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MASTER OF SCIENCE THESIS

**A UHF RFID-BASED SYSTEM FOR REAL-TIME
PRODUCTION MONITORING AND TAG QUALITY
CONTROL IN THE TEXTILE INDUSTRY**

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ABSTRACT

A UHF RFID-BASED SYSTEM FOR REAL-TIME PRODUCTION MONITORING AND TAG QUALITY CONTROL IN THE TEXTILE INDUSTRY

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In the textile industry, labeling errors during the production process present significant challenges for both quality control and product traceability. This study proposes a real-time RFID-based production tracking and label quality control system to address these issues. In the developed system, RFID tags attached to products are read by embedded devices equipped with RFID readers integrated into the production lines. The captured product code data is transmitted to a local server via MQTT. The server verifies the tags by querying a central database and provides instant feedback to the corresponding device. The system runs entirely over a local network and does not require an external internet connection, ensuring uninterrupted functionality even in infrastructure limited environments. This architecture enables all devices on the production line to communicate synchronously with the server, maintaining system-wide consistency and integrity. In this way, the use of a single tag per product is ensured, and faulty tags are filtered out. Furthermore, the system evaluates tag readability to detect quality issues such as stitching errors, physical deformation and alerts the operator through feedback. As a result, defective products are identified and removed before production is completed, helping to reduce time loss, and improve overall production reliability.

Keywords: UHF RFID, IoT, Textile Industry, Garment Manufacturing, Real-Time Production Tracking, Industrial Automation

ÖZ

UHF RFID TABANLI GERÇEK ZAMANLI ÜRETİM TAKİBİ VE ETİKET KALİTE KONTROLÜ: TEKSTİL ENDÜSTRİSİNE YÖNELİK BİR YAKLAŞIM

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Tekstil endüstrisinde, üretim süreci sırasında meydana gelen etiketleme hataları hem kalite kontrol hem de ürün izlenebilirliđi açısından önemli zorluklar oluşturmaktadır. Bu çalışma, söz konusu sorunlara çözüm getirmek amacıyla gerçek zamanlı çalışan RFID tabanlı bir üretim takibi ve etiket kalite kontrol sistemi önermektedir. Geliştirilen sistemde, üretim hattına entegre edilmiş RFID okuyuculu gömülü cihazlar aracılıđıyla ürünlere iliştirilen RFID etiketleri okunmakta ve elde edilen ürün kodu verileri MQTT protokolü üzerinden yerel bir sunucuya iletilmektedir. Sunucu, bu etiketleri merkezi veri tabanında sorgulayarak doğrulamakta ve ilgili cihaza anlık geri bildirim sağlamaktadır. Sistem tamamen yerel ađ üzerinde çalışmakta olup dış internet bağlantısına ihtiyaç duymadan, altyapı kısıtlı ortamlarda dahi kesintisiz şekilde işlevini sürdürebilmektedir. Bu mimari sayesinde üretim hattındaki tüm cihazlar sunucuyla senkron biçimde iletişim kurarak sistem bütünlüğü ve tutarlılıđı sağlanmaktadır. Böylece her ürün için yalnızca tek bir etiketin kullanımı garanti altına alınmakta ve hatalı etiketler sistem dışı bırakılmaktadır. Ayrıca sistem, etiketin okunabilirliđini analiz ederek dikiş hatası, fiziksel deformasyon gibi kalite sorunlarını tespit etmekte ve operatöre geri bildirim yoluyla uyarı sağlamaktadır. Bu sayede, hatalı ürünler üretim tamamlanmadan önce ayıklanmakta; zaman kaybı azaltılmakta ve genel üretim güvenilirliđi artırılmaktadır.

Anahtar Kelimeler: UHF RFID, IoT, Tekstil Endüstrisi, Üretim, Gerçek Zamanlı Üretim Takibi, Endüstriyel Otomasyon

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Ögeday ALTUĞLU

İzmir, 2025

TEXT OF OATH

I declare and honestly confirm that my study, titled “A UHF RFID-BASED SYSTEM FOR REAL-TIME PRODUCTION MONITORING AND TAG QUALITY CONTROL IN THE TEXTILE INDUSTRY” and presented as a Master’s Thesis, has been written without applying any assistance inconsistent with scientific ethics and traditions. I declare, to the best of my knowledge and belief, that all content and ideas drawn directly or indirectly from external sources are indicated in the text and listed in the list of references.

Ögeday Altuđlu

08/2025



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SYMBOLS AND ABBREVIATIONS

SYMBOLS:

dB_i	Decibels relative to an isotropic antenna
dB_m	Decibels relative to one milliwatt
E_{Annual}	Annual production capacity
E_{Max}	Total storage capacity
Ms	Milliseconds
$N_{BoxCapacity}$	Number of items contained in a single box
N_{Day}	Number of working days per year
$N_{Defective}$	Number of defective or incorrectly scanned items.
N_{Line}	Number of production lines in operation
N_{Total}	Total number of scanned items
P_{Box}	Box-level error rate
$P_{Product}$	Product-level error rate
S_{Tag}	Individual Tag Storage Space in bytes
S_{Total}	Usable System Capacity in bytes
$S_{Reading}$	Scanning time per tag in seconds
$T_{Worktime}$	Daily working time in hours

ABBREVIATIONS:

BLE	Bluetooth Low Energy
EPC	Electronic Product Code
ETSI	European Telecommunications Standards Institute
FCC	Federal Communications Commission
HF	High Frequency

IoT	Internet Of Things
MES	Manufacturing Execution System
MQTT	Message Queuing Telemetry Transport
NaN	Not a Number
NFC	Near Field Communication
OEE	Overall Equipment Effectiveness
QoS	Quality of Service
RAM	Random Access Memory
RFID	Radio Frequency Identification
RSSI	Received Signal Strength Indicator
SGTIN-96	Serialized Global Trade Item Number-96
SPI	Serial Peripheral Interface
TCP/IP	Transmission Control Protocol / Internet Protocol
UHF	Ultra High Frequency
UWB	Ultra-Wideband
RTLS	Real-Time Location System

1. CHAPTER: INTRODUCTION

Accurate and uninterrupted tracking of products at every stage of textile manufacturing, along with the early detection of defective or incomplete items and effective inventory management, has become one of the most critical requirements in today's industrial landscape. Manual methods for recording and tracking material flow are prone to errors and delays, often resulting in inventory discrepancies and inconsistencies in material localization (Su, 2024). In this context, Radio Frequency Identification (RFID) technology has emerged as a key component of automation and digital transformation. RFID enables products to be uniquely identified, their movements along the production line to be monitored in real time, and quality control processes to be automated (Scholz & Valilai, 2025).

End-to-end traceability within the supply chain is particularly critical for product recalls and quality analysis processes (Wamba & Chatfield, 2009). Zhou (2009), demonstrated that RFID systems contribute to inventory management, production control, and recovery processes in the textile domain. Similarly, Nayak et al. (2015) noted that RFID systems improve not only stock management but also enable demand-driven manufacturing and the personalization of customer experiences. Given the accelerated production cycles, high-volume orders, and increasingly diversified product ranges, RFID-based systems enhance inventory accuracy and improve supply chain operations by automatically updating stock levels (Singh, Vinoth, Singh, & Singh, 2024).

1.1. Problem Definition

In the textile industry, production tracking processes are still largely conducted using traditional methods such as manual data entry and visual inspections. These approaches are inherently prone to human error, slow processing speeds, increased operational costs, and significant limitations in ensuring inventory accuracy. Particularly in high-volume production facilities with a wide range of product

variations, the shortcomings of manual tracking directly affect critical processes such as shipment accuracy and customer satisfaction.

To overcome these challenges, some companies have begun adopting RFID technology with the aim of digitalizing production processes and minimizing operational errors. However, field observations and experiences show that existing RFID systems still have some challenges in the production of garments. Mostly observed are missing tags or placing multiple tags, using same or duplicated tags to different garments, broken RFID tags due to stitching defects and product code verification. Also, current solutions often fall short in areas such as real-time data transmission, tag quality control or validation before shipment.

In this thesis, these issues are examined by pointing out key challenges related to labeling accuracy, real-time tracking, data integrity, and quality control of the RFID tags.

1.1.1. Lack of Labeling Verification

Even in companies that use RFID for inventory tracking, the labels placed in the garments are not checked during production whether they have been properly tagged or not. While some items may lack a tag entirely, others may carry multiple tags simultaneously. Such inconsistencies can lead to inaccurate data being recorded by the system, potentially causing errors during critical processes such as shipment or goods receipt, and thereby reducing the overall efficiency of the supply chain.

1.1.2. Tag Encoding Errors

Incorrect or faulty encoding of RFID tags assigned to products can lead to confusion during the production process and inventory management. Tags with erroneous codes compromise product traceability and result in inaccurate inventory records. Therefore, such errors must be detected and addressed during the production stage.

1.1.3. Lack of Real-Time Production Tracking

Traditional tracking systems are typically based on periodic manual inspections. The lack of integration of RFID systems that enable real-time data flow makes it difficult to detect errors at initial stages. One of the key benefits of RFID in multiple production lines is its capability to allow real time production management which helps to

determine the issues (Liu, Wang, Ling, & Zhang, 2015). Hence, production monitoring has an important role in the reliability of supply chain.

According to Nayak et al. (2015), RFID has an important advantage compared to manual systems by supporting reliable and automated data throughout production process. Popescu and Neacșu (2024) emphasize that RFID has a significant role in digitalization in textiles, offering product-based visibility. This advanced visibility not only improves the inventory accuracy but also improved the demand and customer satisfaction (Denuwara, Maijala, & Hakovirta, 2019). Furthermore, RFID systems contribute to operational traceability and serve as valuable inputs for decision support mechanisms (Ruile & Wunderlin, 2011).

