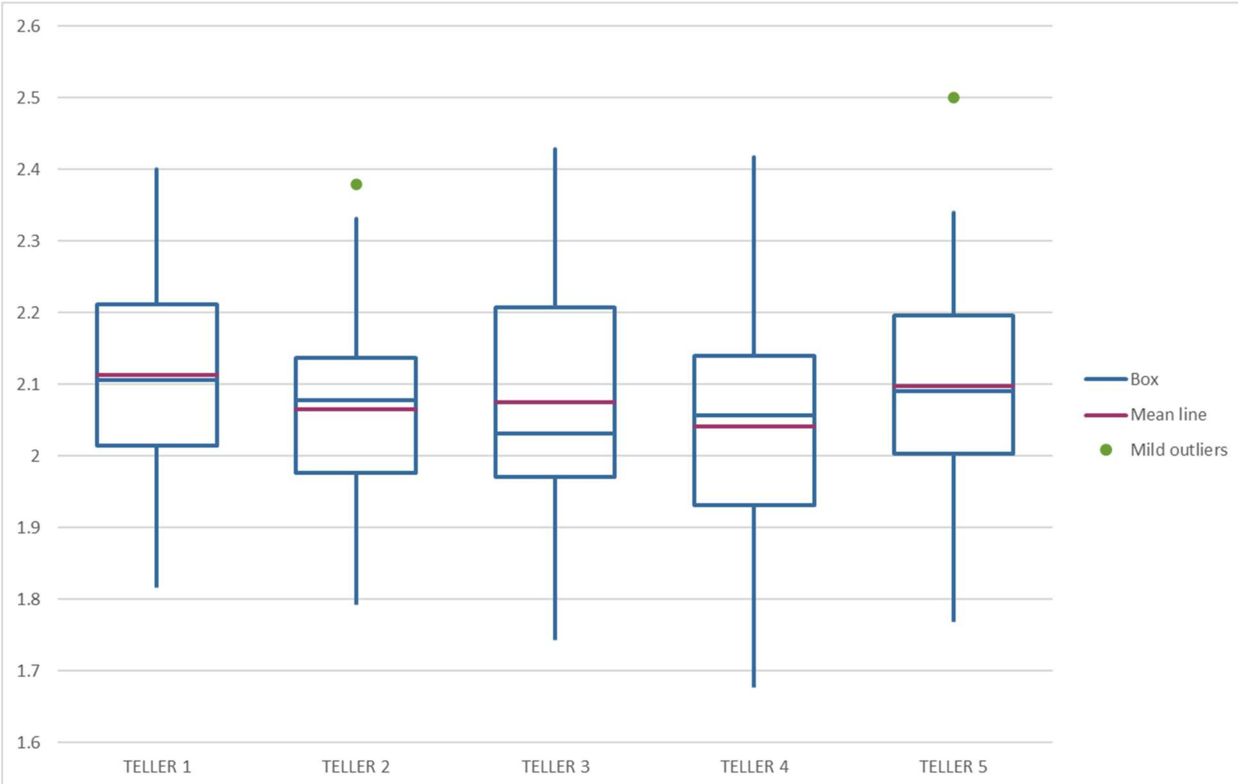

Figure 74 - Future State Teller Utilization Box Plot

Table 27 - Comparison of Current and Future State Teller Utilization

Current Teller Utilization	Count (Days)	Mean	Minimum	Lower whisker	Q1	Median	Q3	Upper whisker	Maximum
Cabinet 1 Sort	100	4.3010	3.7056	3.7056	4.1317	4.3789	4.4920	4.8289	4.8289
Sec CabSort	100	4.2997	3.6642	3.6642	4.1097	4.3532	4.4910	4.8525	4.8525
Early Sort 1	100	2.0773	1.7822	1.8167	2.0035	2.0728	2.1463	2.2931	2.2931
Early Sort 2	100	2.0775	1.7828	1.8139	2.0031	2.0731	2.1451	2.2939	2.2939
Early Sort 3	100	2.0775	1.7850	1.8128	2.0017	2.0738	2.1460	2.2961	2.2961
Early Sort 4	100	2.0773	1.7831	1.8186	2.0051	2.0733	2.1442	2.2928	2.2928
Early Sort 5	100	2.0774	1.7889	1.7889	2.0017	2.0729	2.1453	2.2936	2.2936
Outbnd Sort 1	100	7.3778	6.3614	6.3614	7.0652	7.4971	7.6720	8.2692	8.2692
Inbound Sort 1	100	10.3707	9.0031	9.0031	10.0247	10.4314	10.7522	11.7336	11.7336
Vlt Inbnd Sort 1	100	4.6913	3.8944	3.8944	4.4608	4.6789	4.9049	5.4572	5.4572
Vlt Inbd Sort 2	100	4.7268	3.9294	3.9294	4.5053	4.7003	4.8926	5.4136	5.5247
Vlt Sort Inbnd 3	100	4.6367	3.5697	4.0367	4.4068	4.6303	4.8801	5.2442	5.7794
Overnight 1	101	8.7688	2.9969	7.6706	8.5028	8.8006	9.1872	10.2094	10.2653
Overnight 2	101	8.7697	2.9956	7.6622	8.5089	8.7978	9.1806	9.8783	10.2650
Current Teller		68.3295							
Future Teller Utilization	**Count**	**Mean**	**Minimum**	**Lower whisker**	**Q1**	**Median**	**Q3**	**Upper whisker**	**Maximum**
General 1	101	2.8309	0.1061	2.4978	2.6881	2.7578	2.8733	3.0897	7.1267
General 2	101	2.8360	0.1167	2.4603	2.6928	2.7725	2.8678	3.0625	7.0136
General 3	101	2.8121	0.0689	2.4611	2.6650	2.7461	2.8539	3.0489	7.1058
General 4	101	2.7934	0.0894	2.5003	2.6472	2.7364	2.8183	3.0511	7.1606
General 5	101	2.7951	0.0961	2.4631	2.6708	2.7403	2.8106	2.9628	7.0631
Future Teller		14.0676							
Reduction		79%							

The teller team size can be substantially reduced while at the same time servicing the same number of customers. The new model reduces the tellers' sorting activities from 68+ manhours per day to only 14.1, a 79% reduction. These tellers can be cross-utilized for other tasks while still covering the 24-hr operational needs of the branch. Regarding bag sorting, the general tellers are now only 30% utilized on average. The tellers can spend additional time dealing with any exceptions or handling keys, manuals, PDAs, and phones. Even though the total man hours for sorting is only 14.1 hr, tellers must be available in all shifts. The distribution would be two dayshift tellers, two evening tellers, and one overnight teller. There is also a supervisor on each shift (not addressed in the simulation).

Following the teller utilization is the driver-messenger utilization evaluation done by comparing the total route time of truck crews. The model simulation for the future use case reduces the time in the mantrap and the time at each customer, bank, and perhaps competitor (if the competitor adopts the solution). ATM transaction timing remains the same. Figure 74 illustrates the model box plot, and Table 28 compares the current and future state.

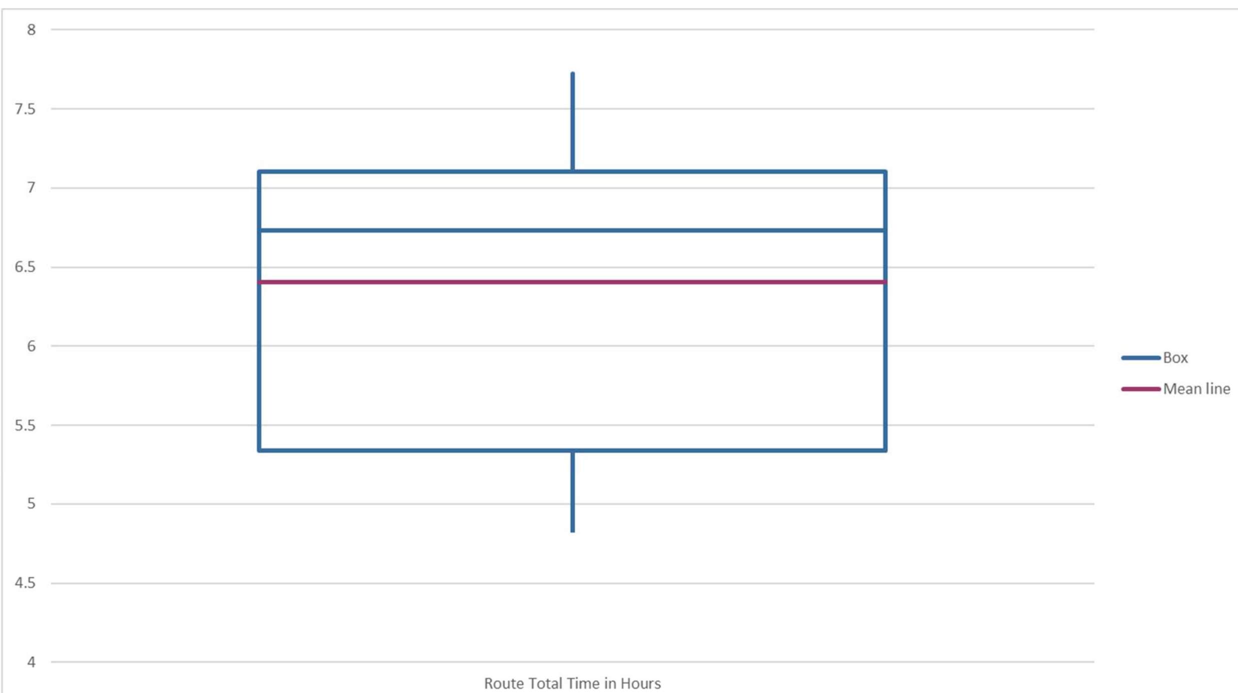

Figure 75 - Future State Route Duration

Table 28 - Comparison of Current and Future State Truck Route Duration

Current State	Count	Mean	Minimum	Lower whisker	Q1	Median	Q3	Upper whisker	Maximum
Route Duration	100	9.4346	6.1383	6.1383	7.0685	10.0300	10.7838	12.4200	12.4200
Overtime	100	1.7732	0.0000	0.0000	0.0000	2.0300	2.7838	4.4200	4.4200
Current Total		11.207							
Future State	**Count**	**Mean**	**Minimum**	**Lower whisker**	**Q1**	**Median**	**Q3**	**Upper whisker**	**Maximum**
Route Duration	100	6.4039	4.8372	4.8372	5.3413	6.7286	7.1053	7.7242	7.7242
Reduction		43%							

Of most significance in Table 28 is the overwhelming reduction in time to conduct the same route. The 43% reduction in route time eliminates overtime and yields additional capacity within the route. The potential savings are significant compared to the maximum values in the table. The mean value here also includes weekend operations which are significantly less. One must also remember that these times are doubled because these values affect both the driver and the messenger.

Considering that the current model's driver/messenger armored crew had been operating at 140% capacity (total work hours with overtime), the armored truck crew is now operating at 80% capacity, avoiding overtime while servicing the same customer base. The additional 20% excess capacity is now available for the business development and sales team to acquire additional customers.

Finally, the truck route timing was reviewed in the current state discussion. Much of the time savings within the future state route duration can be attributed to the reduced time required to interact with customers, especially retailers. Since retailers make up 74% of the stops in the model, any significant change in this category is observed in the truck route duration. The simulation model box chart and a comparison of the current and future states are located in Figure 75 and Table 29, respectively.

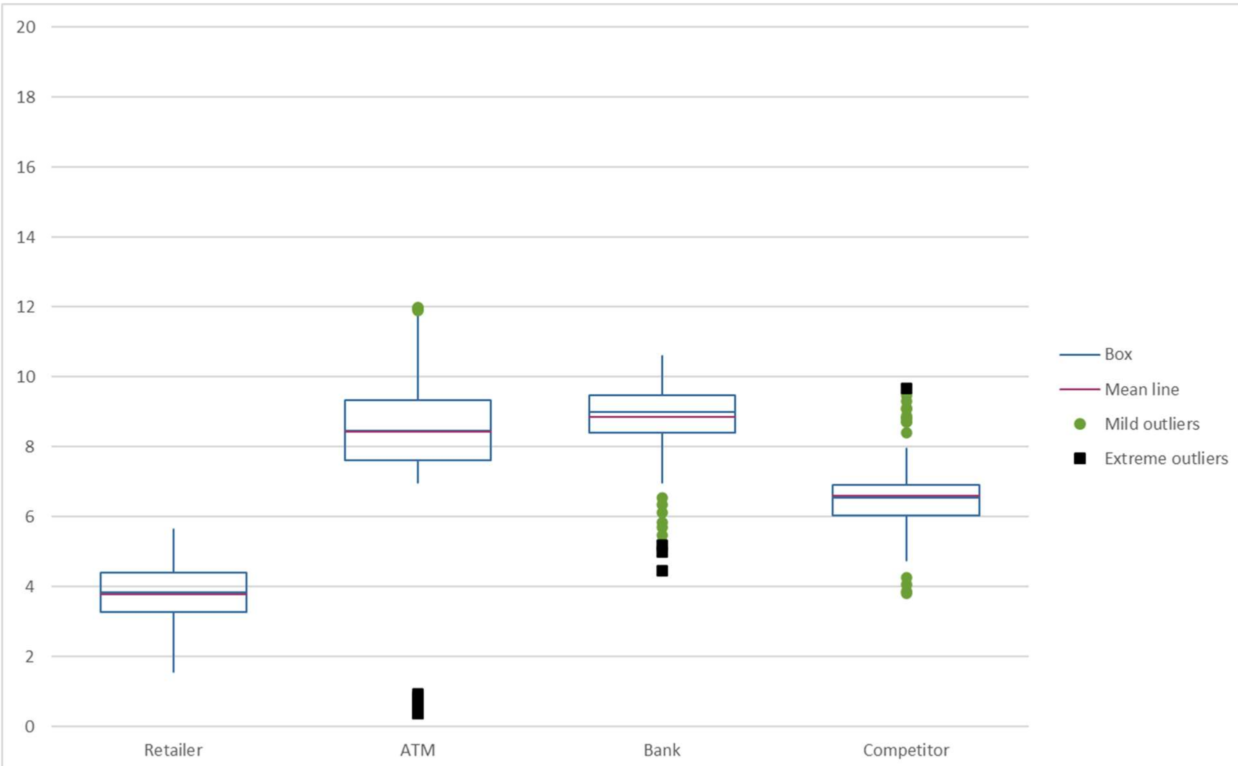

Figure 76 - Future State Route Time

Table 29 - Comparison of Current and Future State Route Duration

Current State	Count	Mean	Minimum	Lower whisker	Q1	Median	Q3	Upper whisker	Maximum
Retailer	2680	8.9484	1.6333	1.6333	6.5000	8.9333	11.4208	15.6333	15.6333
ATM	531	8.2562	0.3667	7.0000	7.6417	8.4333	9.1917	11.5000	11.9833
Bank	288	13.7612	4.7833	10.9333	13.129	14.0833	14.8833	17.1000	17.1000
Competitor	117	10.1101	6.4833	7.1167	9.3667	10.1333	10.9167	12.9833	14.3333
Future State	**Count**	**Mean**	**Minimum**	**Lower whisker**	**Q1**	**Median**	**Q3**	**Upper whisker**	**Maximum**
Retailer	2578	3.7713	1.5833	1.5833	3.2667	3.8333	4.4000	5.6333	5.6333
ATM	531	8.4220	0.3667	7.0000	7.6167	8.4500	9.3250	11.8833	11.9833
Bank	288	8.8499	4.4667	6.9833	8.4167	8.9833	9.4667	10.6000	10.6000
Competitor	110	6.6061	3.8167	4.7667	6.0500	6.5500	6.9083	7.9500	9.6833
Retailer		58%							
ATM		0%							
Bank		36%							
Competitor		35%							

The time on customer site reduction also improves customer engagement with the armored courier. Transactions are completed more quickly and accurately, which in turn should improve the overall customer experience. The transaction with the retailer first has notice before the messenger arrives, allowing the retail manager to be ready. Since the bag information was transmitted to the ATC (and bank) via API, the messenger can do a brief RFID scan and quickly accept the bags.

At a competitor, in the current state, there is a paper manifest and a bag-by-bag check of the transfer. The paper document is completed. In the future state, the messenger can scan the bags, much like the retail experience, and accept the bags more quickly. In the current state, the competitor transaction is notoriously a time-consuming transaction since it lacks integration. In the future state, it will be quicker and significantly reduce error. In addition, even if the competitor does not fully integrate with the API, the bagID and the standard endpoint are stored in the memory of the RFID tag allowing a separate system to consume the data (e.g., manifest on the tag).

In summary, the application of RFID and API integration to the cash transportation system has yielded significant improvement in the cost of operational behaviors. These reductions are as follows: a 43% reduction in route time, elimination of overtime, a 79% reduction in teller utilization, and a 77% reduction in the time spent passing bags in the mantrap. Next, these values are compared to the previous business case.

Future Business Case Model

The future business case model must include the cost of the robotics system, the RFID systems, and the RFID tags. It must also include the installation and maintenance of the equipment. For the most part, the model consists of retail pricing for equipment, although significant hardware price reductions are likely. It is impossible to predict the buying power of an entity, so retail prices are used.

From the workforce perspective, the savings are significant. The model shows savings in all categories. Table 30 shows the future business model breakdown based on the future state simulation model.

Table 30 - Future Case Simulated Manpower Costs

Role	Task	Time on Task (Min)	Cost	#	Daily Cost	Annual Cost
Vault Teller Armed	Outbound Transfer to CIT	7.5418	$3.39	45	$152.72	$55,743.58
CIT Messenger Armed	Outbound Transfer to CIT	7.5418	$3.27	45	$147.07	$53,679.00
CIT Driver Armed	Outbound Transfer to CIT	7.5418	$3.27	45	$147.07	$53,679.00
Teller 1	Mixed/Shared	2.8309	$1.27	1	$1.27	$464.98
Teller 2	Mixed/Shared	2.8360	$1.28	1	$1.28	$465.82
Teller 3	Mixed/Shared	2.8121	$1.27	1	$1.27	$461.88
Teller 4	Mixed/Shared	2.7934	$1.26	1	$1.26	$458.82
Teller 5	Mixed/Shared	2.7951	$1.26	1	$1.26	$459.10
Vault Teller Armed	Inbound Transfer to Vault	4.0375	$1.82	45	$81.76	$29,842.05
CIT Messenger Armed	Inbound Transfer to Vault	4.0375	$1.75	45	$78.73	$28,736.79
CIT Messenger Armed	Waiting Time for Mantrap	0.0430	$0.02	45	$0.84	$305.92
CIT Messenger Armed	Route Operation	384.2340	$166.50	45	$7,492.56	$2,734,785.50
CIT Driver Armed	Route Operation	384.2340	$166.50	45	$7,492.56	$2,734,785.50
CIT Messenger Armed	Route Operation (OT)	0	$-	45	$-	$ -
CIT Driver Armed	Route Operation (OT)	0	$-	45	$-	$ -
				Total	**$15,599.64**	**$5,693,867.92**

The difference between the two models is $2,864,082.51 annually and $7,846.80 daily. It is important to note that trimming almost all overtime, reducing the time required for virtually every task for 95 employees, and eliminating two employees are responsible for this significant reduction.