Moreover, considering common challenges in factory environments such as limited internet access and unstable network infrastructure, the proposed system is designed to operate entirely over a local network to ensure uninterrupted operational continuity.

1.1.4. Lack of RFID Tag Quality Control

Despite the increasing adoption of RFID technology in the textile industry in recent years, sewable tags used during production and it carries a risk of performance degradation due to stitching defects, physical deformations, or improper placement (Percy, Kanthamani, Roomi, & Sabapathy, 2025). Such issues can lead to data loss and traceability problems during shipping and logistics operations. Dai and Tseng (2012) highlight that information distortion within multi-layered supply chains can result in significant costs, and that RFID offers an effective solution to mitigate this degradation. Testing RFID tags throughout the production process not only improves production quality but also enhances the accuracy of shipment planning (Arkan & Landeghem, 2013). Accordingly, real-time testing of RFID tags during production and the automated control of tag quality are significant in meeting the industry's operational needs.

1.2. Relationship to the State of the Art

In recent years, a considerable number of academic studies have been conducted on RFID and IoT (Internet of Things) based systems in retail. Experimental findings demonstrate that RFID implementations offer significant benefits to enterprises in the textile and apparel sectors. Field research has shown that, thanks to RFID's automated

and real-time data collection capabilities, stock visibility has improved dramatically compared to barcode-based methods.

(Bertolini, Bottani, Romagnoli, & Vignali, 2015) demonstrated through field experiments in fashion retailing that RFID can achieve item-level accuracies above 99% while also detecting out-of-stock conditions that are often overlooked by traditional methods. Similarly, in a field study conducted across sixty-two stores in the United States, the implementation of RFID technology was found to improve average inventory accuracy and reduce inventory errors by approximately 26% (Hardgrave, Aloysius, & Goyal, 2013). These improvements are attributed to RFID's ability to perform bulk reading without requiring line-of-sight or human intervention, thereby minimizing erroneous records, counting omissions, and shelf losses.

At the production line level, RFID has also been emphasized for its contributions to traceability and operational efficiency. An RFID-based workflow monitoring architecture applied in denim manufacturing was reported to significantly reduce labor time, excess inventory costs, and shipping errors (Oner, Ustundag, & Budak, 2017). In another example, an RFID-enabled production process management system developed in a garment factory in China improved real-time production control and reduced cycle times, while identifying eight critical success factors for implementation, including top management support, user involvement, and cost-benefit analysis (Ngai, et al., 2012).

The literature also highlights several barriers to widespread RFID adoption. Cost pressures, interference in multi-reader environments, and integration complexity are among the primary challenges for small and medium-sized enterprises (Bertolini, Bottani, Romagnoli, & Vignali, 2015). Moreover, the rapid growth in data volume necessitates improvements in collision management and analytical processing infrastructure (Hardgrave, Aloysius, & Goyal, 2013).

In summary, current academic research confirms that RFID-enabled production and inventory tracking systems hold strong potential in terms of accuracy, speed, and transparency. However, it also emphasizes the need for careful integration design and proactive management of technical and economic constraints.

1.3. Scope of the Thesis

In this study, devices with embedded RFID readers integrated into the textile production lines are used to read passive UHF (Ultra-High Frequency) RFID tags, verify their suitability for each product, and detect quality issues at an early stage. The system transmits the captured EPC (Electronic Product Code) data to a local server using the lightweight, low-latency MQTT (Message Queuing Telemetry Transport) protocol, where each tag is verified for accuracy and checked for prior usage. The results are instantly relayed back to the devices on the production line, thereby preventing errors such as repeated readings of the same tag. Furthermore, thanks to the communication protocol, multiple devices can operate in synchronization, and since the system functions on a local network, it operates securely and uninterruptedly without requiring an internet connection. This solution provides both quality assurance and garment based production tracking, guaranteeing that only properly labeled products and validated tags are goes out from the production before the shipment. This system contributes to supply chain and prevents inventory errors due to labelling issues.

1.4. Outline of the Thesis

This study is divided into five chapters. In the first chapter, background, research problems, objectives, and scope of the study is discussed. It also offers a concise review of the existing literature relevant to the topic. In addition, the organization of the thesis is outlined to provide the reader with a clear understanding of the content and structure of the subsequent chapters.

Chapter two focuses on the general architecture of production tracking systems and their integration with IoT technologies. It begins by defining production monitoring and emphasizing its significance in modern manufacturing environments. Afterwards, RFID-based tracking, as well as the role of RFID in Industry 4.0 is discussed.

Chapter three presents the implementation details and the methods used in the system. It explains the hardware components used, including RFID reader and antenna with their specifications. The communication methods and software algorithms developed within the project are explained in detail.

The experimental validation of the system is devoted to chapter four. It includes the test setup and results of field tests, performance evaluations, and operational analyses. In the final chapter, main findings of the study and the contribution to the field is discussed. It also highlights the practical implications of the proposed system for the textile industry.



2. CHAPTER: PRODUCTION MONITORING SYSTEMS, RFID, AND IOT INTEGRATION

Manufacturing Execution Systems (MES) are the systems that are designed to collect real time data from the production lines to optimize the workstation efficiency, and product quality in industrial environments (Kang, et al., 2016). The MES layer integrates the raw data from the machines in the field such as operator inputs, and RFID tags or sensors, providing better management with real operational traceability. Production lines are progressively transforming into cyber-physical systems equipped with embedded controllers and wireless IoT sensors with Industry 4.0 (Wollschlaeger, Sauter, & Jasperneite, 2017). These systems produce continuous, multi-source data streams that are processed on cloud-based analytics platforms.

This section firstly explains the framework of production monitoring systems, with the explanation of RFID-based tracking. The evolution of production systems is became more popular within the context of IoT and Industry 4.0. The role of the MQTT protocol in real-time data transmission and a comparative evaluation is given between RFID and other location-tracking technologies such as barcodes, BLE (Bluetooth Low Energy), and UWB (Ultra wide-band).

2.1. Production Monitoring Systems: Definition and Importance

Production monitoring systems can offer comprehensive solutions that support the planning, tracking, and control in supply chains. Real-time data can be collected from the various stages or lines in production, including machines or workstations allowing the continuous evaluation of production performance. Analyzing the data from these systems can help to develop and optimize the supply chain. For example, real-time production monitoring can help or alert the managers to detect potential delays or breakdowns immediately and intervene proactively. Also, tracking production in real

time improves the accuracy of delivery delays and helps ensure orders are completed on time (Olanrewaju, Adaji, & Doskenov, 2024).

Another critical benefit of production monitoring systems is their ability to improve efficiency and quality. Using the data collected, businesses can identify bottlenecks, detect frequently malfunctioning machines, or pinpoint workstations with high error rates. For example, performance indicators such as Overall Equipment Effectiveness (OEE) can be calculated automatically through the system. This makes inefficiencies, such as downtimes, speed losses, and quality defects clearly visible (Prakash, kok seng, & Cheah, 2019). Continuous improvement (Kaizen) teams can utilize this data to take corrective actions and support systematic process enhancement.

In traditional methods, production tracking was often based on manual forms, spreadsheets, or operator reports. These approaches were prone to human error, provided delayed information, and lacked a holistic view of the operation. In contrast, modern production monitoring systems collect field data directly from automated sensors, or barcode/RFID readers. This drastically reduces human error and ensures accurate, real-time, and integrated data (Han, et al., 2018).

Unexpected machine downtimes, unnoticed inefficiencies, high scrap rates, late deliveries, human errors or slowness are the typical issues that can be seen if these systems are not being used or implemented. Such issues can be detected through live alerts, feedback mechanisms, and automated tracking. For example, if a workstation breaks down or slows down, the system quickly notifies the maintenance or lead team and reduces downtime. Similarly, if a delay is detected in production, managers can adjust capacity or shift resources to speed up the delivery time (Han, et al., 2018).

In summary, production monitoring systems are a competitive asset and offer lots of advantages in the factories. They provide real-time visibility, improves the operational flexibility and it helps the companies to respond more effectively to demands and improves efficiency, and reduces the costs. Studies show that production monitoring systems increase companies' productivity and delivery performance, and these systems are considered key components of digital transformation initiatives and Industry 4.0 roadmaps. (Olanrewaju, Adaji, & Doskenov, 2024).

2.2. Production and Logistics Management Using RFID

In production and logistics, RFID considerably improves operational efficiency and sustainability by the advance of real-time dataset and traceability. Inventories can be monitored along the production line, leading to improvements in operations in supply chain (Casella, Bigliardi, & Bottani, 2022).

The integration of RFID with the IoT establishes an automated data exchange network between machines, production processes, and environmental systems, thereby improving supply chain transparency and workflow efficiency (Tan & Sidhu, 2022). This integration enables real-time data acquisition throughout the entire value chain, from manufacturing and warehousing to final delivery.

One of the key advantages of RFID in production tracking is the ability to monitor products at the individual item level. Each product is assigned a unique RFID tag at the beginning of production, allowing the system to record which process the product has passed through and at what time. This provides production managers with real-time insights into the status of specific orders, enabling early detection of delays or process disruptions (Casella, Bigliardi, & Bottani, 2022).

From a logistics management perspective, RFID enables automated and fast traceability in distribution and storage processes. Since products are identified via RFID tags upon leaving production, they can be quickly scanned and matched during warehouse entry and exit. Gate antennas allow for automatic comparison with shipment lists, helping to prevent incorrect product deliveries without requiring manual verification (Casella, Bigliardi, & Bottani, 2022).

RFID-enabled systems also reduce human intervention in the field, improving both speed and accuracy. For instance, RFID readers mounted on forklifts can automatically scan pallet tags and transmit inventory data directly to warehouse management systems. This reduces location-related errors and streamlines internal logistics operations (Tan & Sidhu, 2022).