The observed ATC provided some estimates of the reduction in risk because of the cash visibility system. These include reductions in ATM loading errors, loss of currency, accidental loss through inadvertently dropping bags in the garbage, errors in documentation, and errors where customer accounts are not credited with deposits. The risk cost-saving estimates are approximately $59,000 annually.

While the manpower and risk cost savings are significant, the model must include the cost of equipment, installation, maintenance, and recurring purchases (e.g., RFID tags). The cost of a single installation of each location for RFID (truck, mantrap, packing room, and RTLS) are listed in Table 31. These prices, as mentioned earlier, are full retail prices.

Table 31 - Single Installation Costs

Truck	Item	Cost	Quantity	Ext Cost
Reader	Impinj R700	$1,785.00	1	$1,785.00
Cable	RP TNC 10 foot	$50.00	4	$200.00
Router	BulletLTE-NA2	$399.00	1	$399.00
Antenna	Zebra AN-440	$276.00	4	$1,104.00
Misc.	Wiring, cables, etc.	$325.00	1	$325.00
Single Truck				**$3,813.00**

Mantrap	Item	Cost	Quantity	Ext Cost
Reader	Impinj R700	$1,785.00	1	$1,785.00
Cable	RP TNC 10 foot	$50.00	4	$200.00
Antenna	Times 7 A-8060	$240.00	4	$960.00
Misc.	Wiring, cables, etc.	$325.00	1	$325.00
POE Drop	POE Drop for reader	$300.00	1	$300.00
Single Mantrap				**$3,570.00**

RTLS	Item	Cost	Quantity	Ext Cost
Reader	Impinj X-Array	$3,300.00	1	$3,300.00
Misc.	Wiring, cables, etc.	$325.00	1	$325.00
POE Drop	POE Drop for reader	$300.00	1	$300.00
Single RTLS				**$3,925.00**

Office Space	Item	Cost	Quantity	Ext Cost
Desktop Printer	Zebra ZT41143-T0100A0Z	$4,380.00	1	$4,380.00
Single Printer				**$4,380.00**

Multiplying the cost of the single installation by the number of locations at a branch yields the values found in Table 32. Employee RFID badges are also included in the branch cost.

Note that five mantraps are included in the cost estimate to cover additional points where employees travel.

Table 32 - Branch Equipment Cost

Branch	Cost	Quantity	Extended Cost
Choke Points	$3,570.00	5	$17,850.00
RTLS	$3,925.00	15	$58,875.00
Trucks	$3,813.00	45	$171,585.00
Printer	$4,380.00	5	$21,900.00
Employee Badges	$5.00	200	$1,000.00
Total Equipment			**$271,210.00**

The software development and deployment costs are based on an unofficial quotation from a software vendor. The installation costs are based on a percentage of the hardware cost at 5% for branch installation and 7% for vehicle installation. This brings the total cost of hardware and software to $2,788,202.20. See Table 33.

Table 33 - Total of Hardware and Software Costs

Hardware and Software	Cost
Equipment	$271,210.00
Software Development	$2,500,000.00
Branch Equipment Installation (5%)	$4,981.25
Truck Equipment Installation (7%)	$12,010.95
Hardware and Software Total	**$2,788,202.20**

The recurring costs include the lease of the AmbiSort robotic sorting system, the purchase of RFID tags, and annual hardware and software maintenance agreements. The annual hardware and software agreements start in year two of the project. The software maintenance agreement is estimated at 18% of the purchase price. The hardware maintenance agreement is based on 20% of the original purchase price. The estimated tag use is equivalent to the actual monthly bag counts multiplied by twelve. The actual monthly count for the branch observed is 85,362 bags. When multiplied by annual usage, the total comes to 1,024,344 RFID tags for a single branch for one year. The tag cost is estimated at $0.10/tag. See Table 34.

Table 34 - Recurring Expenses

Recurring Expenses	Cost
Tags	$102,434.40
Robotics Lease	$120,000.00
Annual Software Maintenance 2nd Year+	$450,000.00
Annual Hardware Maintenance 2nd Year+	$54,242.00
First Year Recurring Expenses	$222,434.40
Future Year Recurring Expenses	$726,676.40

Given the preceding information, the overall first-year cost of the system is $3,010,633.00, with an annualized savings of $2,922,895.92. The payback period is 1.03 years. In years two and beyond, the annual savings are approximately $2,196,223.12. See Table 35.

Table 35 - Synopsis of Financials

ROI Calculator	
Location	**45 truck Branch**
Initial Costs	
Cost of Equipment	$271,210.00
Software Development	$2,500,000.00
Branch Equipment Installation (5%)	$4,981.25
Truck Equipment Installation (7%)	$12,010.95
Total Capex	**$2,788,202.20**
Operational Costs	
Tags	$102,430.80
Robotics Lease	$120,000.00
Annual Software Maintenance 2nd Year+	$450,000.00
Annual Hardware Maintenance 2nd Year+	$54,242.00
1st year OPEX	**$222,430.80**
Future year OPEX (year 2 & beyond)	**$726,672.80**
Total First-Year Expenditure	**$3,010,633.00**
Future State Savings	**$2,922,895.92**
Period of Return on Investment in years	**1.03**
Period of Return on Investment in months	**12**
Annual Operational savings after ROI	**$2,196,223.12**

Additional Non-Financial Benefits

There are several non-financial benefits to adding such a system to an ATC. These include customer satisfaction, visibility benefits, compliance requirements, reduced loss, and handling errors.

Services, customer satisfaction, and customer retention are inextricably tied together. (Krishnan et al., 1999). An ATC that adopts a new technology that provides greater visibility of cash movement to its customers creates a new service to retain and add new customers. As mentioned earlier, the researcher spoke to several large retail chains and found frustration regarding knowing where their deposits are in the cash movement process. When citing the research, several volunteered to participate in future research.

People inherently understand that knowledge allows informed decisions. Each morning people look at the weather forecast to determine clothing choices and whether or not to carry an umbrella. Stock values and company reports determine whether a person might buy or sell a stock. Customers of UPS and Amazon find satisfaction in regular updates of a delivery. Within factories, informational scoreboards inform the workers of their collective progress for a shift.

On the other hand, people find incredible frustration over a lack of information they consider pertinent to decision-making. With a "black box" process, one only knows the input and output but rarely knows the internal behaviors of the black box. Often, as with the ATC industry, companies are unwilling to share what they consider sensitive information (Fawcett et al., 2012).

From a visibility standpoint, a system can have internal and external benefits. The external benefits are customer-facing and addressed above. The internal benefits yield highly actionable information for ATCs. The CIT manager understands the daily progress of the fleet of armored vehicles, crews, and cash liabilities. If a problem or deviation from the law or corporate policy is detected, the issue can be resolved more quickly. For instance, if a vehicle breaks down, the cash transfer from one vehicle to another would instantly be realized, and truck manifests changed automatically. The vault and CMS managers can know the bag count and make staffing decisions with better information. Employees can watch scoreboards as progress is made in processing deposits.

Customer satisfaction is impacted by the speed and accuracy of exchanging bags by the truck crews, reduction in handling errors, faster resolution of investigations of missing deposits, and providing visibility. Visibility of cash deposits as they move through the armored truck service can keep customers informed and eventually allow ATCs to verify contractual performance measures to their customers. Finally, providing Amazon-like notifications to customers of the arrival of armored trucks can allow customers to be prepared before the messenger's arrival and further reduce the time to make bag exchanges.

Beyond the immediate benefits, researching cash bags when an error exists can be accomplished in record time with live bag tracking. With each employee wearing an RFID badge, employees can be associated with bag movement. As mentioned in the financials, the risk department at the observed ATC felt the company’s risk would decrease by reducing lost/misplaced bags, theft, tampering, customer account credit errors, and documentation errors.

Items Not Included in Business Cost Model

The approach of this model has been focused on a single branch of an ATC and not on the complete industry adoption of this technology. The researcher believes that, with such significant savings, the industry seeks to deploy such systems broadly. The following paragraphs explore additional costs not included in the model.

RFID label printers at retailers and banks are not included in the model. A low-volume RFID label printer costs around $2,500 (Zebra ZD-500). Each customer of the adopting ATC must purchase an RIFD label printer for every location that produces cash bags. Retailers like T-Mobile and Walgreens have told the researcher that this purchase is possible with better traceability and visibility of cash movement. It is impracticable for the ATC to purchase the printer for every customer. An alternative is adding a small portable label printer on the messenger, which adds time to every transaction. A second alternative is adding a printer in the armored vehicle, but again, visibility is lost. The researcher does believe that the ATC should be responsible for purchasing the RFID tags for the customers since the buying power of the ATC is much greater than that of most retailers and banks.

The integration work of an API from the retailer to the bank and ATC is not included in this model. Each retailer has its own business systems that must comply with the transactions. The API already exists and is being promoted in the industry, but adoption is minimal.

The integration work for the API between competing ATCs is very challenging. Competition for clients in the market drives down profit margins between ATCs in specific markets. There is a genuine dislike between ATCs, and the researcher has been told by a senior leader in one of the top three, “I won’t do anything that helps a competitor.”

Additional Challenges

The cash management industry is fragmented, with several competing interests. Some ATCs feel that technology is great, and others are technology-phobic. Some ATCs focus on volume with small profit margins, and others focus on providing additional services, growing the profit margin.

There is a concern in ATCs that providing armored vehicle locations to customers is a security risk, and they strongly object to sharing location information and Amazon-like behaviors. There are some workarounds available that have not been explored in this research.

Coin management is not addressed in this research. There is a growing trend in the industry to outsource coin processes to third-party contractors. Throughout the investigation, coin has been considered but not included in the model. The solution for coin could be to place a generic denomination RFID tag in each box of coins (e.g., a tag that responds with an EPC of "Box of Quarters.").

Summary

Cash movements by ATCs today employ small deployments of technology but lack a cooperative, holistic view of the entire ecosystem of cash traceability and visibility. Adding API integrations between retailers, ATCs, banks, competitors, and Federal Reserve Bank allows a free flow of information about cash movements. By adding passive RFID systems and leveraging information sharing, ATCs and others in the ecosystem of cash can reduce operational costs significantly, increase their operational capacity, and improve customer satisfaction.

During this research, a detailed process mapping study was accomplished and validated through several exchanges with the ATC employees and leadership. The process map was turned into a simulation model using AnyLogic software and tuned to match the process map documentation, observed behaviors, and documents provided by the ATC (e.g., staff pay scales, historical working hours, historical bag processing, and risk analysis information). This output became the baseline for a financial business estimation of operational costs for the branch in specific areas (e.g., bag sorting and bag transfer of custody).

Once a model was established and produced results similar to the branch, an investigation was made into three IoT technologies, comparing them to the requirements and needs of the various use cases of a branch. The time savings produced by transactions and API integration between entities that transfer cash bags were evaluated, and the model was adjusted to operate with those values. A new business financial model was established and then compared, illustrating significant optimizations with the addition of RFID and API integration.

Adopting these proven innovations in the cash industry has now been shown to have a significant financial impact. In the example shown here, the investment in equipment has a payback period of roughly one year. A 45-vehicle branch that processes change orders and deposits can save as much as $2.1 million annually. The system also has non-monetary advantages, including improved customer satisfaction and reduced errors.

CHAPTER 9

RECOMMENDATIONS/CONCLUSIONS

Recommendations

The operational cost savings illustrated in this research are substantial and worthy of further action. While expecting an entire industry to adopt a new technology application overnight is unrealistic, this research strongly indicates that adding RFID technology within the cash transportation industry can reduce costs, improve capacity, and provide visibility to all parties involved in the cash movement. As with any new application, the researcher recommends that a few ATCs, banks, and retailers begin proofs-of-concept to validate these findings within their organizations and the industry.

This research relies on adopting an API that the Federal Reserve Bank and the cash management industry are already exploring. As more ATCs, banks, and retailers adopt the API, the next logical step is integrating RFID. The researcher, however, firmly believes that an ATC that adopts even part of this solution (RFID tags on bags, robotic sorting, mantrap, and truck readers) can reduce costs and expand branch capacity. ATCs that engage at this level find lower costs, increased capacity, and improved cash visibility which, in turn, yields increased customer satisfaction if they share information with their customers.

Conclusions

This research started with an opportunity to discover the complex operations of an ATC through an extensive process mapping exercise. Additionally, a time-motion study was conducted, and the ATC provided several internal documents. With this information, a process mapping document was created and provided for validation to the ATC. The branch manager and several corporate-level executives thoroughly reviewed the process mapping document.

This information was then used to create a simulation model that mimics the operational behaviors of the branch. The model was tuned and validated against both observed data, provided data, and information provided by the ATC employees. A business cost estimate was constructed from this information and the simulation output. This output established a baseline for the research.

Following establishing the baseline, an extensive survey was accomplished of potential IoT technologies that might have an application for the overall use case. Active BLE, passive BLE (Wiliot), and passive RFID were evaluated for several requirements from observing activities at the ATC branch. Passive RFID was chosen because it met all of the established requirements for such an installation. Afterward, a set of RFID requirements were established for RFID tags.

With the chosen IoT technology, a vision was set forth of how an RFID system might reduce costs in the original model by reducing the working time required to perform tasks. These tasks included the operational behaviors of armored truck drivers, messengers, and tellers within the branch. Model changes were made, and the simulation was run with the new parameters. The model results indicated significant task-related work time reductions in every operational process except ATM servicing. An estimation was made of the costs for the RFID system, including equipment cost, installation, and maintenance. The estimation also includes an estimation for software integration and maintenance. From this, a new business cost estimate was accomplished and then compared.

The savings for adding RFID were significant compared to the baseline cost estimate. The annual operational savings are estimated to be over $2.1 million for a 45-truck branch. Not only does the new model save operational costs, but it also adds branch capacity, which, in turn, allows the branch to service more customers. The RFID system also provides visibility to the ATC and, if shared, their customers. Visibility sharing increases customer satisfaction and provides better customer retention.

Having exhausted the topic of the traceability of cash within ATCs, banks, and retailers, this method should positively impact the bottom line of ATCs. Retailers and banks also gain by understanding the cash movement throughout the network. While not discussed in this research, the additional metrics in such a system may lead to additional savings or optimizations.

Clearly, in the case examined, the savings of $2.1 million annually are not trivial. The next step in the research is taking this concept from theory to proof of concept. The researcher hopes this topic does not stop within this document but has a lasting impact on cash visibility in ATCs, banks, and retailers.

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APPENDIX A

PROCESS MAPPING OF THE CURRENT STATE

Process mapping was conducted at a major ATC over a week through observation, interview, and documentation review. The ATC (“Company”) is the cash management company that uses its armored vehicles to safely transport cash for customers, banks, ATMs, and the Federal Reserve Bank. Depending on the contract, the services provided by the Company can be courier services, cash and coin processing, and storage. This Company stores large sums of cash for several banks within its facility to enable a more efficient transfer of funds to and from the customers of these hosted banks. More than half of the operations in the Company branch are conducted between the hosted banks and those banks’ customers within the branch's service area. These transactions with customers are fully processed within the Company facility.

Sometimes, the Company is contracted as the courier service between a customer and a bank not hosted at the Company facility. These transactions (deposits and change orders) are not processed within the Houston branch. Deposits picked up for these foreign (banks not processed in the ATC processing operations) are brought to the branch, sorted, and sent by truck to the bank the following day(s). Change orders from foreign banks are also distributed through Company truck routes on the following day(s).

In addition, some banks are hosted by foreign couriers (competitors to the Company). These courier companies regularly come to the Company branch to pick up and transport deposits to their own hosted banks or banks not serviced by Company. Change orders from these foreign couriers, and the banks they service, are picked up by Company trucks regularly.

Foreign couriers also service customers for whom Company hosts the customer's bank. In these cases, Company trucks go to the foreign couriers' facilities and collect deposits regularly. Those deposits are processed within the Company facility. In addition, the Company prepares change orders destined for foreign courier customers. These change orders are picked up regularly.

Finally, the Company acts as an interface between the Federal Reserve Bank, banks hosted within the Company branch, and banks that are Company customers (those not storing cash at the Company but using their courier services).

Inbound Transfer -Figure 76

Several sources exist for the inbound asset transfer to the Company facility. Tamper-resistant packages are typically used for these transfers. These may be deposits, smart-safe cash, ATM residuals, or foreign deposits and change orders. Company trucks typically picked up these items during Cash In Transit (CIT) operations and transported them back to the Company branch facility. This process may also start at the Federal Reserve Bank.

Customer

The customer is the starting point of the Inbound transfer to the Company facility. The messenger picks up cash bags from the customers for delivery to the Company facility. These bags may contain cash, checks, and coins and represent deposits from customers, returns, smart-safe, ATM residuals, or packages from foreign banks for redistribution, as seen in Figure 72.

The work performed by the messenger varies depending on the starting point. In the case of a deposit, the messenger logs into the PDA (Personal Digital Assistant), inspects the cash bag, scans the bag ID, enters the amount into the PDA, and the customer signs a screen on the PDA application transferring custody of the cash bag to the messenger.

The Company crews also service ATMs. On reaching the ATM, the messenger removes the ATM residual, packages it in a bag, restocks the ATM with fresh cash, prints a receipt, and places the ATM residual cash bags in the truck for transport back to the Company facility. Certain banks have ATM(s) located on the bank premises.

Inbound Cash Transfer

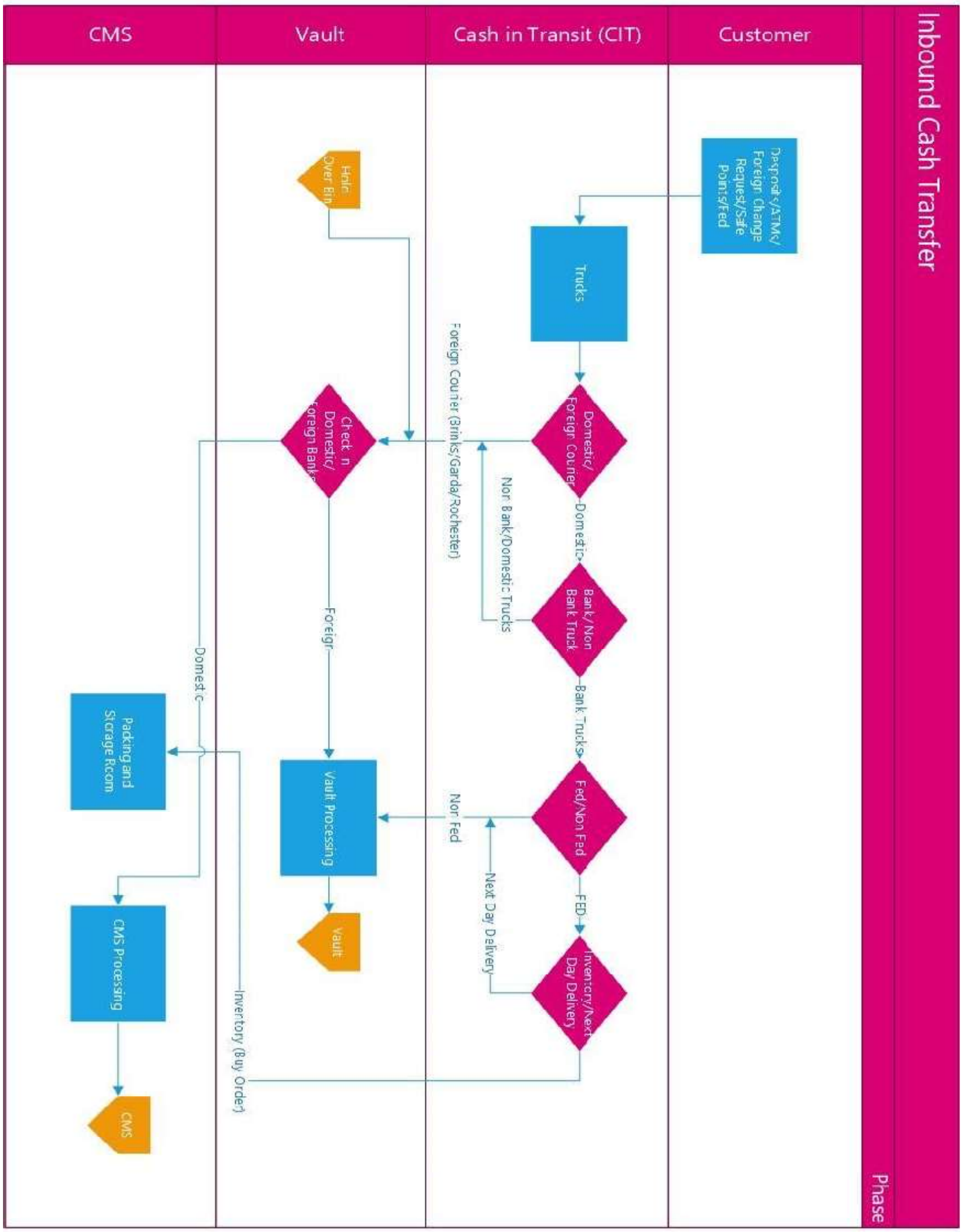


Figure 76 - Inbound Cash Process Mapping

On reaching these banks, the messenger is given cash from the bank, replenishes the ATM, and returns the residual to the bank.