In conclusion, RFID technology provides end-to-end traceability by integrating production monitoring and logistics management into a unified system. Traceability initiated at the production line continues through warehousing and distribution and can even extend to the retail level. However, the successful implementation of such systems requires careful consideration of factors such as data volume management,

interoperability between systems, and adherence to global standards. Ensuring that RFID–IoT systems are secure, seamless, and interoperable is essential for realizing their full potential (Tan & Sidhu, 2022).

2.3. RFID Systems in the Context of IoT and Industry 4.0

Industry 4.0 represents a transformational vision that emphasizes the deep integration of physical production systems with digital technologies. Within this framework, the IoT, cyber-physical systems, cloud computing, and artificial intelligence converge to enable the development of smart factories. RFID systems are recognized as a key technology in this context, particularly for object identification and real-time tracking (Tan & Sidhu, 2022).

IoT can ensure that every device, sensor and product within the factory can communicate between networks and with each other. In the context of IoT, RFID has moved beyond its traditional function of item identification. It is now being used in more dynamic applications, such as through RFID tags with sensors to collect data from the environment (Ferdousmou, et al., 2024). Assigning unique identifiers to physical objects, such as garments, counting and sharing the information about them over the network can be provided by RFID.

IoT can help to communicate multiple devices between each other over a local network or cloud systems. RFID can be implemented in this structure by supporting, such as authentication, monitoring and location tracking. For example, every item such as textile products on the production line may have a unique RFID tag, can be digitally addressed, identified and monitored. When integrated, this data allows the creation of a real-time digital mapping of the production results or outputs.

Many studies have been conducted to reveal the role of RFID in supply chain. For example, (Motroni, et al., 2024) used a robotic system including RFID to make warehouse stock counting and evaluated the impact on inventory accuracy. (Tan & Sidhu, 2022) introduced a model including five distinct IoT layers: perception, network, middleware, business and application. This approach aims to demonstrate the potential integration of RFID technology throughout various stages of the supply chain.

Data read and processed by RFID readers can be used in industrial IoT environments to provide information to users, enabling features such as decision-making and calibration of these machines (Ferdousmou, et al., 2024). RFID also facilitates the creation of digital twin models, where each physical asset is digitally represented and continuously updated with real-time data for simulation and predictive analytics (Tan & Sidhu, 2022).

Communication protocols used in IoT and Industry 4.0 platforms are also evolving to facilitate seamless RFID integration. Lightweight protocols such as MQTT allow factory-level RFID devices to securely communicate with cloud-based analytics systems.

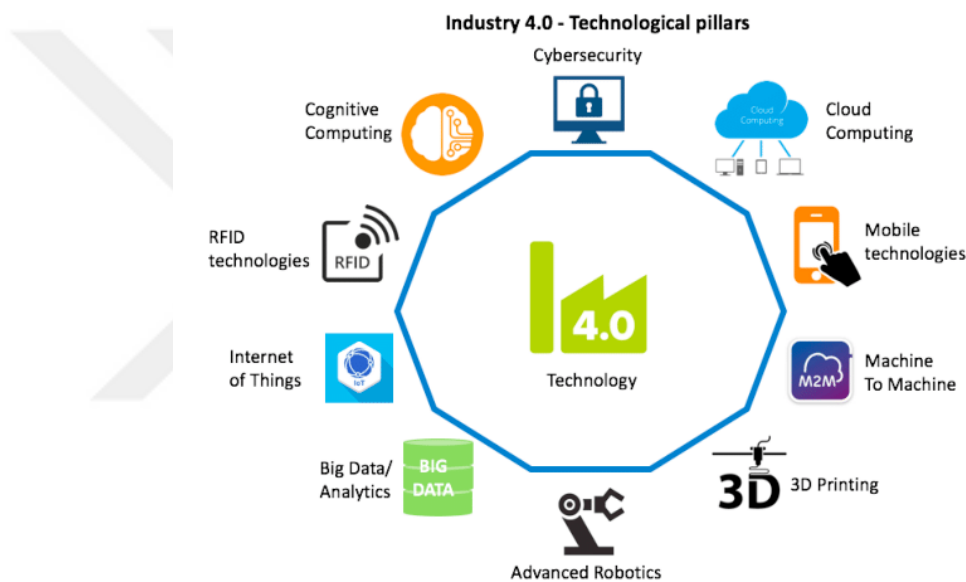


Figure 2.1. Technological Pillars of Industry 4.0

Source: (Saturno, Pertel, & Deschamps, 2017)

2.4. MQTT Protocol and Real-Time Data Transmission

MQTT (Message Queuing Telemetry Transport) is a lightweight, bandwidth-efficient messaging protocol using a publish/subscribe architecture, making it ideal for real-time data transmission in RFID-based production monitoring systems within IoT environments (Saha, Paul, Ji, & Harik, 2024). Key factors contributing to MQTT's effectiveness in real-time data flow include:

- Quality of Service (QoS) levels (0, 1, 2) ensure reliable message delivery.
- Operates over TCP/IP with minimal header overhead, optimizing bandwidth usage.
- The Publish-Subscribe model allows scalable, topic-based data management across multiple devices.

This architecture enables production systems to ensure high data accuracy with minimal latency in message delivery. Major IoT platforms such as AWS IoT and Azure IoT Hub support MQTT communication, facilitating seamless and secure transmission of RFID data to cloud-based storage, analytics, and visualization services (HiveMQ, 2023). This ensures continuous data integration between local systems and cloud applications without interruption.

Figure 2.2. illustrates the communication architecture between the Manufacturing Execution System (MES) and four production lines via MQTT protocol. The bidirectional arrows represent real-time data exchange that ensures synchronization and traceability across all production nodes.

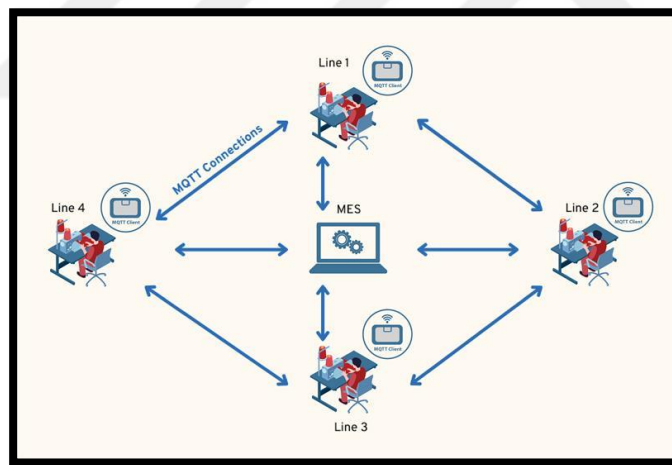


Figure 2.2. MQTT Communication Model Between MES and Production Lines

Source: Author

2.5. Comparison of Different Tracking Methods

Although RFID is widely used for object tracking and identification in production and logistics processes, it is not the only solution available. Alternative technologies such

as barcode/QR code systems, BLE beacons, UWB based Real-Time Locating Systems (RTLS), and computer vision methods are also utilized in various application scenarios. In this part, RFID is compared with other relevant technologies. The discussion focusses on both the strengths and the potential drawbacks of RFID within this context.

2.5.1. Comparison of RFID and Barcode Systems

Barcodes have long been a standard solution in production and logistics due to their maturity as a technology. They are cost-effective and easy to implement, and almost every product is labeled with one. However, there are fundamental differences between barcodes and RFID. Barcodes require optical scanning and must be read individually within line of sight. This makes the process relatively slow and labor-intensive, as an operator has to scan each item one by one, increasing the likelihood of human error. Compared to barcode-based systems, RFID offers several advantages, including reduced reliance on human intervention, the ability to read without line-of-sight, and simultaneous scanning of multiple tags (Ngai , Moon , Riggins , & Yi, 2008). With a single scan, dozens of items inside a box or pallet can be identified without opening the package. Furthermore, unlike barcodes, RFID tags do not need to be visible. They can still be read via radio signals even if placed inside or behind a product.

Another advantage of RFID over barcodes lies in its data capacity and updateability. Barcodes typically store static information and cannot be rewritten or updated. In contrast, RFID tags usually contain a unique identifier and can also store additional user data when necessary. For instance, production date, batch number, or serial number can be saved to the memory of an RFID tag and modified later if needed (Hinz, 2012). This capability enables richer data for traceability and quality control processes. From a security perspective, RFID also offers more robust features; data on RFID tags can be encrypted, protected with access passwords, or even deactivated entirely (Hinz, 2012). On the other hand, barcodes are easier to duplicate and may lose data if the printed label is damaged.

However, barcode technology also offers certain advantages over RFID. Barcode labels are extremely inexpensive and simple to implement, whereas RFID tags still have a relatively higher unit cost compared to barcodes (Hinz, 2012). Moreover,

barcodes adhere to universally accepted standards, enabling any store or warehouse worldwide to read a standard barcode. In contrast, RFID involves various frequencies, protocols, and standards, making global interoperability more challenging than with barcodes. For instance, not all RFID readers can read a high-frequency (HF) Near Field Communication (NFC) tag due to frequency mismatches, and an RFID system used by one brand may not be compatible with other systems.

2.5.2. Comparison of RFID and BLE Beacon Technology

BLE beacons have become increasingly prominent in recent years, particularly in location-based applications. These small battery-powered devices periodically transmit signals to notify nearby BLE receivers of their presence. For instance, a BLE beacon attached to a production cart can be tracked to estimate its approximate location within a facility. The advantages of BLE beacons include their extended detection range (50–100 meters) and compatibility with widely available devices such as smartphones (AssetPulse, 2023). However, these devices require regular maintenance due to limited battery life, and their unit cost is typically higher compared to RFID tags, making large-scale deployments more expensive. Furthermore, in sustainability-focused sectors such as textiles where each item requires a unique, often disposable tag, BLE beacons are economically and environmentally less favorable due to their non-disposable and battery-dependent nature. In contrast, RFID systems utilize passive tags that are both maintenance-free and cost-effective, offering more suitable solutions for such industries (MOKOSmart, 2023).