Change orders are also received by messengers from foreign banks or foreign courier facilities, which are transported to customers usually during the next working day. A manifest is also sent along with these cash bags to the Company facility. The manifests are manually entered into the Company Cash in transit management software to route the cash bags within the Company management systems appropriately.

Cash In Transit (CIT)

Cash In Transit constitutes the operations of the armored vehicles from the customer to the Company facility. The Company has three types of armored vehicles - Route vans, Route trucks, and Bank Trucks. The route van operates with one individual acting as the driver and messenger. The route trucks have two-person crews (messenger and driver), while the bank trucks have three-person crews. The bank trucks are utilized whenever a large amount of cash is handled. Hence bank trucks perform the CIT operations to and from the Federal Reserve Bank and certain foreign banks (e.g., Wells Fargo, Amegy), which courier large cash transfers. In addition, smaller couriers can be contracted by the Company to perform CIT operations for remote customers.

After the messenger scans and receives the cash bags, liability is transferred from the customer to Company CIT. After completing their assigned routes, the messenger takes custody of the cash bags, places them in the truck, and reaches the Company facility. There are multiple security checks performed on returning trucks. The first security check occurs inside the Company premises before entering the lanes. If there is no exception, the drive-through doors are opened, and the truck enters a secure truck area. The messenger removes the cash bags from the truck, places them in totes, and places the totes on a cart. There is another security check of the truck from inside to ensure all liabilities are removed from the vehicle. The messenger enters a controlled area between the truck lane and vault teller windows. Once the contents of the route are in the controlled area and the exterior door is closed, the teller may open the window to start receiving the cash bags. The messenger hands over the cash bags one-by-one and the equipment and list. This process transfers the custody of the bags and equipment to the vault operations teller.

Vault Operations -Figure 77

The vault area inside the Company facility consists of the space between the vault window and the packaging room. There are four vault windows for receiving the cash bags from the CIT, and tellers and supervisors perform different operations inside the vault. The cash bags picked up by the Company trucks are transferred to the vault team through designated controlled areas. Receiving the cash bags from the messengers is referred to as the check-in process. The controlled areas where the cash bags are received are small hallways called “man traps” where the doors cannot be opened simultaneously. If the teller door is open, the door to the CIT area is locked. Once in the man trap, the messenger cannot leave until the vault teller closes their door, releasing the exit door.

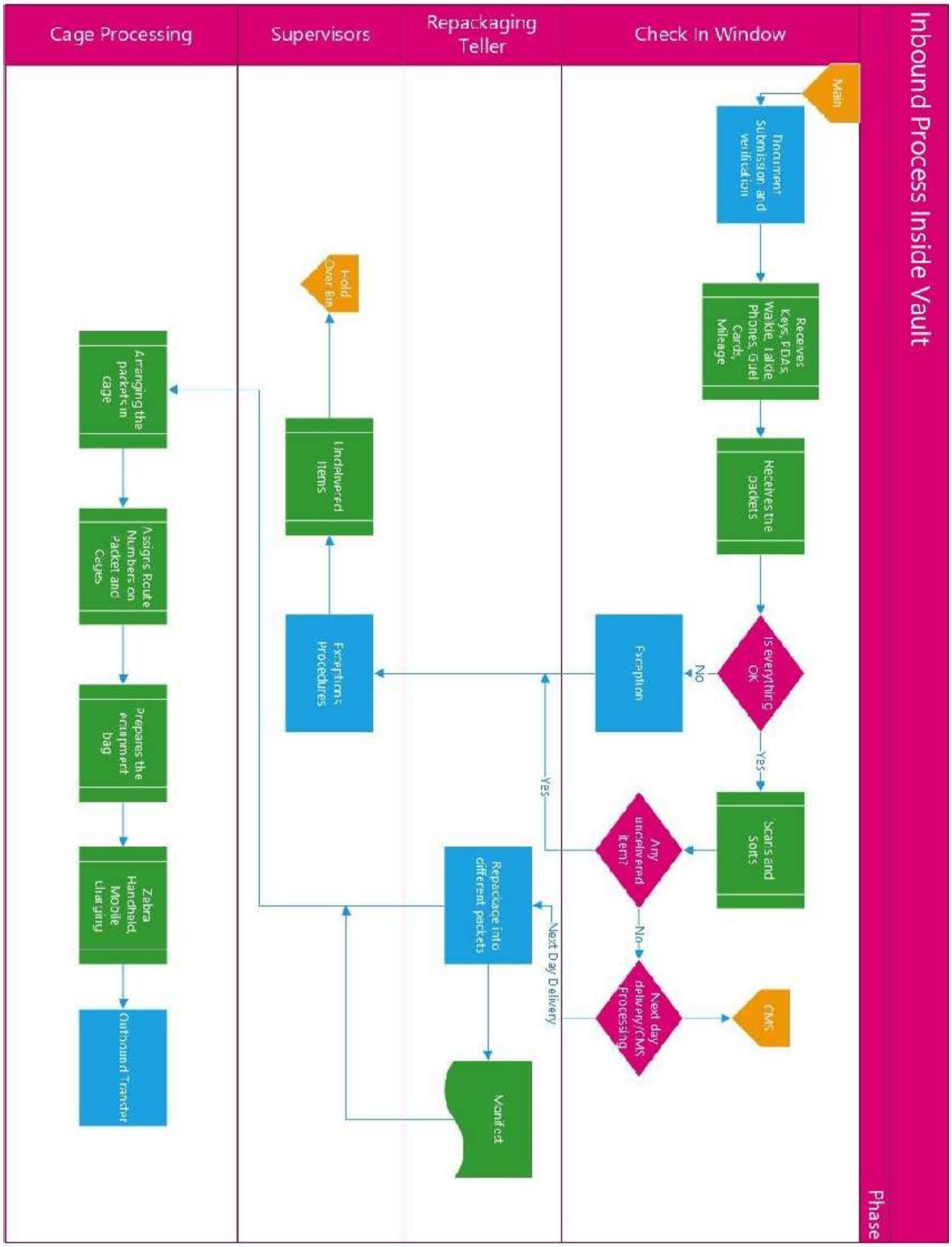


Figure 77 - Vault Inbound Cash Process Map

For Company trucks, during the check-in process, the vault window teller receives the cash bags, equipment (e.g., PDA, mobile phones, keys, radio, fuel cards) mileage logs, equipment list, driver route sheet, ATM operation manual, and outbound delivery sheets from the messengers. The tellers check the integrity of each cash bag by performing a six-sided inspection, scanning the bag barcode, and validating the cash bag in the Cash in Transit management software. Any mismatch or exception is referred to the vault supervisor. After receiving the cash bag, they sort it into various totes or carts. Items are presorted for CMS, distributed to CIT for delivery to another destination, or accepted as returned packages. Any returned package that was not deliverable is given to the vault supervisor for CIT route assignment, typically the next contracted customer day. The cash bags for the CMS processing are sent to a CMS holding room in various totes, carts, and rolling bins.

The foreign couriers' cash bags are received at a specific window operated by the CMS department. These cash bags are deposits from foreign couriers. These are bags that the foreign courier has the contract for transportation but does not process cash deposits for the customer’s bank. The bags received this way are taken directly to CMS processing without being processed through the vault cash in transit management software. Often these bags are in over-pack bags with security seals and an associated paper manifest.

The Federal Reserve Bank buy orders are transferred using large metal and glass securable containers in the Company bank trucks and received in the vault area. Some Federal Reserve Bank cash involves buy orders from foreign banks, which the Company services with courier services. The remaining portion of the Federal Reserve Bank cash is sent from the Vault to the packing room and stored in the associated banks with storage contracts with the Company.

Cash Management Operations -Figure 78

Cash management forms the core of the Company's processing and storage operations. When deposits, ATM residuals, and Smart safe deposits are received, the cash is processed inside the CMS and stored inside the packing room.

Logging Room

The logging room is where tellers assign bags to teller groups within the CMS area. Four to five tellers come in during the early morning shift at 5:00 a.m. and perform a detailed sorting of the cash bags received from the vault team the previous day. The sorting process takes approximately 2 hr. After sorting, the tellers check the cash bags and log the cash bags into the Company cash management system software. After logging, they assign the cash bags to the specific teller teams.

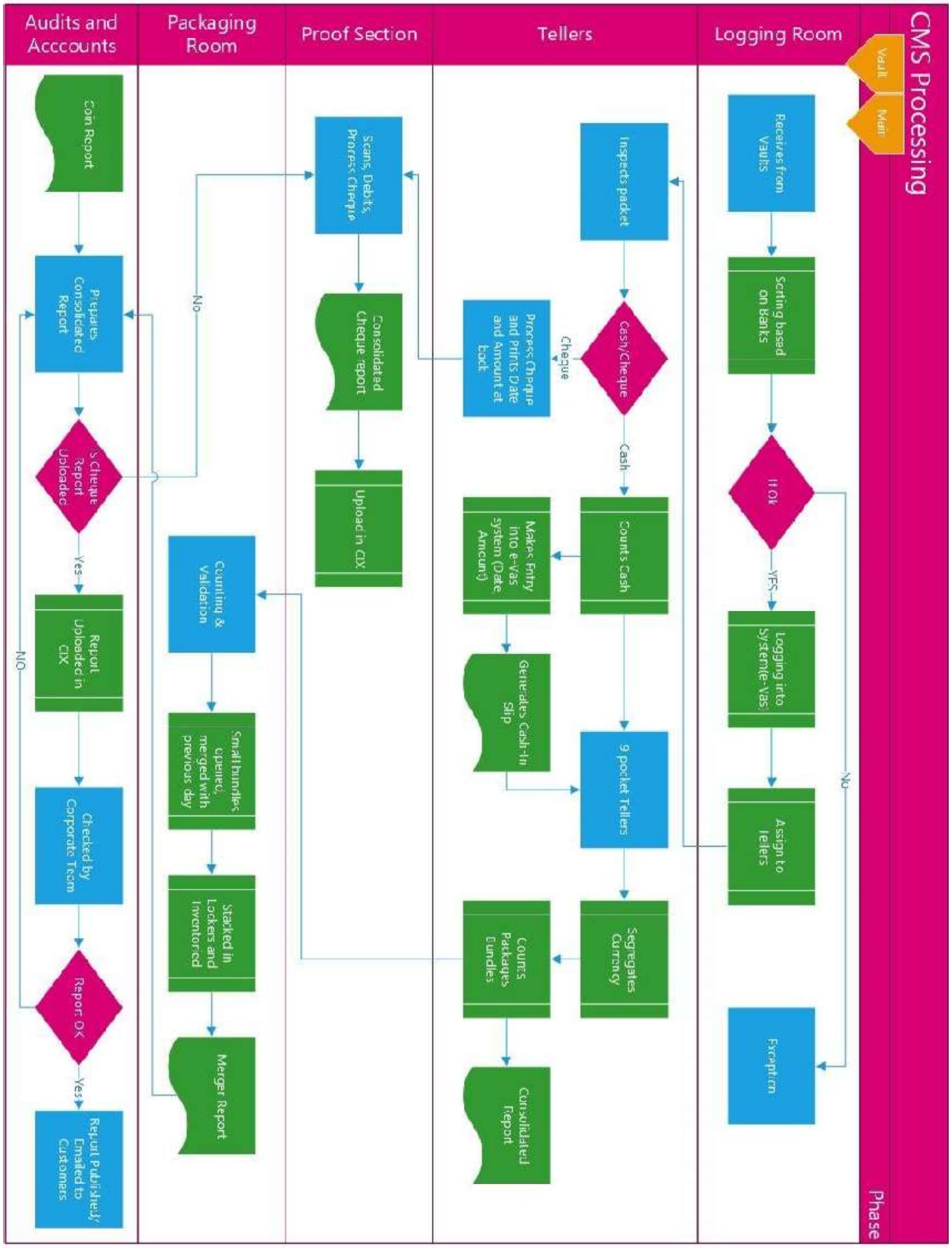


Figure 78 - CMS Processing Process Map

Counting and Processing Tellers

Teller teams process the deposits, ATM residuals, and smart-safe contents. These tellers arrive in the 7:00 a.m. shift and start processing the assigned cash bags. They open the cash bags, process the deposit slips, count the cash, and, if the amounts match, they generate a cash-In slip, print the deposit amount on the back of the deposit slip, and perform an entry into the cash management system software which creates a deposit transaction to the customer’s account. The teller does not process the checks; however, they print the amount on the back of the check deposit slip. The checks with the deposit slips are then sent to the proof section for processing.

Each teller works only for one bank at a time, and once the deposits are made, the cash is stored in a plastic bin for that particular bank. The plastic bins are periodically sent to the cash consolidation tellers. These tellers operate machines that segregate the currency based on denomination. After the cash segregation, these notes are packed into bundles, and a currency band is wrapped around these bundles. This cash is stacked in totes and sorted based on the associated bank. The coins are segregated and sent to the coin room for processing. These tellers then generate a consolidated report of the bundles and send the cash with the consolidated report to the packing and storage room.

Proof Section

After the checks are received inside the CMS, the checks are processed by the proof section tellers. They scan the checks and reconcile the fund transfer between the respective bank accounts. After the checks are processed, they send the checks to storage. After 90 days, the checks are destroyed. After processing the checks, the proof section prepares a consolidated check report in software the audit team uses for further consolidation by the audits and account section.

Coin Room

The coin room is a part of CMS. The coins are delivered to the coin room either through the CMS teller operations, trucks from the Company messengers, or foreign couriers. The Federal Reserve Bank also provides large volumes of coins brought by a private carrier to the Company loading dock.

The coins that come from the CMS tellers are in small cash bags. All these cash bags are a part of the deposits received inside CMS for processing. The coins from the banks come in larger bags for processing. The large cash bags are weighed, and if the bag's weight is inconsistent with the value noted on the bag, it is counted. Some coins come in rolls, while others are mixed denomination coins. All the above types of cash bags are processed and counted inside the coin room.

The processing of coins involves cutting the bag, pouring the coins into the hopper of a machine that counts the bag's value by denomination, segregates the coins by denomination, and places them in different sacks. These large sacks are then stacked on racks/skids.

When creating coin rolls and boxes of coin rolls, the pallets of coins are moved by forklifts. A sizeable rolling machine and two robots roll and box quarters. Other denominations are being processed by three smaller roller machines and boxed on a station by an operator.

For quarters, coins are poured into a large hopper which moves coins onto a conveyor belt. A large, automated quarter rolling machine produces rolled quarters that travel via conveyor to the automated collection and boxing area. A robot opens the coin box, packs the coin into the box, and transfers the box to another robot that stacks the boxed quarters onto skids. These skids are then inventoried inside the coin room. For other denominations of coins, small cash bags are cut manually and poured into the hopper of three small rolling machines that roll the coins packed in the boxes.

The coin room prepares a daily report of all the coins received and dispatched through the trucks and delivers this report to the Audits and Account section inside CMS for consolidation with the master report.

Packing and Storage Room

The packing and storage room is the cash storage room of the Company facility. It stores the cash for the banks that have contracted the Company for storing and processing its cash deposits, change orders, and servicing ATMs.

The packaged cash from the cash consolidation area and the consolidated report are received in the packing room. Upon receiving the cash from the CMS tellers, the packing room supervisor signs and receives the liability. The cash bundle cash bags are counted and validated by the packing room. Any bundle of cash less than 100-count is counted again in the packing room and merged with the previous day's inventory of partial bundles.

Similarly, the packing room receives the Federal Reserve Bank cash from the vault team. These cash bags get stored in the respective bank locations. After receiving all the cash inside the packing room for the day, a merger report is created and sent to the audits and accounts section for reconciliation.

Audits and Accounts section

The audit supervisor receives the coin report from the coin room, a merger report from the packing room, and a check report from the proof section. They prepare a consolidated reconciliation report and upload it into the audit reporting system software. After uploading the consolidated report, this report is cross-checked by the corporate team. Finally, after everything has been validated, the report gets published in the audit reporting system software or emailed to the customers per their requirements. Specific customers can access the audit reporting system software and check their cash and coin reports daily. However, other customers desire to have the report emailed to them at the end of each day.

Other Operations

Several foreign banks with large customers require special handling of inbound packages. For instance, they process a large number of packages from retailers. Often these large retailers use banks that process internally (do not outsource to ATCs). Because of the large volume of cash, the cash is repackaged into larger bags, and manifests are created and sent to a large bank. The repackaged larger bags are then transported by truck to a bank's main vault location for processing. The bank truck is required because the liability is too big for a route truck.

While outsourcing deposits, change orders, and ATM residuals to an ATC, some banks process their checks. These checks are collected and shipped via UPS each day.

Bank trucks also service transactions with the Federal Reserve Bank, making regular trips to deliver cash that is part of a sell order and picking up cash that is part of a buy order. These transactions only occur between banks. As mentioned above, some transactions with the Federal Reserve Bank are for hosted banks, and some are for banks that Company services through CIT.

As mentioned, a large ATC may contract with a smaller ATC to act as an extension of CIT operations in smaller or more distant markets. For this document, these smaller ATCs operate like a Company route truck except for the more detailed chain of custody transfers.

Outbound Transfer -Figure 79

Outbound transfer starts with the receiving of the change orders from customers. These orders may be standing orders or regular orders. Standing orders represent requests from customers that are completed on a regular cycle. For instance, a retailer may have a standing order for change to be shipped every Tuesday and Friday. These orders happen automatically without customers sending additional requests. Regular orders are more intermittent and start with a request from the customer to their bank.