2.5.3. Comparison of RFID with UWB and Other RTLS Methods

UWB technology stands out in real-time location systems (RTLS) due to its high precision. UWB technology excels in RTLS due to its superior positional accuracy, typically around 10–30 cm, achieved using active tags and time-of-flight methods (Sidiropoulos, 2025). Compared to RFID, UWB provides continuous location data on a millisecond basis, enabling true real-time tracking, whereas RFID can only detect an object's presence when it passes near a reader antenna. Therefore, in scenarios where continuous tracking is critical, UWB may be a more appropriate solution. However, UWB tags are significantly more expensive, and their infrastructure requires more complex installation and configuration (WISER Systems, 2024).

2.5.4. Comparison of RFID with Vision-Based Tracking Systems

In certain production tracking applications, object tracking or counting can be performed using cameras and computer vision algorithms, eliminating the need for additional tags. However, this approach requires optimal conditions such as consistent lighting, high-resolution cameras, and powerful processing units at each monitoring location. In contrast, RFID systems require only minimal data for identity verification, typically a unique ID, resulting in significantly lower processing load and allowing operation even in dark or visually obstructed environments (Kumar, 2021). Furthermore, camera-based systems can raise privacy concerns due to the use of visual data, whereas RFID operates using anonymized identifier codes, providing a more privacy-friendly alternative (Liu, Liu, Zhang, Gu, & Li, 2021).

3. CHAPTER: METHODOLOGY AND IMPLEMENTATION

The system consists of IoT devices equipped with RFID readers and antennas, positioned on workstations along textile production lines; garments equipped with or stitched with passive UHF RFID tags; and centralized local server infrastructure (See Figure 3.1.) Each device reads the RFID tag attached to the product and transmits the obtained product codes to a Raspberry Pi-based local server via the MQTT protocol. Through the deployment of these devices at various stages of the production line, tag verification is automatically conducted by the system throughout the process. A Mosquitto MQTT broker configured on the local server receives data from all devices, while an SQLite-based database stores this data along with the EPC, timestamp, and device identity. The incoming data routed through the broker is processed by a local data handling algorithm, which analyzes the information to detect conditions such as duplicate tag usage and sends instant warning messages to the relevant devices when necessary.

The developed system is supported by a user-friendly interface designed for ease of use by production line operators. The devices are capable of operating in fully offline scenarios, with all data communication occurring within the local network. As a result, the system functions reliably even in factory environments without internet access. Moreover, the architecture is designed to be scalable, enabling simultaneous integration across multiple production lines.

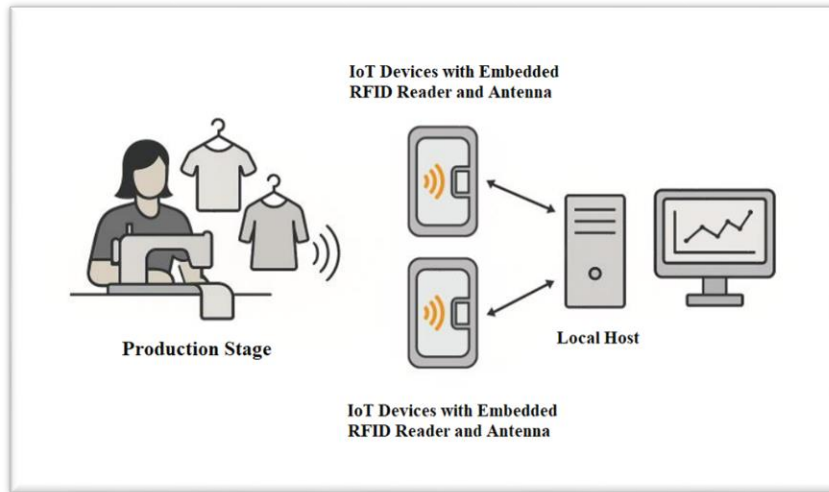


Figure 3.1. System Architecture for RFID-Based Real-Time Monitoring in Textile Manufacturing

Source: Author

3.1. Hardware Components of the System

The developed real-time production tracking system incorporates various electronic components selected to fulfill functions such as data acquisition, communication, processor control, user interface, and centralized data processing. During the hardware selection process, key criteria such as system reliability, communication speed, ease of physical integration, and low power consumption were considered.

3.1.1. RFID Reader

The RFID reader module used in the system is the Zebra RE40 (See Figure 3.2.). This integrated RFID reader is designed to read passive UHF RFID tags and supports both EPC Class 1 Gen2v2 and ISO/IEC 18000-6C protocols. It operates in the 865–868 MHz frequency range and offers a configurable output power from -10 dBm to $+27$ dBm. This feature enables dynamic adjustment of the reading range based on the system's requirements. The module provides a receiver sensitivity of -78 dBm, allowing it to detect even low-power reflected signals.



Figure 3.2. Zebra RE40 RFID Reader

Source: Author

3.1.2. RFID Antenna

In this study, the electromagnetic performance of a circularly polarized UHF antenna, integrated into the RFID system, was analyzed through simulations conducted within a metallic enclosure. The antenna is intended for reliable and accurate tag reading at a maximum distance of 20 cm. The simulation results are interpreted in detail in Figure 3.3. The highest gain was observed near the z-axis, with a calculated co-polar gain of 2.462 dBi, which indicates a sufficient level of directional radiation performance for desktop applications. In addition, the total efficiency was found to be -2.283 dBi (59.2%), and the radiation efficiency was -1.971 dBi (63.6%). Despite potential losses due to the metal enclosure, the antenna can radiate adequate energy. The radiation pattern exhibits a dominant main lobe, while the suppressed back lobes align well with the directional reading requirements of desktop implementations.

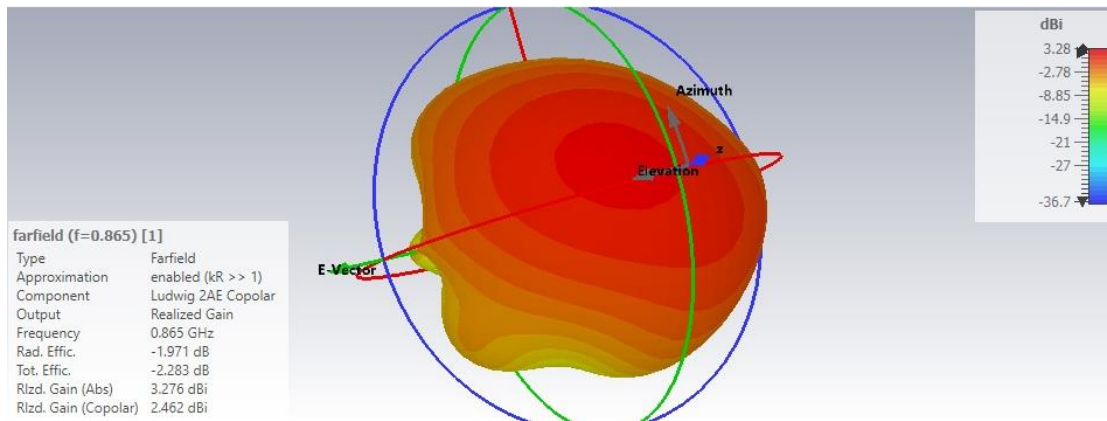


Figure 3.3. 3D Simulation of the Antenna

Source: Author

3.1.3. Local Host Server

As the central server unit responsible for data processing, synchronization control, and record management within the system, a Raspberry Pi 4 Model B was used (See in Figure 3.4.). This unit not only collects and processes data received from edge devices but also performs essential tasks such as duplicate verification, database registration, and feedback broadcasting to ensure the integrity of production tracking.

Despite its low power consumption and compact form factor, the Raspberry Pi 4 offers sufficient processing capabilities to function as a server in embedded applications. The model used in this system features a quad-core 64-bit ARM Cortex-A72 processor (1.5 GHz) and 8 GB of LPDDR4 RAM. These features are sufficient to process messages and perform simultaneous data logging operations.

Running the MQTT broker service is handled by the unit, which relies on Mosquitto as a software. EPC data published by production devices and incoming data is processed and saved in a local SQLite database in Raspberry Pi. Each EPC is checked on central unit to see if the data has already been recorded in the database, and then response is published to devices subscribed to the related topic.



Figure 3.4. Raspberry Pi 4 Model B

Source: Author

3.1.4. Other Electronic Components

ESP32-WROOM-32UE was used as a microcontroller for production devices. Network communication in the system is handled via the WIZnet WIZ5500, which interfaces with the ESP32. It handles data transmission to the central server.

SPI-based TFT display with touchscreen was used in the device to give visual feedback to the user. Additionally, addressable lights were added on the device to visually show the operational state of the system to the user.

3.2. System Overview

In this study, the system was implemented using a distributed IoT structure. Within this setup, each product involved in textile manufacturing can be tagged, verified, and its information transmitted to a central server in real time. The system contains embedded IoT devices with RFID readers placed along the production line. MQTT broker manages communication among these devices. Central unit handles all the data collected.

IoT devices are equipped with several key elements, including an ESP32, RFID reader, and a display screen for user interaction. These devices are fixed in locations in the production area. Garments equipped with RFID tags are read as they pass through the device. After the tag verification process controls, each device sends the data to the local server over the network using the MQTT. The server validates the incoming data and sends updated counter values back to the devices.