Packing Room

The supervisor in the packing room receives the change orders. As soon as an order is received and the paperwork is compiled, the tellers retrieve the cash and coin from the storage area of the affected bank. Multiple change orders are aggregated so the tellers process a series of transactions for a single bank. Each order contains a specified quantity by a denomination of both cash and coins. Those denominations are gathered from the withdrawn cash/coin and placed in tamper-resistant bags. A document containing the location of the delivery point is also placed inside the cash bag. All the packed change orders are then transferred to the vault section. In addition to the cash change orders, the packing room receives coin-only change orders. The small quantity coin orders are processed inside the packing room. However, bulk coin orders are processed by the coin room. The supervisor of the packing room sends the bulk coin demand order to the coin room supervisor.

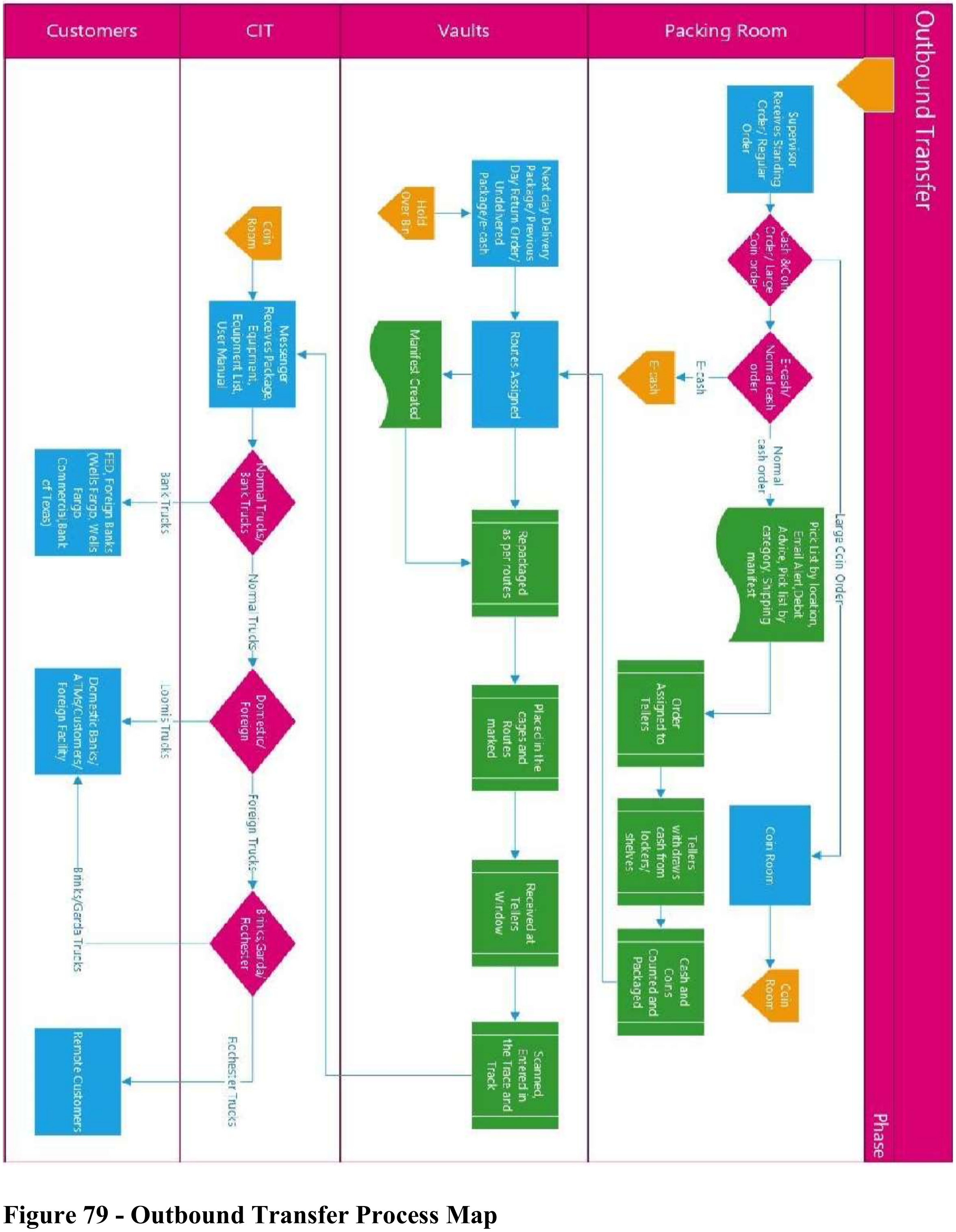


Figure 79 - Outbound Transfer Process Map

Coin Rom Process -Figure 80

The coin room deals with three kinds of orders. First, they are responsible for placing coin into the packing room to support the daily volume of change orders smaller than an entire box of coins. Second, they supply boxes of coins to the CIT truck messengers to fill larger coin change orders that require full boxes of rolled coins. Third, the coin room fills larger orders of coin ordered by foreign banks. These larger orders are placed on heavy-duty skids that are transportable by a forklift. Foreign bank trucks typically pick up these larger orders.

The coin room supervisor receives coin change orders from the packing room. After receiving the order, the coin room responds by compiling the order based on the three scenarios above. The coin room works directly with foreign couriers to dispatch larger quantities of coins, usually boxed and placed on pallets.

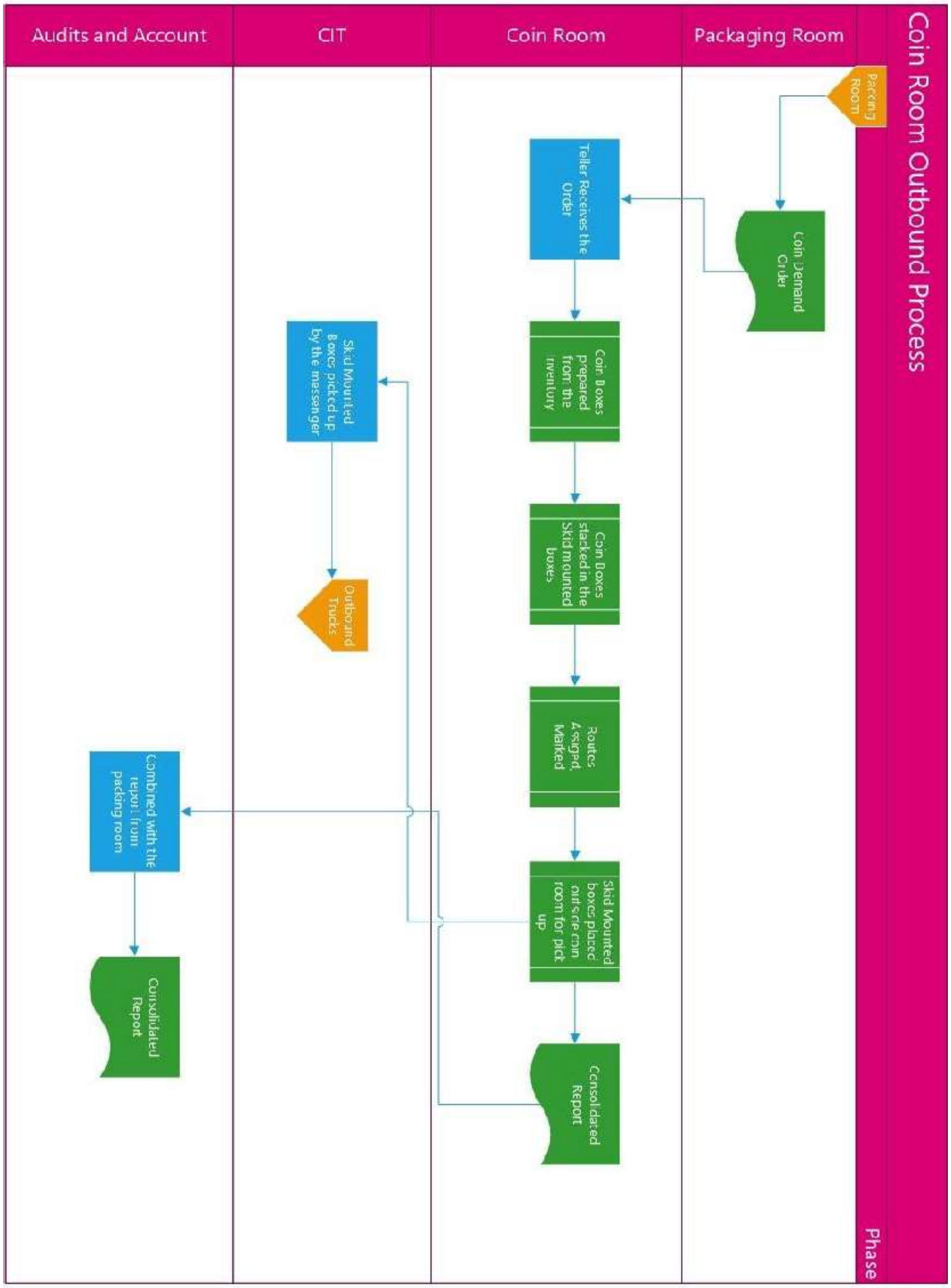


Figure 80 - Coin Room Process Map

Vault

The outbound process inside the vault involves handling two types of cash bags: Cash bags from the packing room and Repackaged cash bags.

Cash bags from the packing room

Change orders prepared in the packing room are delivered to the vault team in tamper-resistant bags containing the necessary paperwork. These bags are scanned and assigned to routes in the Cash in transit management software or to foreign couriers. For the bags assigned to routes, a teller sorts the cash bags based on routes and arranges them in rollable steel cages. This process is usually completed in the evening, but modifications to route assignments may continue overnight. These cages contain up to three routes. When a messenger comes to pick up the bags for the route, the cage is rolled out to the CIT truck lane.

Repackaged cash bags

These cash bags consist of deposits of the customers to be transported to foreign banks and Federal Reserve Bank transfers. These bags are sorted in the vault by tellers, repackaged, and assigned to the routes. The route numbers are marked on these bags. A manifest is created according to the route numbers. The repackaged items are either placed in cages to be delivered by route trucks or placed on large carts to be transported by the bank truck.

Other vault processes

In addition to processing the cash bags, the vault tellers prepare an equipment list during the night shift, check the equipment and organize it for the morning routes, and charge the mobile phones, PDAa, and radios. These items are handed over to the CIT team before handing over the cash bags for the outbound delivery.

Cash In Transit (CIT)

Route trucks, vans, and bank trucks carry out CIT. Contracted foreign couriers perform some CIT operations in smaller markets. CIT starts in the morning when the crews place their truck in the designated lane, and the messenger arrives at the vault window. The messenger reaches the window and receives the equipment list, equipment, route manifest, radio, mobile phone, PDA, and required manuals. The rolling steel cages containing the cash bags for that messenger's route are rolled out to the lane. The messenger scans the cash bags with the PDA and a cash-in-transit management application and places them in the truck. Any discrepancy between the cash bags in the cage and the list of cash bags on the cash in transit management application is resolved by returning to the teller window.

Coin orders may be picked up at the teller window or, for larger orders, picked up directly from the coin room. The trucks then leave the Company facility and deliver the cash bags to the customers according to the schedule and the route.

When a truck reaches a location where they deliver a change order, the messenger uses the cash in transit management application to identify the bags to be delivered to the customer. The messenger registers into the customer's record and takes the bags and coins (if any) to the customer for delivery. Each bag is scanned by the messenger, and the client signs the PDA screen verifying that the delivery is completed, which transfers the chain of custody from the messenger to the customer. The Company bank trucks take the repackaged items to foreign banks. The sell orders to the Federal Reserve Bank are also sent in the Company bank trucks.

Customers

The customers are the final destination in the outbound process. As defined earlier, the customers are retailers, foreign banks, ATMs, foreign courier facilities, and the Federal Reserve Bank.

<u>Foreign Couriers</u>

In addition to the Company trucks, foreign courier trucks receive cash bags from the vault window for the outbound transfer. The Company also cooperates with other armored car companies, as mentioned throughout this document. Foreign couriers pick up change orders from the Company when customers that bank with hosted banks choose a competitive armored vehicle company to act as their courier service. Deposits to the Company hosted banks are also picked up from foreign couriers and brought back to the Company for processing in CMS.

Likewise, a foreign carrier may also host banks within the facility for which the Company is the courier. In these cases, Company trucks pick up change orders from foreign couriers, sort them, and deliver them to customers according to the contracted schedule. The Company also picks up deposits from these customers and then transfers them to foreign couriers for processing.

Additional Processes

Holdover Bin – Figure 81

The holdover bin is a storage location for six types of transactions/situations that may occur during CIT operations.

Undelivered change orders

When a messenger cannot deliver a change order to a customer, the cash bag is returned to the branch. The vault manager checks the contract requirements for the customer and decides when to make an additional delivery attempt. If the manager decides to hold the bag for more than one day, the bag is rescheduled for the next contract delivery day and held in the holdover bin.

Packets from foreign couriers without manifest

When the foreign couriers bring cash bags to the vault window of the Company facility, there may be cash bags that come without a proper manifest. All these cash bags get stored in the holdover bin until the manifest is received, or an investigation reveals the proper cash bag routing.

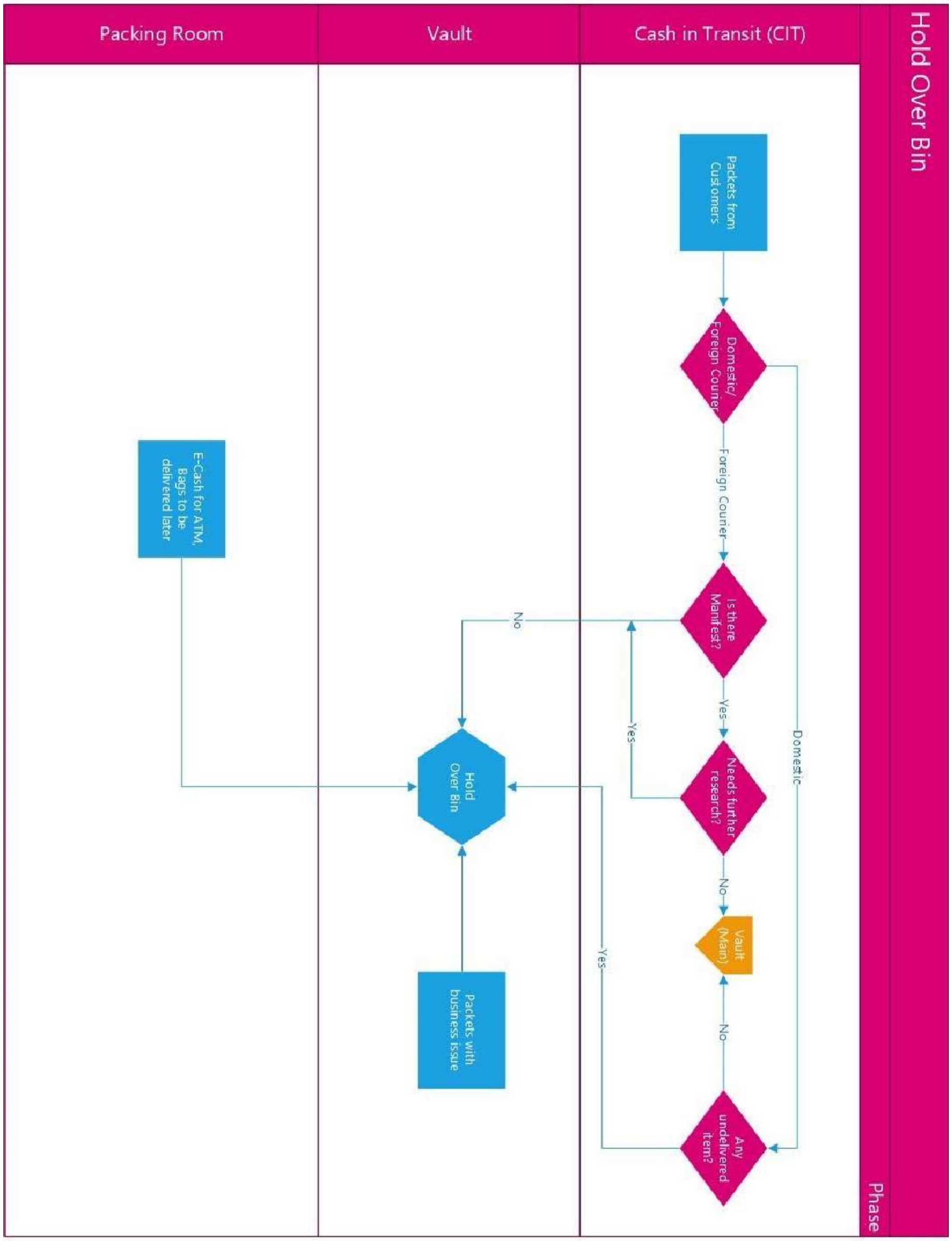


Figure 81 - Hold Over Bin Process Map

e-Cash – Figure 82

There are certain Banks that request ATM emergency refill cash bags. These emergency requests for cash delivery to the ATM are called e-cash. The e-cash orders are prepared by the packing room team and sent to the vault. The vault team puts these packets in the holdover bin. When the bank requests an emergency refill, a crew is dispatched with the eCash bag, and the ATM is serviced. Once the ATM is serviced, the bank puts in a new order for a new eCash bag. In some cases, eCash bags are provided to messenger crews daily to respond more quickly to unexpectedly low machines or out of cash.

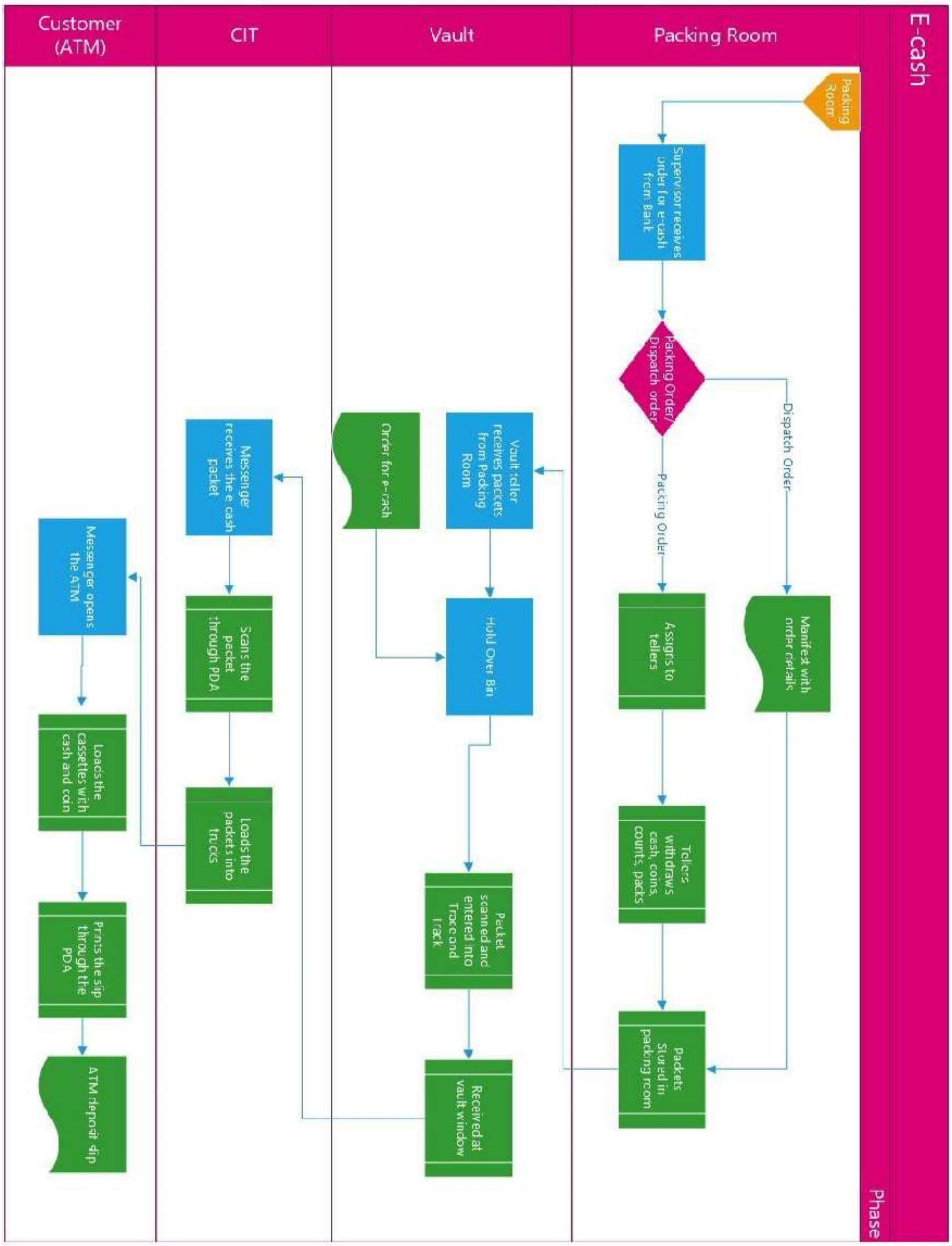


Figure 82 - eCash Process Map

Packets to be delivered later

Some customers place change orders earlier than needed. After processing and packing these cash and coin orders, the packets are sent to the vault. The vault team puts these cash bags in the holdover bin until the delivery date arrives.

Packets from a foreign courier which require further research

Some cash bags from foreign couriers need further research to determine the proper delivery location. After check-in, these cash bags get placed in the holdover bin until the research is completed.

Change orders with a business issue.

When a payment from a customer is past due, the cash bags for these customers get placed in the holdover bin and are delivered to the customer only when the customer account issues are resolved.

APPENDIX B

NRF52840 DATA SHEET

nRF52840

High-end multiprotocol Bluetooth Low Energy (LE) SoC supporting: Bluetooth 5.3/Bluetooth mesh/Thread/ Zigbee/802.15.4/ANT

Ready for Bluetooth 5.3 and high grade IoT security

The nRF52840 is an advanced, highly flexible single chip solution for today's increasingly demanding ULP wireless applications for connected devices on our person, connected living environments and the IoT at large. It is designed ready for the major feature advancements of Bluetooth LE and takes advantage of increased performance capabilities which include long range and high throughput modes. Inherent industry-grade security is essential in today's applications. The nRF52840 adds best-in-class security for Cortex™-M Series with on-chip ARM® CryptoCell cryptographic accelerator.

	nRF52805	nRF52810	nRF52811	nRF52820	nRF52832	nRF52833	nRF52840	nRF5340
Bluetooth 5.3	X	X	X	X	X	X	X	X
Bluetooth 2 Mpbs	X	X	X	X	X	X	X	X
Bluetooth Long Range			X	X		X	X	X
Bluetooth Direction Finding			X	X		X		X
Bluetooth LE Audio								X
Bluetooth mesh				X	X	X	X	X
Thread			X	X		X	X	X
Zigbee				X		X	X	X
Matter							X	X

Advanced performance, lowest power consumption

The nRF52840 employs the same hardware and software architecture as existing nRF52 Series SoCs. At its core is an Arm Cortex-M4 processor allowing quicker and more efficient computation of complex functions for DSP and those requiring floating point math. There is extensive memory availability in both flash and RAM, 1 MB and 256 KB respectively. The combination of Cortex-M4 with floating point and memory availability offers unparalleled capabilities for true single chip applications. A full-speed (12 Mbps) USB 2.0 controller is included on-chip. An extensive range of peripherals are available with a number of high performance digital interfaces such as high speed SPI (32 MHz) and quad SPI (32 MHz) to allow direct interfacing to displays and external memory sources. The nRF52840 can operate from +5.5 V down to 1.7 V supply voltages allowing direct supply from rechargeable batteries and USB supplies.

Key features

- 64 MHz Arm® Cortex-M4 with FPU
- 1 MB Flash + 256 KB RAM
- Bluetooth 5.3 multiprotocol radio
  - 2 Mbps
  - CSA #2
  - Advertising Extensions
  - Long Range
  - +8 dBm TX power
  - -95 dBm sensitivity
  - Integrated balun with 50 Ω single-ended output
- IEEE 802.15.4 radio support
  - Thread
  - Zigbee
- 1.7-5.5 V supply voltage range
- Full-speed 12 Mbps USB
- NFC-A tag
- Arm CryptoCell CC310 security subsystem
- QSPI/SPI/TWI/I²S/PDM/QDEC
- High speed 32 MHz SPI
- Quad SPI interface 32 MHz
- EasyDMA for all digital interfaces
- 12-bit 200 ksps ADC
- 128 bit AES/ECB/CCM/AAR co-processor
- On-chip DC-DC buck converter
- Regulated supply for external components up to 25 mA

Applications

- IoT
  - Smart Home products
  - Matter connected home products
  - Industrial mesh networks
  - Smart city infrastructure
- Advanced wearables
  - Connected watches
  - Advanced personal fitness devices
  - Wearables with wireless payment
  - Connected Health
  - Virtual/Augmented Reality applications
- Interactive entertainment devices
  - Advanced remote controls
  - Gaming controller

For more information please visit: nordicsemi.com/nRF52840

nRF52840 SoC Product Brief Version 3.0

Thread certified and 802.15.4 support

The nRF52840 is a Thread certified component and as such is ideal for home networking products using the Thread mesh stack. This means it is suitable for developing products for the Matter connected home ecosystem. The radio supports 802.15.4 PHY and MAC layers and makes it suitable for additional stacks using 802.15.4 such as Zigbee.

Arm CryptoCell 310

The nRF52840 features an on-chip Arm CryptoCell 310 cryptographic hardware accelerator. CryptoCell offers a wide range of ciphers and security features for building solid security into applications from the ground up. Use of CryptoCell also makes associated security operations run faster and uses less processing time and power than equivalent operation carried out in software by the CPU.

nRF Connect SDK

The nRF Connect SDK is the software development kit for the nRF52 Series SoCs. It supports development of Bluetooth Low Energy, Thread and Zigbee applications. It integrates the Zephyr RTOS, protocol stacks, samples, hardware drivers and much more.

nRF Connect SDK also offers integration of HomeKit Accessory Development Kit for developing products using HomeKit.

nRF52840 Development Kit (DK)

The nRF52840 DK is the development kit for the nRF52840 SoC. It is affordable, and has everything needed for development on a single board. All features and GPIOs of the nRF52840 SoC are made available to the developer, and it comes with an onboard SEGGER J-Link debugger enabling both programming and debugging of the nRF52840 SoC, without additional hardware investments.

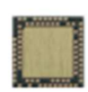
The nRF52840 SoC and the nRF52840 DK is available through Nordic Semiconductors distribution network.

Related Products

nRF52840 DK	Development kit for nRF52811 and nRF52840 SoCs
nRF Connect SDK	Main software development kit for the nRF 52840 SoC and other nRF52 Series SoCs
Power Profiler Kit II	Hardware tool for current measurement and power profiling your applications
nRF21540 RF FEM	Range extender front end for Bluetooth LE, Thread and Zigbee applications
nPM1100 PMIC	Higly efficient power management IC for low power small form factor devices

Specifications

Protocol support	Bluetooth 5.3/802.15.4/ANT/2.4 GHz proprietary
Microprocessor	64 MHz 32-bit Arm Cortex-M4 with FPU
Memory	1 MB Flash + 256 KB RAM
On-air data rate	Bluetooth LE: 2 Mbps/1 Mbps/500 kbps/125 kbps 802.15.4: 250 kbps 2.4 GHz proprietary: 2 Mbps/ 1 Mbps
TX power	Programmable from +8 dBm to -20 dBm in 4 dB steps
Sensitivity	Bluetooth LE: -103 dBm at 125 kbps -95 dBm at 1 Mbps 802.15.4: -100 dBm at 250 kbps 2.4 GHz: -93 dBm at 1 Mbps -89 dBm at 2 Mbps
Radio current consumption DC/DC at 3 V	16.40 mA at +8 dBm TX power, 6.40 mA at 0 dBm TX power, 6.26 mA in RX at 1 Mbps
Oscillators	64 MHz from 32 MHz external crystal or internal 32 kHz from crystal, RC or synthesized
System current consumption DC/DC at 3 V	0.4 µA in System OFF, no RAM retention 1.86 µA in System OFF, full RAM retention 0.97 µA in System ON, no RAM retention 2.35 µA in System ON, full RAM retention 3.16 µA in System ON, full RAM retention and RTC
Hardware security	128-bit AES CCM, ECB, AAR
Security subsystem	Arm TrustZone CryptoCell 310
Digital interfaces	USB 2.0, 4 × SPI master/slave, 2 × TWI master/slave, 2 × UART, 4 × PWM, QPSI, I^2S, PDM, QDEC
Analog interfaces	12-bit 200 ksps ADC, GP comparator, LP comparator
Peripherals	5 × 32 bit timer/counter, 3 × 24 real-time counter, 20 × PPI channels, 4 × GPIOTE, temperature sensor, watchdog timer, RNG
NFC	NFC-A tag
Voltage supply	1.7 to 5.5 V LDO or DC/DC
Package options	7 × 7 aQFN73 with 48 GPIOs 6 × 6 QFN48 with 30 GPIOs 3.5 × 3.6 WLCSP94 with 48 GPIOs



7×7 mm

6×6 mm

3.5×3.6 mm

APPENDEX C

SIMULATION MODEL DESCRIPTION

A SIMULATION MODEL STUDY FOR CASH TRACEABILITY

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Highlights

- Novel research in cash movements through armored couriers using observation, process mapping, simulation, and the Internet of Things.
- An API integration between banks, retailers, and armored couriers sets the stage for automation.
- Adding RFID to Cash movements can reduce staffing, increase capacity, and improve efficiency.

Abstract

The movement of cash between banks and their customers is often done through the use of armored courier services. These armored couriers are hesitant to adopt new technologies because the business's nature requires well-documented custody transfers of cash bags. Often these transfers are still based on paper receipts.

The researchers believe that using radio frequency identification (RFID) and an application programming interface (API) between all parties in the cash management ecosystem reduces cost, improves efficiency, and increases capacity. To alleviate the hesitancy of armored couriers, a simulation model is made that operates much like an existing 45-vehicle branch. Once the model was validated, changes to the model were made to adopt the API interfaces and RFID systems required. In addition, an RFID-based sorting robot was implemented. A comparison focused on the manpower utilization of armored vehicle crews and branch tellers.

The resulting model shows a significant reduction in manpower requirements, improved efficiency, and increased capacity, as expected. The operational behaviors of tellers were reduced by 79%, and truck route durations were reduced by 43%. The expectation is that this research helps armored couriers see the advantages of adopting such a system and spur additional investigation of the solution.
Keywords: Armored Couriers, Armored Truck Companies, RFID, API, Cash Management, Banks, Retailers, ATMs.

A Simulation Model Study for Cash Traceability

Introduction

The cash management industry has been slow to adopt technology solutions to improve the traceability of cash. This is not without good reason. The highly secure nature of the cash movement by armored vehicles requires a level of traceability that eclipses typical supply chain traceability solutions. Every time cash changes hands, a custody transfer is accomplished to relieve the previous holder of the cash of responsibility and place that responsibility for the liability on the receiver. This is often accomplished with paper receipts as proof of the transfer. Replacing physical receipts with electronic receipts has been slow in the industry, but acceptance is starting to take hold. The electronic custody transfer typically requires the receiver to electronically sign a personal data assistant (PDA) or other signature capture device. Cash management companies are hesitant to move to automated receipt capture through means based on radio frequency identification (RFID) because they are unsure of the technical solution and concerned if it has adequate return on investment.

To address the uncertainty of cash management companies, the researchers have developed a simulation tool that imitates a regular armored courier operation in a large city. After validation, the model is changed to adopt RFID tags on cash bags. A comparison is made to illustrate the potential of RFID in this application. The model can easily be adapted to each company's needs, and an understanding of the benefits can be thoroughly explored.

Literature Review

The topic of cash visibility with IoT in Cash-In-Transit (CIT) operations is an area that has very little literature in academic journals. In cooperation with the standards organization GS-1, the industry has developed the U.S. Guide for Cash Visibility Standard [1]. This guideline establishes the terminology and the primary traceability of cash bags through the use of barcodes. Mostly, barcodes have been adopted by most of the industry, but little else from the guideline has been implemented.

Valentine [2] describes the transfer of typical banking behaviors from banks to processing facilities like ATCs. The author describes how the consolidation of banking services at ATCs reaches an economy of scale and allows bank customers to be serviced more safely and logically. In addition to regular banking services, ATCs enable a smart-safe option to bank customers that immediately sorts and counts cash credits and deposits into the customer's account.

Several researchers have attempted to provide recommendations for better CIT security by optimizing the routing of armored vehicles [3]–[7]. This area of research seeks to save money, reduce the risk of robbery, and optimize operational behaviors. Xu et al. suggest that the risk of armored vehicle robbery correlates with the amount of cash on the truck and the distance the vehicle is required to travel. They also indicate that travel in areas of low socio-economic status dramatically increases risk.

In Automatic Teller Machine (ATM) servicing, researchers have explored several paths to predict the supply of cash availability in these machines and optimized operations. [8]–[16].

Methods

The researchers spent five days within an armored truck courier (ATC) operation observing and documenting every process in a process map. In addition, the ATC provided manpower documentation and a general flow of handling cash. Leveraging this information, a simulation model was developed that aligned with the branch's operational behaviors. Following the simulation development, it was further tuned and validated against the physical branch. The management of the ATC assisted in the researchers' understanding through many in-person and online meetings.

Next, the attention turned to establishing RFID points of interest to read the RFID-tagged cash bags to ensure custody transfers could be collected automatically. Once the technical solution was established, the model was adapted to support RFID. Finally, the model was run, and a comparison was made with the original model.

Model Description

AnyLogic University Researcher edition was used to create the model. The model has several operations that are effectively digital twins of the branch operations. The model is broken down into behaviors and locations that occur during a typical business day. Cash bags move bidirectionally through the system. Customers request cash from their bank and make deposits. In addition, automatic teller machines (ATMs) are serviced by armored couriers. Couriers also interact with competitors and banks. Finally, couriers transfer cash to and from the Federal Reserve Bank.

The simulation that was developed is based on a single ATC branch. This model may not match other branches within the same company or their competitors. Generally, though, the operational behaviors are the same between all ATCs.

Branch

The branch is the hub for all ACT operations. Some branches process cash on behalf of banks, and some only transport bags between customers and banks. The observed location processes cash on behalf of the bank. For the explanation, this description starts in the morning as Cash In Transit (CIT) crews show up to begin their day.

Transfer of Cash to CIT Crew

Figure 1 illustrates the model behavior each morning. Each process in this operation was timed, and a set of values were determined using triangular or uniform distributions to create the variability witnessed in the branch. Each process has a resource pool for the simulation model, including people, mantraps (locations where custody transfers occur), and vehicles. Each morning the messenger arrives at the mantrap, and an exchange of custody is made through passing a trolly with bags to be delivered. The messenger loads the truck and verifies all transactions on a handheld computer. The custody transfer is completed when the trolly is returned and physical paperwork is signed and exchanged. The CIT crew can now begin their route. It is important to note that this branch had 45 trucks, so this operation happens 45 times each morning.

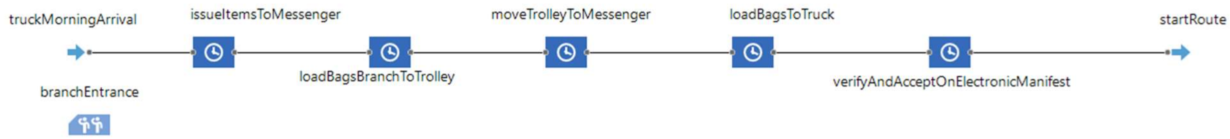

Figure 1 - Transfer of Cash to CIT Crew

Transfer of Cash from CIT to Vault

At the end of the CIT route, the crew returns to the facility, and several security checks are made outside the secure area. The messenger unloads the truck (deposits, change orders from outside banks and competitors, and ATM residuals) into a trolly and, if available, enters a mantrap. The messenger may be forced to wait for an open mantrap during busy times. Upon entering, the messenger starts the exchange of custody of all cash bags, keys, and other issued items. Each item is handed over individually, verified, and inspected by a vault teller. Once all items are transferred, and there are no exceptions (e.g., missing bags, keys), the paperwork to transfer the custody to the branch vault team is completed, and the messenger is free to depart the mantrap. See Figure 2.

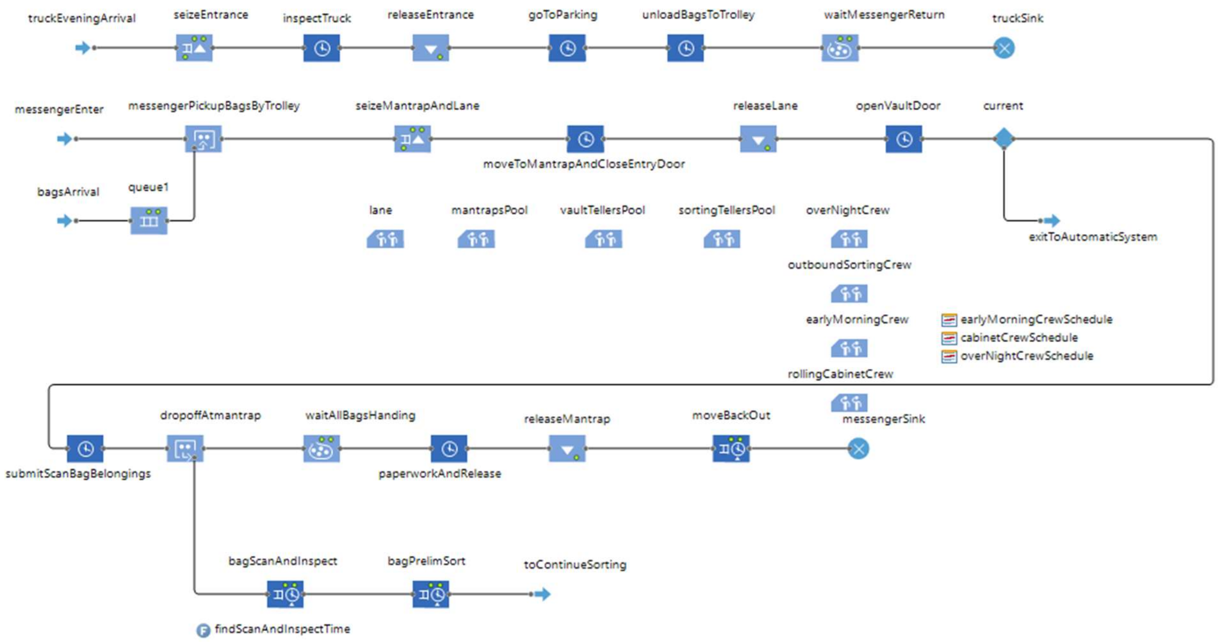

Figure 2 - Transfer of Cash from CIT to Vault

Sorting Bags

The vault area of the branch is responsible for sorting bags based on several situations. Vault tellers initially sort bags during the receiving process from CIT by where each bag is processed. The bags not processed internally are sorted by destination and placed in route trollies throughout the evening and night for dispatch the next day. Those bags that are internally processed are stored by the bank. Each bank has its own bin or sort location.