A single IoT device is sufficient for each production line. This ensures that every RFID-tagged product passing through the line is uniquely counted and error-checked. In factories with multiple production lines, deploying one device per line is recommended to improve system accuracy and balance scanning load. This setup also enables line-specific statistical analysis. A block diagram illustrating the desktop-type RFID reader device and the local server system is presented in Figure 3.5.

At the heart of each device, the microcontroller unit (MCU) serves as the control hub that communicates with all peripheral components. The MCU is directly connected to the RFID reader, touchscreen display, RGB LEDs, buzzer, WIZ5500 Ethernet module, and the local network (LAN). It transfers the data with these components using communication protocols such as UART or SPI via digital I/O pins.

Power distribution is supplied by an external power source, with appropriate voltage levels regulated for different components via dedicated voltage regulator circuits. The RFID reader is powered through separate regulators, while notification elements such as RGB LEDs, touchscreen, and buzzer are directly powered by the main supply and controlled by the MCU.

In terms of communication infrastructure, the system is designed to operate primarily over Ethernet. It uses the WIZ5500 hardware TCP/IP module and an RJ45 port to establish a connection to the local network (LAN) and communicate with the central server. However, the system is also designed to support Wi-Fi communication for factory environments where Ethernet cabling is impractical. In such cases, wireless connectivity ensures uninterrupted operation.

RFID tag detection is handled through the RFID reader and its connected UHF antenna. The reader transmits data to the MCU, where the EPC values are processed and internal counters are updated accordingly.

As the system's backend unit, the Raspberry Pi-based local server listens for incoming messages via the MQTT protocol over the local network. It receives and parses structured data from connected ESP32-based clients and stores it in a local SQLite database. A lightweight MQTT broker is used to handle the data flow, integrating published EPC values into a centralized data layer. This architecture allows all RFID readings from multiple production lines to be centrally monitored and analyzed.

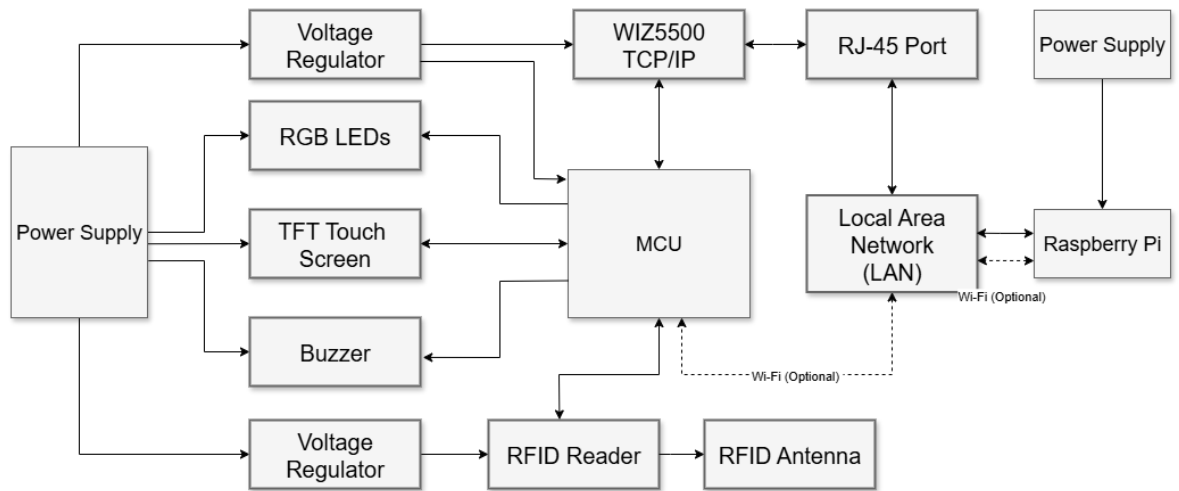


Figure 3.5. Block Diagram

Source: Author

To represent the system’s software workflow and decision-making mechanisms, a general process flow diagram is presented in Figure 3.6. This diagram sequentially and conditionally illustrates the steps involved in tag validation, verification, and data transmission following the reading of an RFID tag. Error scenarios that trigger visual feedback to the user are also incorporated into the process flow.

In the initial step, the RFID reader reads the EPC data. The system then checks whether multiple tags have been detected simultaneously. If more than one tag is read, this situation is classified as a multiple tag error, and the user is alerted through a flashing red light. This condition is based on the system’s assumption that only a single product should be validated at a time on the production line.

When a single tag is detected, the next step involves checking the syntactic validity of the EPC data. Tags that do not comply with the predefined data format are considered invalid and likewise trigger a red light error alert for the user.

Following the format validation, the quality control step is initiated. This step includes quality criteria such as signal reliability, readability status, and software-defined threshold checks. Tags that fail the quality control are rejected and again trigger a red light warning. The algorithm used in this part of the process is described in detail in subsequent sections.

If the tag passes both the format and quality checks, the data is transmitted to the server via the MQTT protocol. Upon reception, the server queries the local database to determine whether the EPC has been previously recorded. If the EPC is unique, being read for the first time, the system increments the production amount counter and provides the user with positive feedback via a flashing green light. However, if the tag has already been scanned, it is classified as a “duplicate tag,” and a red light alert is triggered. These verification and matching operations are handled by a server-side algorithm, the specifics of which are discussed in a later section.

Overall, the process flow diagram illustrates the system’s end-to-end data validation, error management, and user interaction cycle. It also forms the logical basis of the implemented software algorithms.

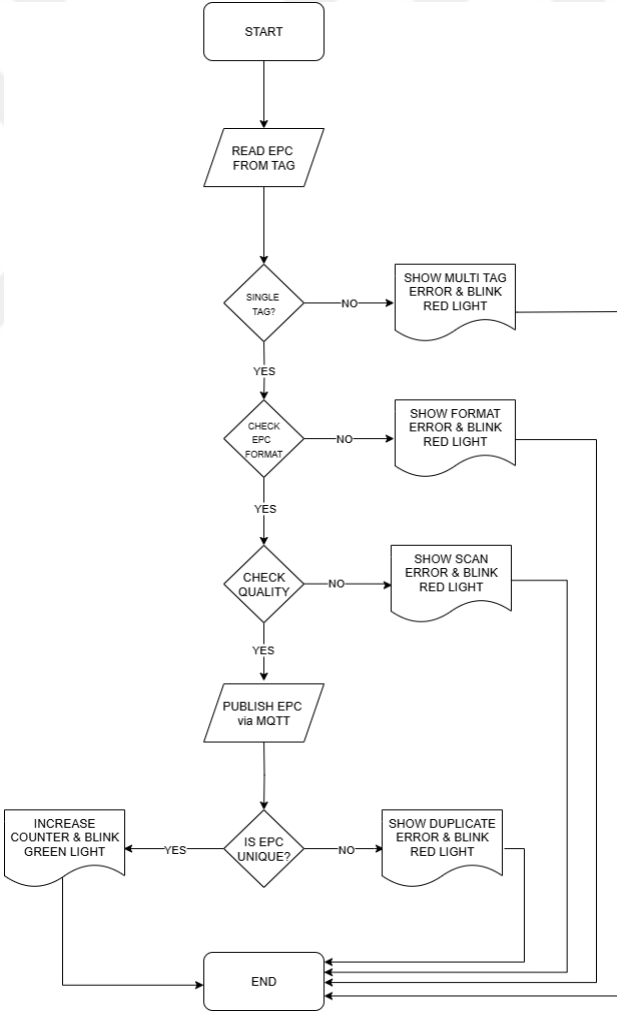


Figure 3.6. Flowchart

Source: Author

3.3. Software Architecture and Control Algorithms

This section presents the algorithmic structures of the embedded software components developed for the system. The firmware running on the microcontroller is designed with a modular architecture to perform key functions such as receiving RFID data, conducting format and quality validation, transmitting the data to the server, and providing user feedback. The system operates based on an event-driven control logic.

At the application level, the software models not only focus on the accurate acquisition and interpretation of EPC data but also incorporate decision-making mechanisms aimed at improving the reliability of the production process based on tag quality. Furthermore, data transmission via the MQTT protocol over the network plays a critical role in enabling device-to-device synchronization and centralized data management within the system.

3.3.1. Reading EPC Memory and Format Validation

The RFID reader reads the EPC memory bank of RFID-tagged products. This product code simultaneously encodes both what the item is (e.g., product type or category) and which individual item it is (i.e., its unique serial number). In this study, the validation algorithm is configured to process RFID tags that conform to the SGTIN-96 encoding format, which is defined under the GS1 EPCglobal standard. The use of GS1 standards in RFID systems is particularly important for supply chain tracking, anti-counterfeiting, inventory control, and item-level identification (GS1, EPC Tag Data Standard Version 2.2, 2025). The SGTIN-96 (Serialized Global Trade Item Number) format, defined by GS1, is an EPC data structure that enables the globally unique identification of products. This structure provides a fixed-length 96-bit (12-byte) EPC format. Thanks to this standard, both large manufacturers and small businesses can uniquely identify their products within a unified system (GS1, Guideline SGTIN and RFID, 2018). The SGTIN-96 format, as outlined in Table 3.1. It includes fields such as Header, Filter, Partition, Company Prefix, Item Reference, and Serial Number, each serving a specific role in ensuring global uniqueness and product traceability.

Table 3.1. SGTIN-96 Binary Structure

Field Name	Size (Bits)	Description
Header	8	Identifies the EPC scheme (for SGTIN-96: 0x30)
Filter	3	Application-based filtering (item, case, pallet, etc.)
Partition	3	Determines the length split between Company Prefix and Item Reference
Company Prefix	20-40	GS1-assigned number identifying the company
Item Reference	24-4	Identifies the product
Serial Number	38	Unique identifier for the product

Source: (GS1, EPC Tag Data Standard Version 2.2, 2025)

The following steps are performed for EPC data parsing:

- The Payload section of the response packet is extracted.
- The first 8-bit Header field is checked (it must be 0x30).
- Next, the 3-bit Filter and 3-bit Partition fields are parsed.
- Company Prefix and Item Reference values are determined. Based on the Partition value.
- The final 38 bits are interpreted as the Serial Number.
- If the total length is not exactly 96 bits or the Header is invalid, an EPC format error occurred.