Internally processed bags are sorted multiple times by the vault teller at the window, by an additional vault teller, then by five early morning tellers. The additional sorting is done because there is so much human error in the sorting process. See Figure 3 for the sorting processes.

Also in Figure 3 is the outbound sorting process where change order bags created internally or bags brought in by the previous day's route are combined into cabinets for the messengers.

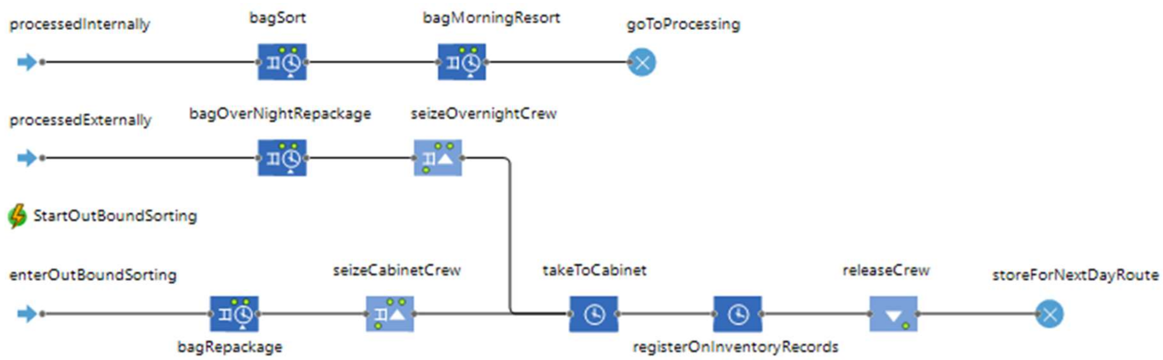

Figure 3 - Sorting Bags

Cash in Transit

As mentioned in the branch model, at the beginning of each day, armored truck crews (typically a driver and messenger) arrive at the branch and prepare the vehicle. They accept the cabinet with their bags for distribution during the route and load the bags on the vehicle. As they load the items on the vehicle, they utilize a PDA with an electronic manifest of the cabinet. Each bag is barcode-scanned and placed on the vehicle. Once the crew has completed the manifest, they return the cabinet and exchange paperwork with a vault teller. This process transfers custody of the bags to the CIT team. This process is illustrated in Figure 2 above.

When the CIT team departs the branch, they drive to their first stop and start delivering change orders, picking up deposits, servicing ATMs, and servicing smart safes. Each stop type is simulated below.

Servicing an ATM in the model is the most simple. ATMs generally take the same about of time to service. The only key difference is that some machines are single denominations (only $20 bills) and some are multiple denominations ($5, $10, and $20). Another difference is whether or not the ATM has a deposit capability. The single-denomination machines represent 80% of the ATM stops in the model. Both single and double have uniform distributions for stop duration. ATMs do not require interaction with any other person.

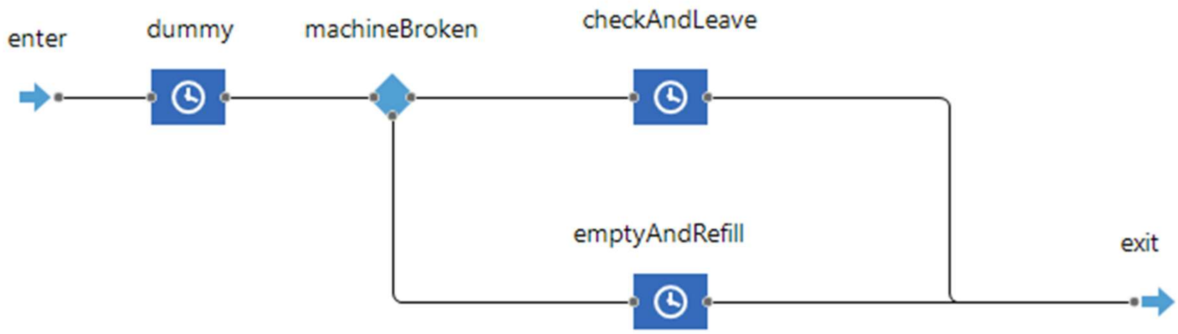

Figure 4 - ATM Servicing

Bank transactions are complicated because the bank may accept bags (ATM residuals, deposits, buy orders from Federal Reserve Bank) or give bags to the courier (change order, ATM cash, and sell orders to Federal Reserve Bank). See Figure 5.

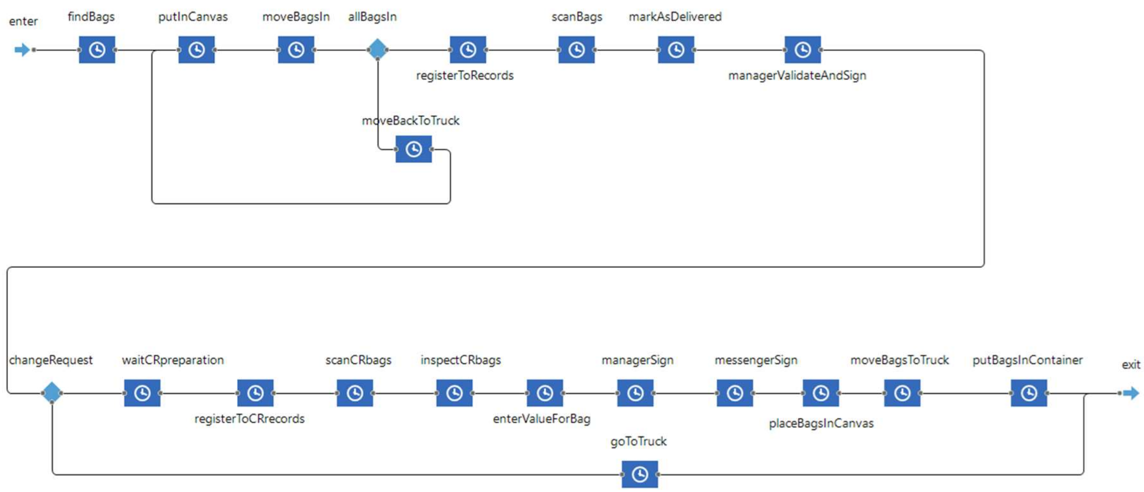

Figure 5 - Bank Interactions

Each trip to a bank may require multiple trips to and from the vehicle. Larger banks may have overpacked cash bags (smaller bags in a large bag with a large bag manifest). Conversely, some banks may have many change orders to distribute to customers or fill ATMs.

When the messenger arrives, they gather the bags for that bank and then transport them inside. Bag barcodes are scanned, and custody of the bags is transferred to the bank manager. Next, change orders are provided to the messenger, and each change order must be entered into the PDA by scanning and choosing the eventual delivery location. The value of each bag is also entered into the PDA software. Once all are accepted, it may take multiple trips to the vehicle. Once all bags are processed, the messenger accepts the custody of the bags, and the PDA and the bank's record book are signed.

Competitors also transfer bags to one another. A customer may contract a courier to move their cash bags, but the customer's bank may outsource deposit processing to another armored courier. This situation requires a transfer of cash bags between couriers. Typically, competitive couriers pick up bags from other competitors. They are not typically delivered. For this simulation, all bags are picked up by the receiving armored courier. See Figure 6.

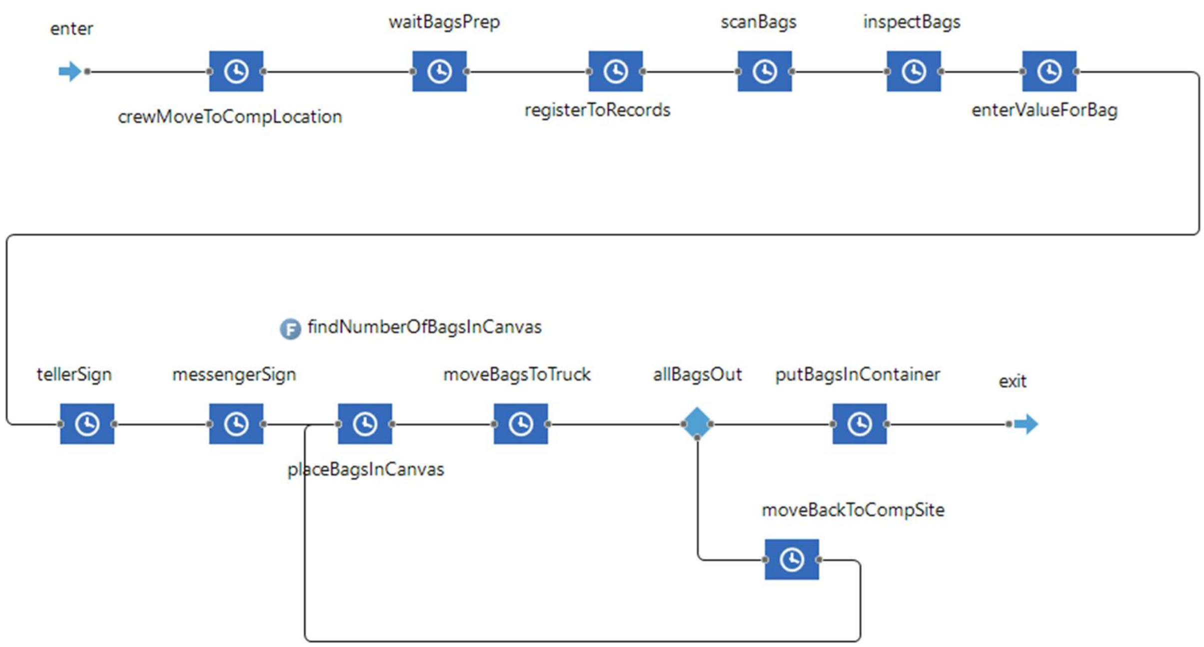

Figure 6 - Competitor Interactions

A series of transactions occur for each bag when a courier arrives at a competitor's location. A manifest is provided, and bags are handed one by one to the messenger. Each bag is inspected for tampering, scanned by the PDA, entered into the database, and checked off the manifest. Each bag is placed in a trolly or canvas bag. Once the transaction is complete, they sign a custody transfer that includes the manifest, and the courier loads the bags on the truck.

Retailers have several transactions that may occur. They may have requested change from their bank (change order), prepared a deposit, and/or have a smart safe that needs to be serviced.

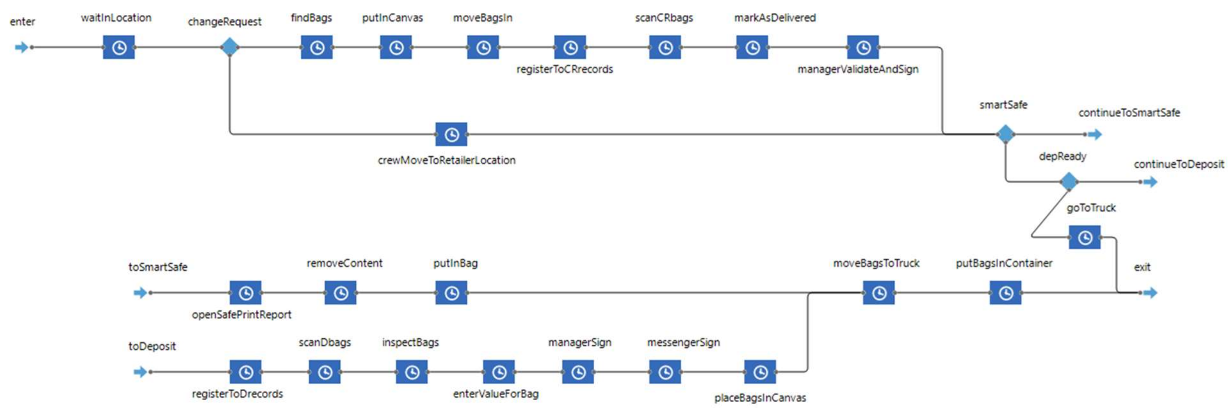

Figure 7 - Retailer Interactions

Retailers have designated days of the week that an armored courier stops to deliver change orders and pick up deposits. The contract between the retailer and the armored courier sets these days and frequency. Upon arrival at the retailer, the messenger finds the bags for that customer and logs in to that customer's account on the PDA. The bags are placed in a black over-bag, and the messenger exits the vehicle to enter the retailer. The store manager meets the courier, and change orders are scanned and signed for by the manager. Deposits are scanned and entered into the PDA, and the manager signs for the deposit transfer. Some retailers require the messenger to sign paperwork or a book for accepting deposit bags.

Retailers may also have smart safes. These safes accept cash and immediately credit the retailer's bank account. Smart safes are also serviced during stops. The messenger has a key and opens the safe. A receipt is printed from the safe and placed in a bag with the deposited cash. The bag is sealed and scanned into the PDA with the value. The messenger puts all deposit bags and smart safe bags in the black over bag and returns to the vehicle.

Data Collection and Validation

The researchers collected many quantitative and qualitative operational behavior data (process mapping) on-site and during subsequent interactions. An objective of the research was a time-motion study of teller-messenger interactions in the mantrap, but the ATC did not allow much time for a time-motion study quantitative data collection. Some activities were observed and timed, and other activities were explained by ATC personnel but not observed. Three days of time-motion study data collection for a single teller were observed and timed. Additionally, quantitative data was provided by the ATC indicating the bag processing for the top 30 branches within the company and hourly employee work hours for 22 weeks. The remainder of the data was collected anecdotally through observations and interviews. In addition, some assumptions made by the researchers were validated through meetings with the ATC operational management team.

The time-motion study provided 46 observations of vault tellers receiving bags and accessories from messengers. Two of the observations were excluded from the analysis because of the operational behavior in the process (e.g., passing one emergency ATM refill bag and a truncated route with 12 bags). The values of total time in the mantrap, time passing bags, time passing accessories, and time for checkout were collected. The observed data were collected by observing one vault teller for three shifts on a Wednesday, Thursday, and Friday. For this investigation, the researchers consider this information equivalent to one day for one teller. Therefore, the observed data is regularly compared to a single day/single teller of simulation data.

The simulation model was developed based on the holistic operation of an ATC branch with 45 armored vehicles that conduct outsourced bank operations. The primary purpose of the simulation is to look at operational times when bags are handled through the CIT and vault operational procedures. The model does not evaluate or simulate CMS processing but includes CMS's bag sorting behaviors. The model is evaluated based on general operational timing that is observed (e.g., total time frame for transfer of bags from the vault to CIT and reverse) and from data provided by the ATC. In addition, where possible, the model was validated by comparing the mean, first and third quartile, and median of observed quantitative data with model simulation data.

Discussing sample sizes, the observational data, and the provided data established the value of n for all cases. For the simulation data, the model has a limit of 100 days. This constraint is a software memory utilization limit. A single day of the simulation produces 3000+ bags, 45 truck routes, and 12,000+ bag touches. Running the model at a maximum of 100 days produces a multiple of the single-day values.

In some cases, large data files were manipulated through R first and then Microsoft Excel. For instance, bag touches by tellers for 100 days produce 1.2M transactions. Those transactions were sorted by the teller type in R, and new files were created to evaluate further in Excel (e.g., pivot tables, box plots, histograms). In all cases, the simulation data from the model were used as a complete dataset (no sampling). In addition, when daily values were required, the simulation data was manipulated into a pivot table by date, and totals or value means were taken for each date. These values appear as 100 samples in some tables, but each is a total or summary of many additional samples.

Evaluation of Transfer of Custody

One key area of focus for the research is the time it takes for a messenger from CIT to transfer bags picked up from the route to a vault teller. The observed branch collects bags for 45 trucks between 2 PM and 9 PM. The flow of trucks peaks between 4 PM and 6 PM. In addition, it was observed that tellers work more quickly during peak times and more slowly during slack times. In the model, the time to process a bag is established in a triangular distribution between 2 and 16 seconds with a mean of 8 seconds, but the values for time per bag are shifted during slack times by adding a multiplier to simulate the observed behavior accurately. An example is that bags collected during the 2 PM hour have a multiple of 1.2 which shifts the uniform distribution from 2.4 to 19.2 with a mean of 9.6 seconds per bag.

Table 1 compares observed and simulation runs of 1, 7, 30, and 100 days and the resulting results. The 100-day simulation data was compared with the observed data (highlighted in blue), indicating the model's accuracy for this process. Note that the mean, first and third quartiles, and median are well within the ascribed 15% threshold.

Table 1 - Comparison Validation of Observed and Simulation Data

Variable	Count	Mean	Minimum	Lower whisker	Q1	Median	Q3	Upper whisker	Maximum
Obs1day	43	9.6225	3.3833	3.3833	6.4917	9.1000	12.0750	18.3833	18.3833
CM1day	44	9.7978	3.6079	3.6079	8.0836	9.7570	11.6683	16.3681	16.3681
CM7day	308	9.2408	3.6079	3.6079	6.7428	8.8423	11.2855	17.8486	18.4616
CM30day	1320	9.3614	2.7867	2.7867	7.0880	8.9967	11.4276	17.8646	19.1386
CM100day	4400	9.4597	2.7867	2.7867	7.1487	9.1478	11.6022	18.0965	19.3050
Δ Obs1day		98%	82%	82%	110%	101%	96%	98%	105%

However, the standard deviation of the data is approximately 25% more narrow in the simulation, as indicated in Table 2. The range of the model prevented a wider spread of the standard deviation while maintaining the mean and first and third quartiles. The researchers felt that the amount of observed data was too small to establish an accurate value for standard deviation and placed more value in the mean and first and third quartiles of the limited dataset.

Table 2 - Observed vs. Model Standard Deviation

Observed 1 day	Model 1 day	Model 7 day	Model 30 day	Model 100 day
4.002	3.059	3.060	3.105	3.086

Looking at a 95% confidence interval (CI) for the observed data, the $CI = \sqrt{\frac{2(1.96+1.6449)^2 4.002^2}{43}}$ = 9.6225 ±2.783 minutes. The low number of samples for this observation significantly impacts the wider confidence interval. Referring back to Table 3, the simulation mean is well within the 95% CI.

Linear regression was also attempted and yielded uncertain results because of the limited number of observations and did not yield a conclusive correlation. Figure 8 illustrates the regression for the observed data and a single-day simulation run.