To ensure correct processing of the EPC, the data must be parsed and checked against format rules. Only valid EPCs are accepted, while mismatch data is rejected. This prevents the incorrect, or non-compliant tags in the production line. This filtering approach reduces the error rate and has a contribution to sustainable data structure throughout the product lifecycle.

3.3.2. Single Tag Verification

Attaching only one RFID tag to each product is important for accurate inventory and stock tracking. In the developed system, a multi-tag verification algorithm is used to ensure that each garment has only one RFID tag.

This approach operates based on the number of tags detected by the RFID reader during each reading cycle. How many tags are detected within a time interval (100 milliseconds) was counted. If only one EPC is detected within this interval, the RFID tagging is considered valid, and the process continues. If two or more EPCs are detected, the system shows multi-tag error. In this case, the device alerts the user with both visual and auditory warnings, and the data is recorded to the system as an error.

This warning prompts the operator to physically inspect the product and remove any additional tags. Once the excess tags are removed, the scan is repeated, and the process is only completed successfully if a single EPC is detected. This control mechanism is directly integrated into the RFID reader hardware and embedded into the system's decision logic, functioning in coordination with operator intervention. As a result, the system ensures that only correctly tagged products are admitted into the production process.

3.3.3. Tag Quality Control Algorithm

With the increasing adoption of RFID technology in the textile industry, sewable RFID tags used for item-level identification during the production process are typically integrated into garments through direct stitching (See Figure 3.7.). These tags are designed to enable durable, item-level traceability by being permanently affixed to the product, thereby supporting accurate production monitoring and lifecycle tracking.



Figure 3.7. Example of an RFID Tag Sewn onto a Garment

Source: Author

During the stitching phase of the production process, various integration-related errors may arise that negatively impact tag performance. Improper stitching techniques can compromise the structural integrity of the RFID tag and directly affect its functionality. Physical issues such as chip damage, antenna breakage, misalignment, and antenna bending may disrupt data transmission, leading to complete or inconsistent reading failures. Below are common RFID tag defects encountered during the sewing process and their impact on the system:

- **Excessively Tight Stitching (Damage to Chip or Antenna):**

Sewing the tag too tightly or applying pressure on the tag can deform the conductive structure of the antenna or create microcracks in the chip area, disrupting circuit integrity. This can result in a completely non-functional tag.

- **Physical Damage from Needle Contact (Chip Puncture):**

Direct contact of the needle with the chip area during the stitching process physically damages the chip. This type of defect is typically irreversible and renders the tag entirely unusable.

- **Folding or Wrinkling of the Tag (Deformation of the Antenna Structure):**

The tag antenna is designed to have a specific physical size and geometric structure. If folding, wrinkling, or bending occurs during stitching, the antenna impedance

changes, and energy transfer is significantly disrupted. This may lead to weak signal reception or complete failure to read the tag.

Figure 3.8. presents three different examples of sewable RFID tags: one with a cut antenna tip, one that is folded, and one intact. The figure clearly illustrates how sewing-induced physical deformations affect the structural integrity of the tag.



Figure 3.8. Examples of RFID Tags Deformed Due to Sewing Defects and an Intact Tag

Source: Author

Physical deformations in sewable RFID tags have significant implications not only in terms of visual appearance but also in terms of electromagnetic performance. These effects can be quantitatively evaluated using specialized analysis devices developed by industrial verification systems. In this study, the effects of various stitching defects on RFID tag performance were comparatively analyzed using the Voyantic Tagformance. The resulting graphs illustrate the frequency-power characteristics of sewable RFID tags and are based directly on measurement data obtained from the device.

The horizontal axis (X) of the graphs represents the frequency range used in RFID systems (800 MHz – 1000 MHz). Within this range, operating band 865–868 MHz is visually highlighted with a grey band. The vertical axis (Y) shows the Power on Tag – Forward (dBm) value, which indicates the minimum power that must be received from the reader for the tag to be successfully activated. Therefore, the lower this value, the higher the sensitivity of the tag is. Each colored curve on the graphs represents an

individual RFID tag of the same model and physical structure but sourced from different production batches or individual samples. This allows for the observation of performance distribution among similarly structured tags subjected to the same physical conditions, thereby enabling the identification of variations. The red curve, labeled as the “tag sensitivity mask,” serves as a reference indicating the system's maximum acceptable read threshold. Tags performing above this curve are considered readable by the system, while those below are deemed unreadable.

The three graphs presented below offer a comparative view of how the same model of sewable RFID tags perform under different stitching scenarios. The tags shown in Figure 3.9. are physically intact, fully functional samples taken directly from production without any mechanical deformation. Their curves demonstrate a low and stable power requirement between -15 dBm and -18 dBm within the 865–868 MHz range. These values fall within acceptable limits for industrial applications, ensuring system reliability.

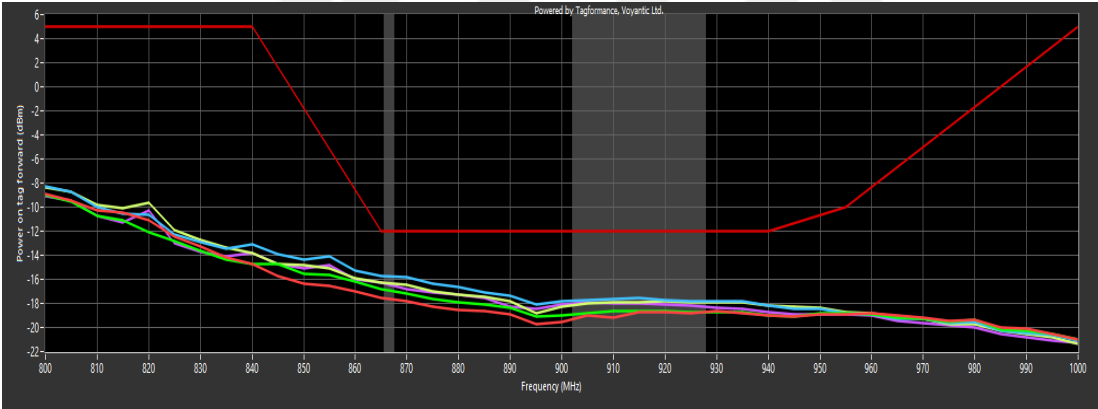


Figure 3.9. Frequency–Power Performance Curves of Intact Tag Samples

Source: Author

In the tags presented in Figure 3.10, a moderate level of deformation is observed. These tags exhibit a forward power requirement that exceeds -12 dBm within the ETSI (European Telecommunications Standards Institute) frequency band, and their performance curves remain just above the masking threshold in the FCC (Federal Communications Commission) band, making them unsuitable for practical use.

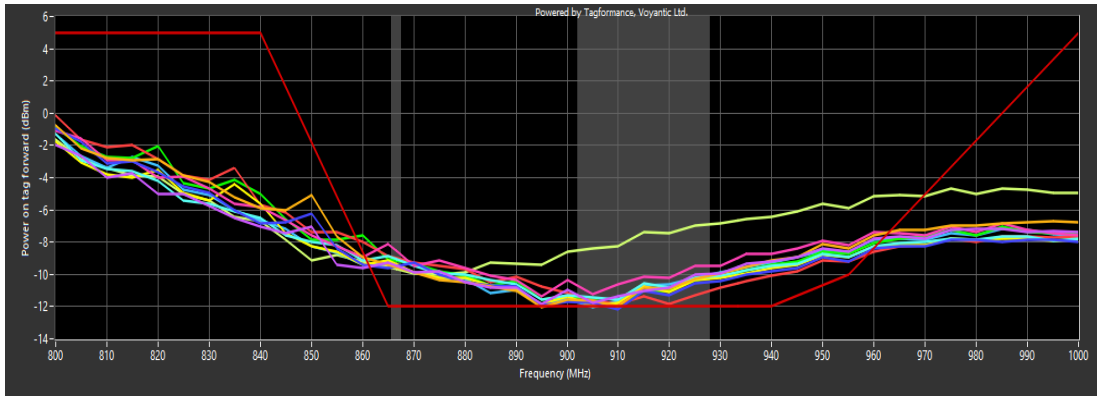


Figure 3.10. Frequency–Power Performance Curves of Moderately Deformed RFID Tag Samples

Source: Author

Figure 3.11. includes measurements of RFID tags that have undergone severe physical deformations, particularly in the antenna region, such as cuts or folds. Within the same frequency band, most of these tags require a significantly higher activation power, around -5 dBm. Furthermore, the curves show noticeable fluctuations and instability, which represent a critical risk to overall system reliability.

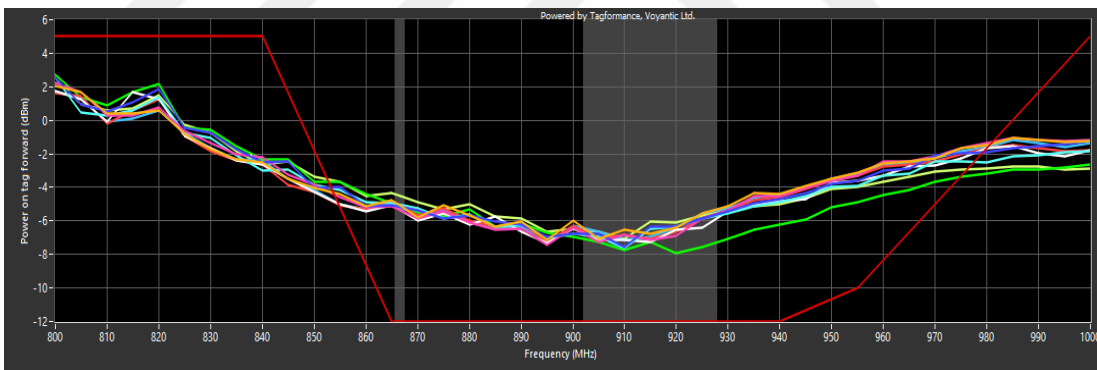


Figure 3.11. Frequency–Power Performance Curves of RFID Tags with Severe Antenna Deformation

Source: Author

Based on these measurement results, the signal strength transmitted by the tag during reading has been identified as a key parameter for detecting damaged or low-performance tags. Accordingly, the developed system implements a tag quality control algorithm based on RSSI and read consistency to detect such defects during the production process. This algorithm evaluates not only the physical presence of the tag

but also its electronic functionality, allowing defective tags to be excluded from the system.

In this way, the system ensures that every RFID tag integrated into the production line is both physically intact and electronically functional, and fully compliant with relevant standards. As a result, potential traceability issues, customer complaints, and inventory errors that may arise in later stages of production or post-sale processes can be effectively prevented.

3.4. Server and Network-Based Communication

In the developed system, RFID data readings performed at the edge devices are not limited to local processing but are also managed through a centralized server structure. This structure gives synchronized feedback mechanism to production devices.

The local server is handled by Raspberry Pi, and it communicates with production devices over MQTT. After the incoming data is checked, it is processed in the SQLite database, and the response is transmitted to the devices.

The system operates on a local network which provides a major advantage in production lines requiring low latency. It is possible for any device to send data and get response from other devices at the same time with publish–subscribe approach. For example, when a valid label is read from a device, it is saved in the database and counters on the screen on other devices are increased simultaneously.

3.4.1. MQTT-Based Communication Structure

In the system, each production device is configured as an MQTT client, while the central server, running on a Raspberry Pi, operates as the broker. On the server side, Mosquitto, a lightweight and open-source MQTT broker, is utilized.

The data packets sent from the devices to the broker contain three key fields: an id representing the unique identifier of the device, an EPC field containing the Electronic Product Code obtained from the RFID reader, and a timestamp indicating the exact moment the tag was read, formatted in accordance with the ISO 8601 standard. These packets are transmitted from the devices to the server using the publish method, following the topic structure defined in Table 3.2.

Table 3.2. MQTT Topic Structure

Topic Name	Description
fabrika-A/epc	Contains the EPC data sent from the devices to the server.
fabrika-A/response	Contains the response message sent from the server to the devices.
fabrika-A/start/<id>	Represents the initialization message sent by a device

Source: Author

This publishing/subscribe structure enables access to time-based data regarding when and how many tags have been read by each device on the production lines, allowing production performance to be evaluated over time. Additionally, it ensures that the devices positioned along different production lines within the factory operate in a synchronized manner, with each device maintaining continuous communication with the central server.

When an error is detected during the tagging process, the server broadcasts a warning message via the response topic to all devices subscribed to it. Upon receiving this message, the relevant device provides visual and/or auditory feedback to the operator, prompting them to remove the faulty tag from the production line.

3.4.2. Database Capacity Analysis and Evaluation in Terms of Production Continuity

The Raspberry Pi is equipped with a 32 GB microSD card for storage and 8 GB of RAM. In the system, the SQLite database is physically stored on the SD card. As a result, all recorded tag data remains persistent even after the device is restarted. RAM is used only for temporary operations, such as executing queries or managing memory buffers, while permanent data storage is handled exclusively via the SD card. This configuration ensures both data security and continuity of production. Each individual tag record occupies approximately 75 bytes of storage space, as detailed below:

- The id field requires up to 10 bytes
- The EPC field consists of 24 characters in hexadecimal format → 24 bytes

- The timestamp is stored in ISO 8601 format (e.g., "2025-08-03T10:30:00") → approximately 20 bytes
- Additionally, 20 bytes are used for SQLite record headers, table metadata, indexing structures, etc.

After accounting for system files and logs, the usable capacity of the 32 GB SD card is approximately 25 GB. Based on this available space, the total storage capacity of the system can be calculated as follows in equation (1):

$$E_{Max} = \frac{S_{Total}}{S_{Tag}} = \frac{25 * 1024^3 \text{ byte}}{75 \text{ byte}} = 357.913.941 \quad (1)$$

Thus, the system is theoretically capable of storing approximately 357 million tag records. In practice, this number may be slightly lower due to overhead from the file system structure, database indexing, and other operational files. As a sample scenario, consider a facility with four production lines, where each line reads one RFID tag every 10 seconds on average. Assuming a daily operation time of 8 hours and a total of 312 working days per year, the annual total number of tag readings for such a facility can be calculated using equation (2). Based on the calculation:

- Annual total number of tag reads: 3,594,240 (Eq. 3)
- This corresponds to approximately 1.00% of the system's total theoretical capacity (Eq. 4)

$$E_{Annual} = \frac{T_{Worktime} * 60 * 60}{T_{Reading}} * N_{Line} * N_{Day} \quad (2)$$

$$E_{Annual} = \frac{8 * 60 * 60}{10} * 4 * 312 = 3.594.240 \quad (3)$$

$$U_{Annual} = \frac{E_{Annual}}{E_{Max}} * 100 = \frac{3.594.240}{357.913.941} * 100 \approx \%1 \quad (4)$$

As demonstrated, the system is capable of continuously storing multiple years' worth of production data with the current hardware configuration. This enables long-term operation in the field without requiring data deletion, backup, or manual intervention.

4. CHAPTER: EXPERIMENTAL RESULTS AND SYSTEM EVALUATION

This chapter explains the experimental results of the proposed system. A series of tests were performed to evaluate the performance of the system in different scenarios, including tag readability, quality degradation due to physical deformation, field deployment, and system response under high-load conditions. The results provide insight into the applicability of the developed solution in industrial environments.

4.1. Experimental Setup and Test Methodology

The setup consists of multiple embedded devices equipped with readers, with a central server operating within a local MQTT-based network.

All tests were conducted under same conditions to ensure consistency and repeatability. The reader output power was fixed to +5 dBm which is observed sufficient for the application. Tags were placed directly above the reader surface, and garments were scanned at 100 ms intervals.

To assess tag quality, a series of experiments were conducted using the developed device by placing both intact and physically deformed sewable RFID tags on the reader surface. The system collected RSSI values across multiple read cycles, and the resulting data were visualized as heatmaps to highlight variations in tag response. Additionally, filtering and classification algorithms based on RSSI thresholds and temporal stability were implemented to detect unreliable or unreadable tags.

For field validation, the system was deployed in a real production line environment with three independent devices positioned at separate stations. Error detection metrics were recorded under continuous operation, and the system's ability to identify production errors such as duplicated tags, unreadable tags, and incorrect tag formats was evaluated.

In the final phase, stress tests were conducted by simulating tag reading events to measure system response times, communication stability, and database handling under

load. All tests were performed using the finalized firmware and production-ready hardware configuration to ensure accurate reflection of real deployment scenarios.

4.2. Tag Quality Analysis

This study investigates whether passive UHF RFID tags affected by stitching errors, physical deformations, or manufacturing defects can be detected by the developed system. For this purpose, a test setup consisting of a 9×5 grid was mounted on top of the RFID reader device (see Figure 4.1.) The test tags were read for approximately 1–2 seconds at each of the 45 positions, and the average RSSI value from the reader was recorded for each region as a basis for the measurements.

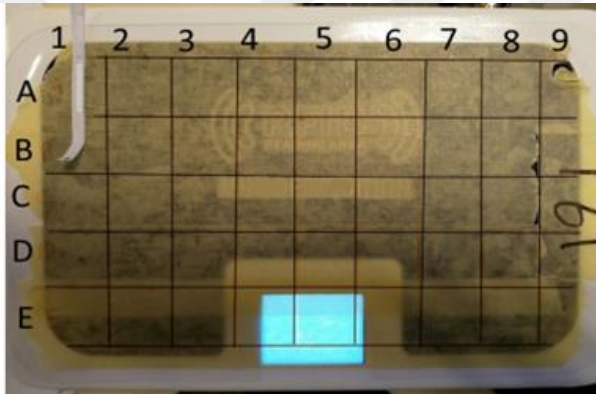


Figure 4.1. Physical Layout of the RFID Test Setup

Source: Author

Based on the collected data, it was observed that the signal strength from intact tags was strongly received by the system, whereas tags with stitching errors or physical damage exhibited significantly weaker signal levels. As illustrated in the corresponding heatmaps, regions containing the intact tag especially near the center of the device, produced higher RSSI values, ranging between -22 dBm and -30 dBm (see Figure 4.2.). In contrast, for the damaged tag, no readings were obtained from the corners (recorded as NaN), and the central regions showed notably lower RSSI values in the range of -47 dBm to -50 dBm (See Figure 4.3.).

These results demonstrate that the developed system can deliver reliable and repeatable outcomes for tag quality control.