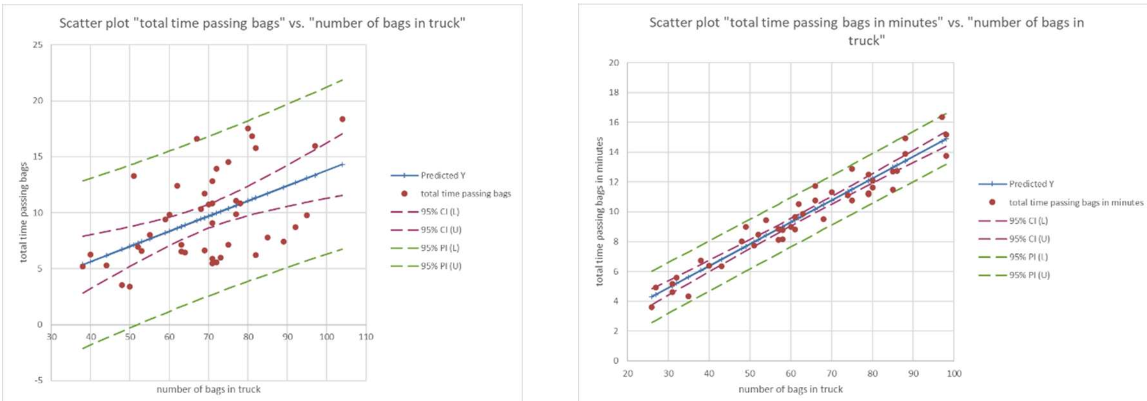

Figure 77 - Linear Regression Comparison of Observed to Simulation Data

The R^2 value of the observed data is low, at 0.2568, because of the limited number of observations. The R^2 value of the simulation model is 0.9296. Overall, the time involved in passing bags and the total time spent in the mantrap between the observed and simulated data is well within validation limits.

Bags per Truck

In addition to the time passing bags, the model can be validated through a report provided by the ATC indicating the number of bags the branch handles during a typical month. The report indicates that the observed branch handles approximately 85,500 bags of cash each month with 45 trucks. These bags break down further to 25% delivered (e.g., change orders, ATM refills) and 75% pickups (e.g., deposits, ATM residuals, bank-created change orders). The mean of this would indicate approximately 63 bags per truck per day. From observation and interviews, there are more bags on Monday and Friday, and Saturday and Sunday are fewer. Table 3 shows data from the observed and simulated periods of 1, 7, 30, and 100 days. The variance from 63 (the average daily value provided by the ATC) is denoted in blue in the rightmost column. Also, note that the observed data included data from only weekday operations. The standard deviation for the number of bags per truck is 14.9814.

Table 3 - Comparison of the Number of Bags Per Truck

Variable	Count	Mean	Minimum	Lower whisker	Q1	Median	Q3	Upper whisker	Maximum	Average 63
Obs1day	43	69.4419	38.0000	38.0000	61.0000	71.0000	77.5000	97.0000	104.0000	110%
CM1day	44	63.3864	26.0000	26.0000	50.5000	62.5000	79.0000	98.0000	98.0000	101%
CM7day	308	59.5487	22.0000	22.0000	43.0000	58.0000	74.2500	109.0000	109.0000	95%
CM30day	1320	60.2379	22.0000	22.0000	46.0000	58.0000	74.0000	110.0000	110.0000	96%
CM100day	4401	60.9275	21.0000	21.0000	46.0000	59.0000	75.0000	112.0000	112.0000	97%

Utilizing the 95% CI for the number of bags per truck, the $CI = \sqrt{\frac{2(1.96+1.6449)^2 14.9814^2}{43}}$ = 69.4419 ±11.647 bags per truck. The simulation mean for bags per truck is well within the CI limits of observed and ATC-provided data.

Teller Utilization

The remaining variables are discussed below based on observed behaviors and facility constraints. There are three teller windows/mantraps used for vault teller-messenger interactions. Three vault tellers work eight-hour shifts. The tellers work shifts that support the behaviors of the branch. During the reception of bags in the afternoon, the vault window tellers perform bag inspections (six-sided inspections), locate the deposit slip in the bag, annotate the bag with the receiving bank name, and pre-sort bags. The pre-sort is done by identifying bags as internally processed, externally processed, and bags that need to be delivered to other entities in the following days.

A single teller accepts the bags that are internally processed and sorted by receiving bank. The observed branch processed bags for more than 50 different banks. This teller accepts the bank name written on the bag as accurate as the bags are sorted. The bags are resorted again the following morning by five CMS tellers that verify the deposit slip inside the bag. Each day, approximately 3000 bags are processed internally.

The overnight tellers sort the bags that are not processed internally. This process is referred to as "repackaging." These bags have a destination bank or customer, typically for the next day, and are sorted and prepared as outbound bags. Two overnight tellers perform this action. The overnight tellers also prepare all other outbound materials for CIT, including accessories (e.g., keys, manuals, radios).

During the day, a teller takes bags from the bag preparation room and assigns them to routes. A teller and a security guard place the bags in lockable carts and maintain a running inventory of each cart.

Finally, two vault tellers interface with CIT messengers in the mornings, moving carts and issuing accessories. They also supply route sheets and a truck manifest to each messenger.

The researchers focused on each teller's observed behaviors and the teller shift's limits to validate the teller transactions. For instance, it is known that afternoon vault tellers are receiving bags from messengers from 2 PM to 9 PM. The model must support this. In addition, tellers and messengers have known shifts, and the researchers were provided overtime data for several employee types.

For the most part, the researchers know the overall flow of the branch through observation, process mapping, and discussions with employees. The company's management validated many of the assumptions (or corrected them) during the observation period.

As accurately as possible, the simulation model attempts to simulate the branch's operational behaviors as the bags flow into and out. For instance, the manager of the vault operation indicated that 60% of the bags entering the branch from CIT each afternoon go to CMS for processing. Therefore, in the model, this proportion was maintained. See Figure 9 for inbound bags from CIT and Figure 10 for outbound bag preparation.

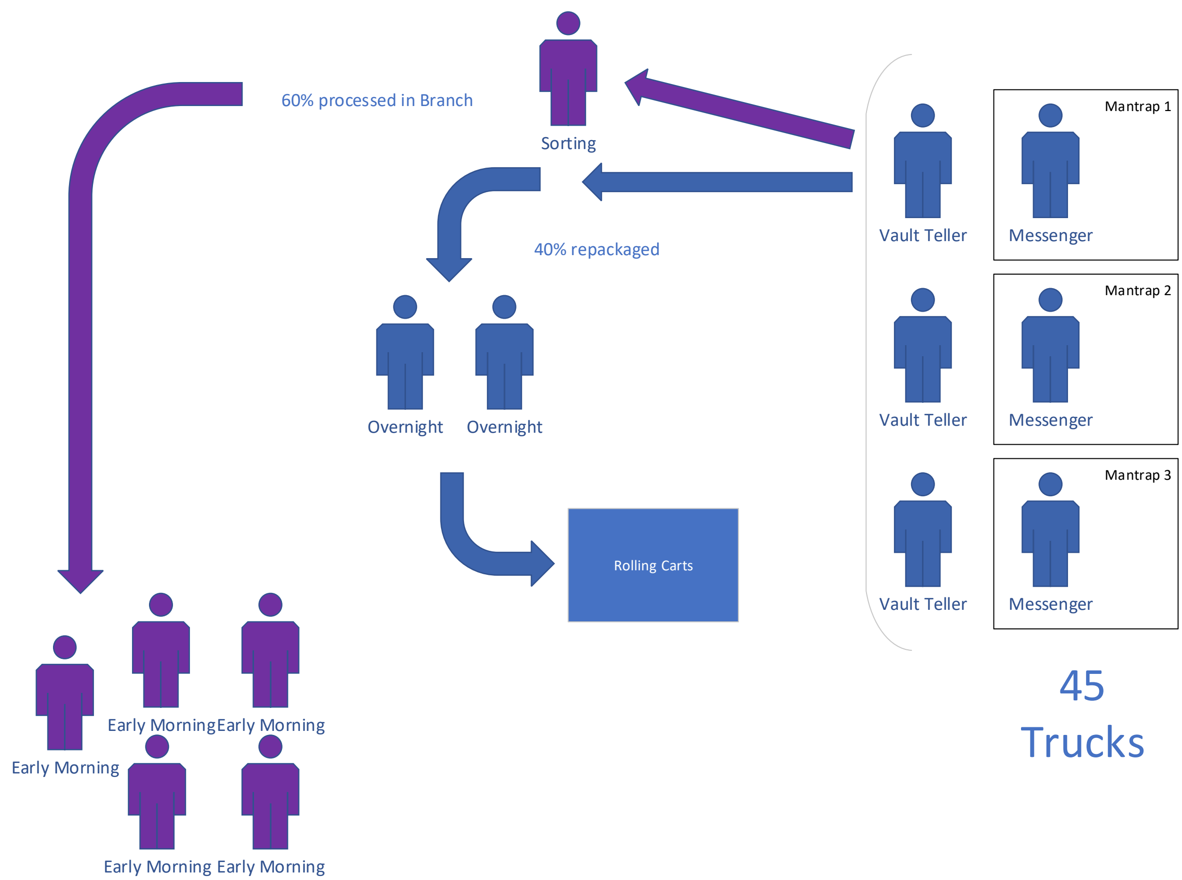

Figure 9 - Flow of Inbound Bags from CIT

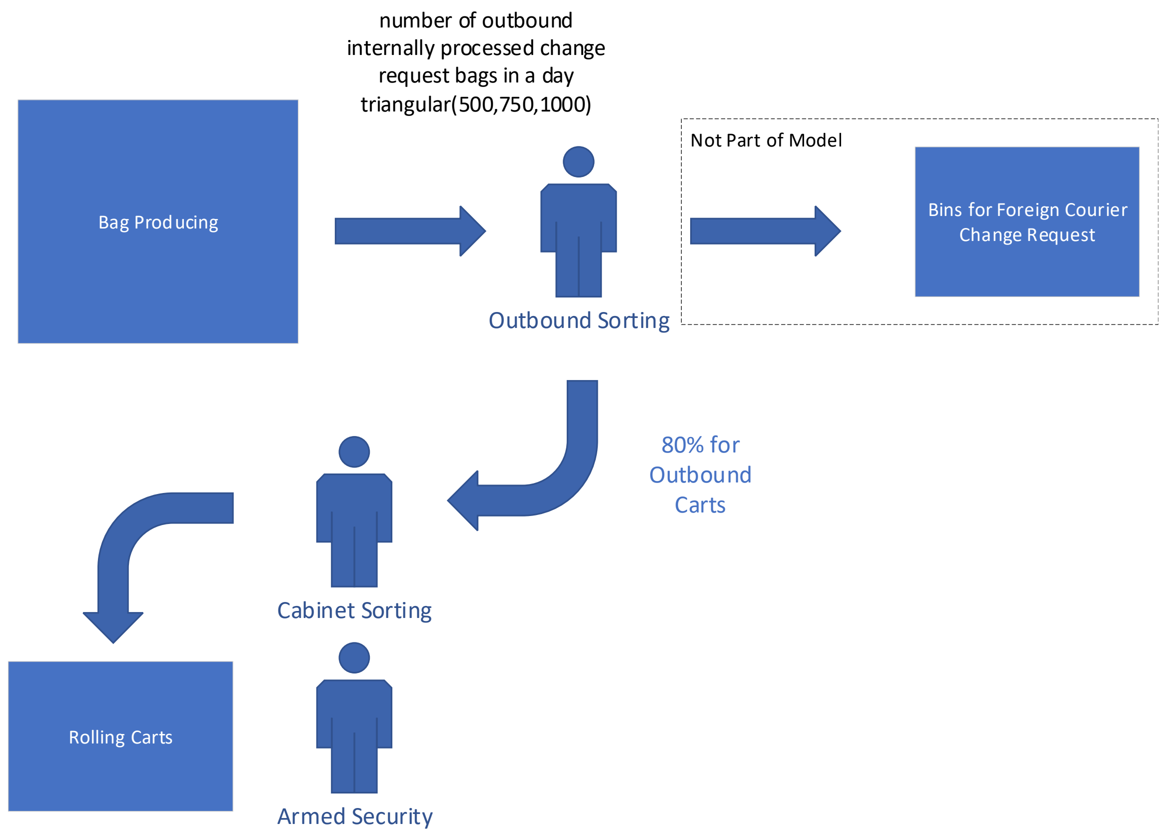

Figure 10 - Outbound Bag Preparation

The ATC supplied teller hours for 22 weeks. Table 4 shows the average weekly work hours for 43 workers over 22 weeks. This document also includes partial weeks for employees that left and for new hires. The document also does not include paid time off for employees. This information skews the manpower hours lower. These data are also based on work weeks.

Table 4 - Vault Teller Actual Work Hours over 22 Weeks

Vault Teller	Count	Mean	Minimum	Lower whisker	Q1	Median	Q3	Upper whisker	Maximum
Reg_Hours	624	33.3206	0.0000	14.1000	29.5575	38.7600	40.0000	50.5400	50.5400
OT_Hours	624	2.0377	0.0000	0.0000	0.0000	0.0000	2.0075	5.0000	35.5100

Given the work hour standard deviation of 9.9122, the 95% $CI =$

$\sqrt{\frac{2(1.96+1.6449)^2 9.9122^2}{624}}$ = 33.3206 ±2.023 work hours/week.

Given the overtime standard deviation of 4.1687, the 95% $CI =$

$\sqrt{\frac{2(1.96+1.6449)^2 4.1687^2}{624}}$ = 2.0377 ±0.8508 overtime hours/week.

From the previous work hour data for tellers, by removing weeks for which the person worked less than 30 hours a week, the regular weekly work hours mean is 38.483, and the standard deviation is 3.636. For overtime hours, the new mean is 2.3629, and the standard deviation is 4.476. Both have n=452. Applying these values to the 95% CI yields these values:

The Regular Hours $CI = \sqrt{\frac{2(1.96+1.6449)^2 3.636^2}{452}}$ = 38.483 ±0.8719 regular hours and

Overtime $CI = \sqrt{\frac{2(1.96+1.6449)^2 4.476^2}{45}}$ = 2.363 ±1.073.

The model simulation also evaluates teller hours but focuses only on the sorting behaviors of each teller type. Tables 5 and 6 illustrate the sorting activities in minutes and hours, respectively. Comparing the values above and the "only sorting" responsibilities become a loose comparison. Some tellers only sort bags (e.g., outbound sorting, sorting 1), while others have additional duties beyond sorting.

Table 5 – Teller Sorting Utilization by Task in Minutes - Simulation

Variable	Count	Mean	Minimum	Lower whisker	Q1	Median	Q3	Upper whisker	Maximum
VAULT 1	31	265.0220	0.0000	235.7000	258.8250	270.8500	283.0000	311.9667	326.0667
VAULT 2	31	271.6161	0.0000	248.7000	263.6000	282.2667	289.2750	311.4333	311.4333
VAULT 3	31	266.5274	0.0000	239.9000	261.1833	271.8333	289.0750	313.2500	313.2500
SORTING 1	31	596.8759	106.4333	544.3167	581.7750	611.4833	640.9917	703.8167	703.8167
OUTSORT 1	31	430.6522	0.0000	388.2000	431.6833	444.8667	461.3833	486.2333	486.2333
CABINET 1	31	252.4992	0.0000	224.3333	246.2533	261.3000	276.9300	292.1000	292.1000
Security 1	31	252.5133	0.0000	224.7833	246.6383	261.6000	276.6217	291.6333	291.6333
OVERNIGHT 1	31	505.1129	180.0000	466.9333	504.8483	516.7833	537.3750	581.1267	581.1267
OVERNIGHT 2	31	505.1102	180.1667	466.9233	505.0450	517.1333	537.1083	581.2767	581.2767
EARLYAM 1	31	118.6118	0.0000	112.6167	117.4500	122.6833	125.7250	132.9500	141.5167
EARLYAM 2	31	118.6000	0.0000	112.9333	117.4833	122.5833	125.7167	133.0667	141.1167
EARLYAM 3	31	118.6070	0.0000	112.7333	117.3250	122.3333	125.7750	133.1500	141.3833
EARLYAM 4	31	118.5672	0.0000	112.7500	117.4167	122.3000	125.8083	132.8333	141.3333
EARLYAM 5	31	118.6129	0.0000	112.7167	117.2667	122.4500	125.9167	133.2167	141.3500

Table 6 - Teller Sorting Utilization by Task in Hours - Simulation

Variable	Count	Mean	Minimum	Lower whisker	Q1	Median	Q3	Upper whisker	Maximum
VAULT 1	31	4.4170	0.0000	3.9283	4.3138	4.5142	4.7167	5.1994	5.4344
VAULT 2	31	4.5269	0.0000	4.1450	4.3933	4.7044	4.8213	5.1906	5.1906
VAULT 3	31	4.4421	0.0000	3.9983	4.3531	4.5306	4.8179	5.2208	5.2208
SORTING 1	31	9.9479	1.7739	9.0719	9.6963	10.1914	10.6832	11.7303	11.7303
OUTSORTING 1	31	7.1775	0.0000	6.4700	7.1947	7.4144	7.6897	8.1039	8.1039
CABINET 1	31	4.2083	0.0000	3.7389	4.1042	4.3550	4.6155	4.8683	4.8683
SECURITY 1	31	4.2086	0.0000	3.7464	4.1106	4.3600	4.6104	4.8606	4.8606
OVERNIGHT 1	31	8.4185	3.0000	7.7822	8.4141	8.6131	8.9563	9.6854	9.6854
OVERNIGHT 2	31	8.4185	3.0028	7.7821	8.4174	8.6189	8.9518	9.6879	9.6879
EARLYAM 1	31	1.9769	0.0000	1.8769	1.9575	2.0447	2.0954	2.2158	2.3586
EARLYAM 2	31	1.9767	0.0000	1.8822	1.9581	2.0431	2.0953	2.2178	2.3519
EARLYAM 3	31	1.9768	0.0000	1.8789	1.9554	2.0389	2.0963	2.2192	2.3564
EARLYAM 4	31	1.9761	0.0000	1.8792	1.9569	2.0383	2.0968	2.2139	2.3556
EARLYAM 5	31	1.9769	0.0000	1.8786	1.9544	2.0408	2.0986	2.2203	2.3558

Driver-Messenger Utilization

The time utilization of the CIT crew (driver and messenger) is in Table 7. These values were taken from an ATC-provided document that covers 22 weeks of driver-messenger hours for 167 crew members. Of note, while the mean hours is below 40, 47.8% of these employees earn some overtime each week, with some obtaining more than 20 hours of overtime pay. This document also includes partial weeks for employees that left and for new hires. The document also does not include paid time off for employees. This information skews the manpower hours lower. These data are also based on work weeks.

Table 7 – Driver-Messenger Actual Weekly Work Hours for 22 Weeks

Driver/ Messenger	Count	Mean	Minimum	Lower whisker	Q1	Median	Q3	Upper whisker	Maximum
Reg_Hours	3049	32.4797	0.0000	9.0500	27.6100	39.9900	40.0000	52.8600	52.8600
OT_Hours	3049	6.5066	0.0000	0.0000	0.0000	4.1200	10.5600	26.3800	39.7600

The Driver-Messenger regular work hours standard deviation from the provided information is 11.7348. Evaluating the 95% $CI = \sqrt{\frac{2(1.96+1.6449)^2 11.7348^2}{3049}}$ = 32.480 ±1.083 regular hours per week @ 95%CI.