Figure 4.2. RSSI Heatmap of Intact Tags Read at Test Points

Source: Author

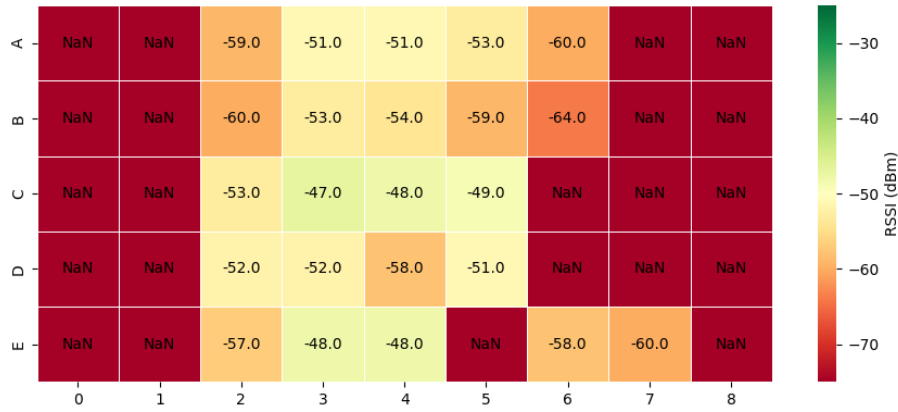


Figure 4.3. RSSI Heatmap of Defective Tags Read at Test Points

Source: Author

This observation demonstrates, in practice, the potential applicability of RSSI-based software filters for detecting defective or improperly stitched tags. However, when interpreting these test results, it is important to consider the system’s physical limitations and operator-induced variability. Due to the antenna being positioned at the center of the device, the electromagnetic field distribution tends to concentrate around the central regions, which naturally leads to lower RSSI values in the corner areas. Additionally, the way in which the operator presents the tag can significantly influence signal strength. Factors such as the angle of the tag relative to the antenna, its orientation, surface contact, or whether the tag is held too close or too far from the device can all contribute to signal attenuation. Such human-induced variations may

result in low RSSI values even from intact tags, particularly in corner regions. Therefore, when interpreting RSSI data, not only the absolute values but also test conditions, antenna positioning, and operator behavior should be considered. If possible, a normalization and classification algorithm should be implemented on the software side to compensate for these variables and improve reliability.

4.3. Field Deployment Results and Error Metrics

The effectiveness of the proposed RFID-based production tracking system in detecting faulty tags under real-world conditions was also evaluated. The tests were conducted in an active textile and garment manufacturing facility during ongoing production. Devices with RFID readers, each operating independently, were installed in three different zones within the factory (See Figure 4.4.). Each device classified the tags read during production over a period of three consecutive days, and the data was transmitted in real time to the central MQTT server.

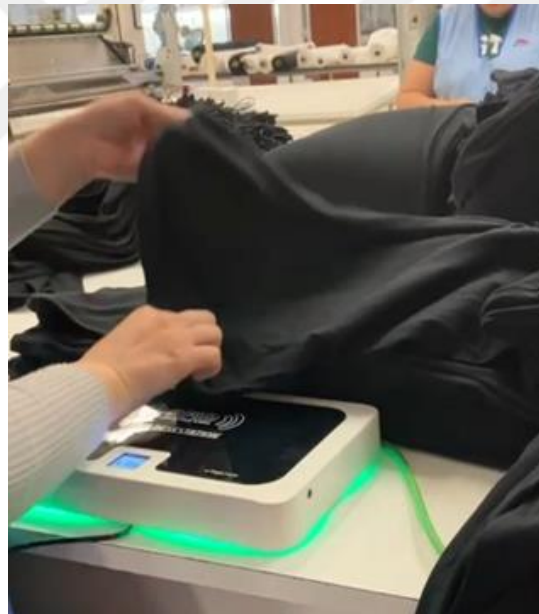


Figure 4.4. RFID Reader Deployed in the Field

Source: Author

During the field test, a total of 6,254 valid tags were read over a period of 3 days by RFID-enabled devices deployed production lines. Within the same period, the system

detected 15 duplicated tag errors, 23 tag format errors, and 5 multi-tag errors (see Table 4.1.).

Table 4.1. Tag Reading and Error Detection Results of Devices on Different Production Lines

Device	Valid Tag	Duplicate Error	Format Error	Multi-Tag Error
Device-1	2074	7	10	0
Device-2	2063	3	6	2
Device-3	2117	5	7	3

Source: Author

When evaluated on a per-product basis, the error rate in the factory's 3-day production was calculated to be 0.68% (Eq5). While this margin of error appears quite low and acceptable, when assessed on a per-box basis, assuming 50 products per box, the probability of at least one defective item being present in a box is approximately 29% based on the compound probability method (Eq6). According to this data, around 3 out of every 10 shipped boxes are expected to contain a defective item.

$$P_{Product} = \frac{N_{Defective}}{N_{Total}} = \frac{43}{6297} = 0,0068 \quad (5)$$

$$P_{Box} = 1 - (1 - p_{Product})^{N_{BoxCapacity}} = 1 - (1 - 0,0068)^{50} \cong 0,29 \quad (6)$$

Based on this, if labeling errors go undetected, the inclusion of defective products in shipment boxes becomes inevitable. This leads either to discrepancies in inventory records or the need to reopen and manually inspect boxes before customer dispatch. In both cases, the supply chain suffers from significant errors and time losses, increased labor costs, and delays in product shipments to retail stores.

The conducted test is crucial in demonstrating the system's ability to detect such errors in real time and alert the operator accordingly. As a result, defective tags are identified during the production stage, and faulty products are removed from the system before

they reach the shipment phase. This prevents inventory errors caused by labeling issues, ensures accurate product-tag matching, and ultimately enhances overall production reliability.

4.4. System Performance Under Load Conditions

In the performance tests conducted as part of this study, the relationship between database size and response time on the central server was evaluated, as shown in Table 4.2. For these tests, random EPC values were generated using a custom Python script, and manual entries were inserted into the database to simulate various data loads. The measurements revealed that when the database contained between 0 and 50,000 records, the system's average response time remained in the range of 20–50 milliseconds, indicating that query operations were completed very quickly within this range. As the database size increased, a gradual rise in response time was observed. Particularly beyond 1,000,000 records, the average response time increased to 500–700 milliseconds. This indicates that the system consumes more resources under heavy data loads, resulting in slower database queries.

Overall, the MQTT-based architecture demonstrated significantly faster response times compared to traditional HTTP-based systems. To maintain consistent and fast performance, it is recommended to periodically clean the database. For example, exporting records to Excel annually or after each shipping cycle can help ensure low query times.

Table 4.2. Server Response Time Based on Database Size

Number of Records in Database	Server Response Time Range (ms)
0 – 50.000	20 – 70
100.000 – 200.000	100 – 150
1.000.000+	> 500

Source: Author

4.5. Summary and Interpretation of Results

The results obtained in this study show that the proposed system gives a robust framework to overcome the challenges in production, particularly in retail where tag readability is often compromised due to physical constraints such as improper stitching or antenna deformation. As explained in Section 5.2, separation between functional and damaged sewable labels can be achieved by applying RSSI-based filtering. By detecting such unexpected manufacturing errors that would go unnoticed in a traditional setup, this significantly improves overall label quality assurance.

Three embedded devices were placed on separate production lines and the devices worked synchronously for three days and shared data synchronously with the local server in the test factory. This distributed yet coordinated system allowed for seamless tag verification across production lines, thereby eliminating the bottleneck that would arise in a single-device system. Moreover, the findings highlight that systems relying on multiple unsynchronized devices are prone to consistency errors, such as duplicated scans or missing reads, which the proposed communication model successfully mitigated. Importantly, even when the individual item-level error rate was observed to be around 1%, probabilistic modeling indicated that this translates to a ~30% likelihood of at least one defective item per box (based on 50 items per box). This underscores a critical vulnerability in downstream processes such as shipping or inventory management and emphasizes the importance of systematic, box-level validation mechanisms in RFID-enabled supply chains.

Section 5.4 explored the system's performance under simulated high-load conditions, focusing on its ability to sustain real-time data acquisition and centralized processing during peak activity. The results show that the Raspberry Pi-based server architecture, in conjunction with lightweight MQTT communication and optimized database operations, remained stable and responsive even when subjected to a high frequency of tag reads. Although minor delays in query response times were observed as the load increased, these delays were within acceptable limits for production environments, particularly when measured against annual throughput requirements. It has been seen that when the necessary backups and maintenance are made, the proposed solution can be used for a long time without causing performance degradation. Tests have shown that the system improves both its reliability and operational efficiency, which makes

it suitable not only for small and medium-sized companies but also for larger facilities aiming to implement synchronized RFID monitoring.



5. CHAPTER: CONCLUSIONS

In this study, an RFID-based production tracking and label quality control system is comprehensively examined in terms of traceability, technical performance, and industrial contributions.

5.1. Technical Performance and Traceability Efficiency

Field tests have shown that faulty, already used, incorrect, and unique tags can be detected before shipment. Additionally, all scanned tags can be saved without the need for external servers. This system increases reliability and gives continuous operation even in environments prone to network instability. Furthermore, the information of which line and when labels were scanned allows for root cause analyses in case of shipping errors or customer complaints.

5.2. Operational Contributions and Efficiency Improvements

The improved system significantly reduces the margin of error associated with human oversight and increases efficiency by streamlining the quality control and workflow. Labels that should not be shipped are identified and alerted, prompting customers to replace or reencode them.

Local network-based infrastructure improves performance by enabling high-speed data communication without requiring an internet connection. This approach ensures uninterrupted functionality in factories with limited or problematic network infrastructure.

5.3. Industry-Level Impact and Corporate Benefits

The proposed system eliminates the internet dependency, eliminating infrastructure and license costs associated with remote server maintenance and cloud services. In addition to this, system is designed to support multiple devices operating together on different production lines, the devices remain synchronized, ensuring accurate and consistent tracking of labeled products throughout the facility. This prevents incorrect

data entry and transaction conflicts. As a result, labeling-related errors that typically manifest later in the supply chain can be eased directly at the point of origin.

From a corporate perspective, the system offers both operational and economic advantages by reducing manual labor and minimizing errors in inventory tracking and automatically contributing to decision-making processes. Furthermore, by maintaining transparency and accountability in supply chain, companies can strengthen customer confidence, address quality audits with better efficiency, and fulfill compliance obligations which made possible through the ability to monitor each product in detail.



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