Overtime work hours for the Driver-Messengers are based on the standard deviation of 7.5445 derived from the supplied data. Evaluating the 95% $CI = \sqrt{\frac{2(1.96+1.6449)^2 7.5445^2}{3049}}$ = 6.507 ±0.697 overtime hours per week.

From the previous work hour data for Driver-Messengers, by removing weeks for which the person worked less than 30 hours a week, the regular weekly work hours mean is 39.016, and the standard deviation is 2.997. For overtime hours, the new mean is 7.8605, and the standard deviation is 7.8013. Both have n=2175. Applying these values to the 95% CI yields these values:

The Regular Hours $CI = \sqrt{\frac{2(1.96+1.6449)^2 2.9970^2}{2175}}$ = 39.016 ±0.2376 regular hours and

Overtime $CI = \sqrt{\frac{2(1.96+1.6449)^2 7.8605^2}{2175}}$ = 7.8605 ±0.8593.

The simulation model created a single truck route to simulate a crew earning one to four hours daily Overtime. The model assumes a truck route is operated seven days per week, with the weekend routes servicing fewer customers and developing less Overtime. The data in Table 8 assumes the same crew for five weekdays (excluding weekends). The model data for this route purposefully simulates a very busy route with high Overtime for comparison purposes in the future state. The twelve hours of Overtime is expressly intended.

Table 8 - Driver-Messenger Model Route Simulation for 14 weeks

Variable	**Count**	**Mean**	**Minimum**	**Lower whisker**	**Q1**	**Median**	**Q3**	**Upper whisker**	**Maximum**
Average	14	52.0991	47.8247	51.0111	51.4709	52.6319	52.9278	53.7428	53.7428
Overtime	14	12.0991	7.8247	11.0111	11.4709	12.6319	12.9278	13.7428	13.7428

Another view of the Driver-Messenger utilization comes from the simulation model route simulation by evaluating the routes' daily start and finish times. The model was run for 100 days, and the results of the start and finish times for the model are shown in Table 9.

Table 9 - Simulation Model Route Start and Completion

Variable	Count	Mean	Minimum	Lower whisker	Q1	Median	Q3	Upper whisker	Maximum
Average	100	9.4488	6.2869	6.2869	7.3114	10.0590	10.6299	12.1214	12.1214
Overtime	100	1.7548	0.0000	0.0000	0.0000	2.0590	2.6299	4.1214	4.1214

Extending the daily value to a five-day workweek would approximate the Overtime at 7.1 – 8.8 hours per week. Given the 95% CI for Overtime as 7.8605 ±0.8593, the simulation model aligns with the provided data from the ATC.

Truck Route Timing

The truck stops at retailers, banks, ATMs, and competitors as part of a regular daily route. The duration of a stop includes finding the appropriate delivery bag(s) (if applicable), loading the bag(s) in a black canvas over-bag, leaving the truck and entering the facility, interacting with the manager (or ATM), exchanging bags, transfer of custody processes, placing cash bags (if applicable) in black canvas over-bag and entering the truck. These processes were not observable at the ATC facility. The typical transaction timing was gathered through interviews with ATC managers and drivers/messengers. The time was also deduced from work-hour reports and observed transactions. Table 10 illustrate the average simulation model timing for each type of encounter on a route. The model was run for 100 days. The weighting for the simulation model stops is a retailer – 74%, ATM – 15%, bank – 8%, and competitor – 3%.

Table 10 - Simulation Route Stop Timing by Type

Current State	Count	Mean	Minimum	Lower whisker	Q1	Median	Q3	Upper whisker	Maximum
Retailer	2680	8.9484	1.6333	1.6333	6.5000	8.9333	11.4208	15.6333	15.6333
ATM	531	8.2562	0.3667	7.0000	7.6417	8.4333	9.1917	11.5000	11.9833
Bank	288	13.7612	4.7833	10.9333	13.1292	14.0833	14.8833	17.1000	17.1000
Competitor	117	10.1101	6.4833	7.1167	9.3667	10.1333	10.9167	12.9833	14.3333

In summary, the metrics produced by the simulation model were validated by several methods to ensure a baseline model behavior. This baseline is used for building the business model and comparison to the future state in Chapter 8. See Table 11 for a summary of data, the source, and the means used to validate the simulation model.

Table 11 - Data Sources and Validation

Item	Source	Model Validation
Messenger Route Transaction Timing	Interview/Observation	Comparison to Operational Behaviors/Validation with Managers/Work hour data
Transfer of Custody from CIT to Vault	Time-Motion Study/Observation	Comparison Time-Motion Study/Work Hour Evaluation
Teller Utilization - Inbound	ATC Data/Observation	Work Hour Evaluation/Comparison to Operational Behaviors
Teller Utilization - Outbound	ATC Data/Observation	Work Hour Evaluation/Comparison to Operational Behaviors
Total Route Duration	ATC Data/Observation	Work Hour Evaluation/Comparison to Operational Behaviors
Bags Handled by Trucks	ATC Data/Time-Motion Study	Work Hour Evaluation/Comparison ATC Data

Summary

In the original model, there is a great deal of human interaction with bags. The system is fragmented but generally works to move cash throughout the financial system. The original system does lack positive control of each cash bag, and there is a lack of visibility for customers.

New Model with RFID

There are three fundamental changes to the model with RFID. First, the model adds an application programming interface (API) between all parties to transfer information about bags that are created. The second is tagging bags and installing RFID infrastructure in the mantraps, vehicles, and within the branch facility. The third item is an RFID-enabled robotic bag sorting system that can be utilized for inbound and outbound sorting.

The API integration is an effort that is already underway within the industry. The Federal Reserve Bank started the conversation and has grown to discussions within the trade organizations for cash management. This integration shares information about bag contents, bag identification (bagID), and the bag's final destination (endpoint).

The RFID infrastructure reads RFID tags as they move within the financial ecosystem capturing the locations of bags in real-time. The RFID tags can be read much more quickly than barcodes, and with the API integration, there's no need to enter bag information in a PDA manually.

The robotic sorting system creates a highly reliable sorting system where bags of cash can be sorted quickly and accurately. The robotic sorting system also eliminates the touching of bags by humans, eliminating errors and opportunities for theft.

The model was adapted for these improvements considering the increased speed of several operational activities. As with the original model, the branch and CIT operations are addressed. The model adaptations are in Table 12.

Table 12 - Model Adaptations

Current Processing Times Configuration	**Current Model Parameters**			
Parameter	value at retailer	value at bank	value at competitor	units
courier waits for bags and manager to be ready	uniform(0,10)	triangular(3,5,7)	triangular(3,5,7)	minutes
find bags in truck	triangular(20,30,60)	triangular(20,30,60)	triangular(20,30,60)	seconds
enter info of bag on phone or PDA	5	5	7	seconds
Future Processing Times Configuration	**Future Model Parameters**			
Parameter	value at retailer	value at bank	value at competitor	units
courier waits for bags and manager to be ready	uniform(0,2)	triangular(1,2,3)	triangular(1,2,3)	minutes
find bags in truck	triangular(3,4,5)	triangular(20,30,60)	triangular(20,30,60)	seconds
enter info of bag on phone or PDA	1	1	7	seconds
Current Branch Processing Times Configuration	**Current Model Parameters**			
submit, scan, and bag messenger belongings	uniform(1,2)	units		
one bag inspect and scan by vault teller	triangular(2,16,8)	minutes		
one bag preliminary sort by vault teller	triangular(2,16,9)	seconds		
one bag sort by sorting teller	uniform(15,30)	seconds		
paperwork and release	uniform(1,3)	seconds		
one bag overnight re-sort	uniform(15,30)	seconds		
issue keys, manuals, phone/PDA(s), radios, a manifest, and a detailed route sheet for that day to the messenger	uniform(1,2)	seconds		
load bag from branch to trolley	5	seconds		
move trolley from branch to truck	triangular(20,30,60)	seconds		
verify and accept bag to the electronic manifest on the phone/PDA	5	seconds		
one bag sort by early morning crew member	uniform(15,30)	seconds		
assign outbound change request bag to route or competitor	uniform(20,40)	seconds		
take bag to relevant rolling cabinet	triangular(15,30,45)	seconds		
register bag on inventory records	5	seconds		
Future Branch Processing Times Configuration	**Future Model Parameters**			
Parameter	value	units		
scan group of bags by RFID	triangular(5,10,15)	seconds		
transfer of custody between messenger and vault teller	triangular(1,3,5)	seconds		
move one bag from trolley to bin	2	seconds		
move bin trolley and place it in robotic sorter	uniform(1,3)	seconds		
sort one bag by robotic sorter	triangular(6,7,8)	seconds		
sort one bag by worker	triangular(1,2,3)	seconds		

Branch

Figure 11 illustrates the branch operations in the new model. The new model is more straightforward in its operations and requires fewer employees. The new model also assumes an electronic transfer of custody behavior between CIT and the vault tellers.

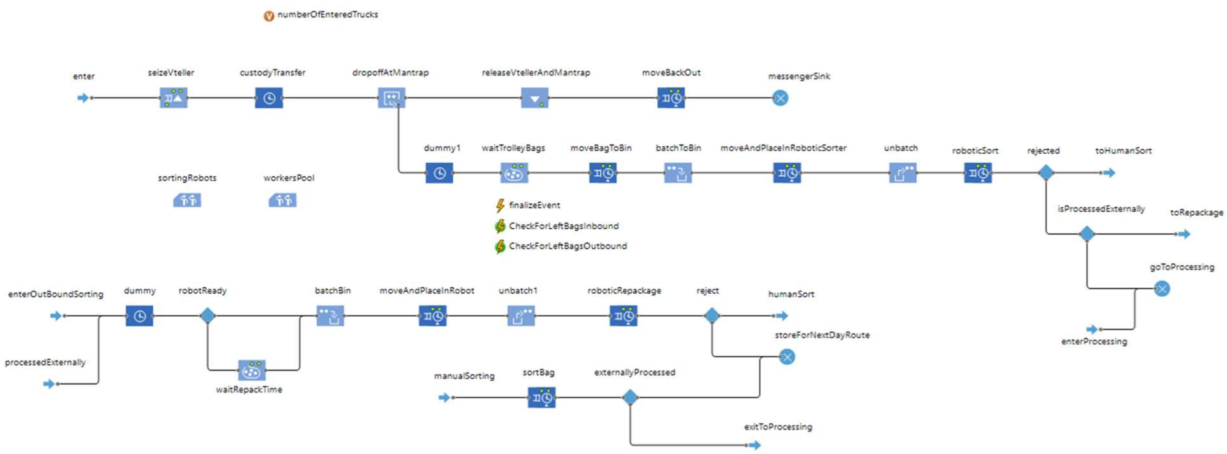

Figure 11 - New Model Branch Operations

The model starts when CIT delivers bags to the vault teller in the mantrap. When the trolley with bags is pushed into the mantrap, the RFID system reads all bags, keys, and accessories. The truck's manifest and the trolley's contents are matched through RFID, and the custody transfer can occur in seconds without touching the bags, keys, and accessories. If the load matches the manifest, the messenger is released to leave. The trolley is placed into the robotic sorting machine, and bags are sorted.

Outbound bags are also sorted in the same way. Noting that outbound bags consist of new change orders processed internally and bags received the previous day, the sorting machine places the bags in routes automatically.

Within the model, there is an accounting for a certain percentage of bags that the robot cannot sort. These bags are handled and sorted by hand by tellers.

Cash in Transit

The new model has a constant live manifest for every truck as bags of cash are delivered and picked up. In addition, messengers can scan bags for delivery much more quickly, speeding up deliveries. For deposits, since the deposit details are transmitted via API, the bags can be scanned with RFID, and no human interaction is required other than the final signature on the PDA by the transferring manager. Within the model, the transactions at retailers, banks, and competitors were increased to show the behavior change. The system does not affect ATMs from a time perspective, but the resulting bags are still traceable.

Summary

In the new model, most processes are accomplished more quickly with less human interaction. There are fewer human touches of bags which decreases the opportunity for error and reduces loss.

Results

The comparison of the two models provides dramatic results in operational time savings. Table 13 illustrates the operational time savings between the two models for transferring bags between CIT and the vault. The new model almost eliminates waiting for an open mantrap and reduces the time in the mantrap by 77%.

Table 13 - Mantrap Comparison

Current State	Count	Mean	Minimum	Lower whisker	Q1	Median	Q3	Upper whisker	Maximum
wait for mantrap	4400	2.9506	0.0000	0.0000	0.0000	0.0000	4.8051	11.9900	31.0113
time in mantrap	4400	12.969	5.3728	5.3728	10.535	12.6659	15.167	22.0390	23.3367
Future State	**Count**	**Mean**	**Minimum**	**Lower whisker**	**Q1**	**Median**	**Q3**	***Upper whisker***	***Maximum***
wait for mantrap	4400	0.0355	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	1.3244
time in mantrap	4400	2.9956	1.0274	1.0274	2.3976	2.9997	3.5922	4.9555	4.9555
Wait reduction		99%							
Trap reduction		77%							

Teller utilization is also affected by the new model. Table 14 shows several key differences. First, the new model requires fewer tellers who are not dedicated to specific tasks. Second, tellers are no longer sorting bags since a robotic sorting system accomplishes that task. Tellers only need to deal with exceptions from the sorting system. Overall, teller utilization drops by 79%.

Table 14 - Teller Utilization

Current Teller Utilization	Count (Days)	Mean	Minimum	Lower whisker	Q1	Median	Q3	Upper whisker	Maximum
Cabinet 1 Sort	100	4.3010	3.7056	3.7056	4.1317	4.3789	4.4920	4.8289	4.8289
Sec CabSort	100	4.2997	3.6642	3.6642	4.1097	4.3532	4.4910	4.8525	4.8525
Early Sort 1	100	2.0773	1.7822	1.8167	2.0035	2.0728	2.1463	2.2931	2.2931
Early Sort 2	100	2.0775	1.7828	1.8139	2.0031	2.0731	2.1451	2.2939	2.2939
Early Sort 3	100	2.0775	1.7850	1.8128	2.0017	2.0738	2.1460	2.2961	2.2961
Early Sort 4	100	2.0773	1.7831	1.8186	2.0051	2.0733	2.1442	2.2928	2.2928
Early Sort 5	100	2.0774	1.7889	1.7889	2.0017	2.0729	2.1453	2.2936	2.2936
Outbnd Sort 1	100	7.3778	6.3614	6.3614	7.0652	7.4971	7.6720	8.2692	8.2692
Inbound Sort 1	100	10.3707	9.0031	9.0031	10.0247	10.4314	10.7522	11.7336	11.7336
Vlt Inbnd Sort 1	100	4.6913	3.8944	3.8944	4.4608	4.6789	4.9049	5.4572	5.4572
Vlt Inbd Sort 2	100	4.7268	3.9294	3.9294	4.5053	4.7003	4.8926	5.4136	5.5247
Vlt Sort Inbnd 3	100	4.6367	3.5697	4.0367	4.4068	4.6303	4.8801	5.2442	5.7794
Overnight 1	101	8.7688	2.9969	7.6706	8.5028	8.8006	9.1872	10.2094	10.2653
Overnight 2	101	8.7697	2.9956	7.6622	8.5089	8.7978	9.1806	9.8783	10.2650
Current Teller		68.3295							
Future Teller Utilization	**Count**	**Mean**	**Minimum**	**Lower whisker**	**Q1**	**Median**	**Q3**	**Upper whisker**	**Maximum**
General 1	101	2.8309	0.1061	2.4978	2.6881	2.7578	2.8733	3.0897	7.1267
General 2	101	2.8360	0.1167	2.4603	2.6928	2.7725	2.8678	3.0625	7.0136
General 3	101	2.8121	0.0689	2.4611	2.6650	2.7461	2.8539	3.0489	7.1058
General 4	101	2.7934	0.0894	2.5003	2.6472	2.7364	2.8183	3.0511	7.1606
General 5	101	2.7951	0.0961	2.4631	2.6708	2.7403	2.8106	2.9628	7.0631
Future Teller		14.0676							

The duration of the truck routes also decreases because of the reduced time it takes to accomplish deliveries and pickup of deposits. Table 15 shows the comparison of time at each type of stop, and Table 16 shows a comparison of overall route times for 100 days. Apart from ATM service times, the duration of stop times decreased from 35 to 58%.

Table 15 - Comparison of Stop Duration

Current State	Count	Mean	Minimum	Lower whisker	Q1	Median	Q3	Upper whisker	Maximum
Retailer	2680	8.9484	1.6333	1.6333	6.5000	8.9333	11.4208	15.6333	15.6333
ATM	531	8.2562	0.3667	7.0000	7.6417	8.4333	9.1917	11.5000	11.9833
Bank	288	13.7612	4.7833	10.9333	13.1292	14.0833	14.8833	17.1000	17.1000
Competitor	117	10.1101	6.4833	7.1167	9.3667	10.1333	10.9167	12.9833	14.3333
Future State	**Count**	**Mean**	**Minimum**	**Lower whisker**	**Q1**	**Median**	**Q3**	**Upper whisker**	**Maximum**
Retailer	2578	3.7713	1.5833	1.5833	3.2667	3.8333	4.4000	5.6333	5.6333
ATM	531	8.4220	0.3667	7.0000	7.6167	8.4500	9.3250	11.8833	11.9833
Bank	288	8.8499	4.4667	6.9833	8.4167	8.9833	9.4667	10.6000	10.6000
Competitor	110	6.6061	3.8167	4.7667	6.0500	6.5500	6.9083	7.9500	9.6833
Retailer		58%							
ATM		0%							
Bank		36%							
Competitor		35%							

Table 16 - Comparison of Route Duration

Current State	Count	Mean	Minimum	Lower whisker	Q1	Median	Q3	Upper whisker	Maximum
Route Duration	100	9.4346	6.1383	6.1383	7.0685	10.0300	10.7838	12.4200	12.4200
Overtime	100	1.7732	0.0000	0.0000	0.0000	2.0300	2.7838	4.4200	4.4200
Current Total		11.2078							
Future State	**Count**	**Mean**	**Minimum**	**Lower whisker**	**Q1**	**Median**	**Q3**	**Upper whisker**	**Maximum**
Route Duration	100	6.4039	4.8372	4.8372	5.3413	6.7286	7.1053	7.7242	7.7242
Reduction		43%							

Discussion

The simulation illustrates an extraordinary shift in manpower utilization. Other factors are not in the simulation model. Reduction in risk, customer satisfaction, performance improvements, additional capacity, and the effects on the processing of deposits is not addressed but are expected to improve with such an application of RFID and an API.

Having explored the potential manpower savings through applying RFID through a simulation, the next logical steps are to validate these activities through trials at armored couriers.

Conclusion and Future Research

The application of RFID with API integration in an ATC has the potential for significant savings, operational efficiencies, and increased capacity. This research may relieve some concerns with ATCs considering this technological advancement.

In the future, researchers need to seek to understand and measure customer satisfaction because of the visibility such a system may provide. In addition, a look at how RFID may improve cash bag processing should be addressed.

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