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Automating the Part Identification Method of Automotive Assembly Lines Through RFID Technology

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Master of Science

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Automating the Part Identification Method of Automotive Assembly Lines Through RFID Technology

Production Engineering and Management, Master of Science
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Abstract

Barcode scanning has been used for many decades in the assembly process to identify individual parts. Besides the fact that scanning is a non-value-adding operation, it also is prone to error. It cannot be ensured with certainty that the scanned part will be the part installed. Furthermore, if any part is interchanged, it leaves the manufacturer with the challenge of detecting this and correcting the data. The genealogy data is important as it enables precisely tracing which parts are built into which vehicle. Strong confidence in the integrity of the genealogy data allows a manufacturer to minimize the scope of recalls, which reduces cost and harm to the brand’s reputation. In addition, scanning impacts the assembly line uptime. When scan errors occur, the factory execution system could stop the production line to fix the issue and ensure high quality. Therefore, this thesis proposes an alternative and innovative approach to the part identification and verification process in an assembly line. The approach is to replace the traditional barcode with a passive ultra-high frequency RFID label. It automates the identification process when a part is installed in the vehicle, which makes manual scanning redundant. The suggested approach also proposes a final traceability scan. Hereby the completely assembled vehicle and its components with the RFID tags are read again to verify the same parts are still installed. The result would be enhanced genealogy data of each vehicle. This thesis aims to determine the technical feasibility of both processes and investigate the economic feasibility.

The conducted empirical research of this thesis is based on a literature review about RFID technology and its applications. To prove the technical feasibility, a series of experiments were carried out for the in-station part identification and the final traceability verification. With a determined number of test parts, a total of 498 experiments were conducted in a real production environment. Moreover, the proposed dual-antenna approach and software logic enables accurate part identification. Lastly, for the assessment of the economic feasibility, a comprehensive data model was developed to assess the production impact of scanning.

Literature and a theoretical investigation show that most of the already consumed scan results can be related to human errors. The experiments for the automated in-station identification reveal; that it is possible to accurately identify the installed part under at least one setup with the suggested dual-antenna approach. However, every single part needs its setup adjusted to the environment in which it is assembled. There is not one out-of-the-box solution that suits every individual application. The finding from the final traceability scan experiment is that all tested parts are identified by the determined setup. It becomes apparent that reading the individual parts even after a car is completed is possible, despite the interference of the vehicle’s metal chassis and radio frequency waves. The conclusion from the economic feasibility is that although the RFID tags are more expensive than barcode labels, the implementation could still offer significant financial benefits to a manufacturer. To summarize the topic, the proposed method based on RFID technology is an innovative approach that is technically feasible and offers a variety of benefits.

Keywords: RFID, General Assembly, Part identification, Traceability, Automotive industry, Genealogy, Barcode scan, Vehicle scan
Sammanfattning


Nyckelord: RFID, allmän montering, Identifiering av delar, Spårbarhet, Fordonsindustrin, Genealogi, Skanning av streckkoder, Skanning av fordon
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Lastly, I would like to extend my sincere thanks to my family for their continuous support and advice throughout my studies. I could not have undertaken this path without you.

Felix Buchner

Austin, Texas – September 30, 2022
Declaration

This master’s thesis is a presentation of my original research work. I declare that this thesis contains no material that has been submitted previously, in whole or in part, for the award of any other academic degree or diploma. Wherever contributions of others are involved, every effort is made to indicate this clearly, by reference to the literature or acknowledgment of collaborative research and discussions. Except where stated otherwise, the work presented is entirely my own.

Felix Buchner

Austin, Texas – September 30, 2022
# Table of Contents

ACKNOWLEDGEMENT .......................... III  

DECLARATION ................................. IV  

ACRONYMS ................................. VII  

LIST OF FIGURES ........................ VIII  

LIST OF TABLES ........................ IX  

I INTRODUCTION .......................... 1  

1 PREFACE ........................... 2  

2 TESLA ............................... 3  

3 SCANNING OPERATION IN GENERAL ASSEMBLY ............................... 3  

4 GENEALOGY PROBLEM STATEMENT ............................... 4  

5 RFID PART CONSUMPTION THEORY ............................... 5  

6 RESEARCH QUESTIONS ............................... 7  

II STATE OF THE ART TECHNOLOGY AND LITERATURE REVIEW ............................... 8  

7 BARCODE SCANNING IN MANUFACTURING ............................... 9  

8 RADIO FREQUENCY IDENTIFICATION ............................... 10  

9 RFID APPLICATION IN MANUFACTURING ............................... 14  

III METHODOLOGY .......................... 15  

10 RFID EXPERIMENTAL DESIGN ............................... 16  

10.1 IN-STATION EXPERIMENT SETUP ............................... 18  

10.2 FINAL TRACEABILITY SCAN SETUP ............................... 19  

11 LINE IMPACT OF SCANNING ............................... 19  

IV PROPOSED RFID APPROACH ............................... 23  

12 METHODS FOR ACCURATE PART DIFFERENTIATION ............................... 24  

13 PROCESS FLOW OF THE RFID SYSTEM ............................... 26
### Acronyms

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>AIDC</td>
<td>Automated identification data capture</td>
</tr>
<tr>
<td>BOM</td>
<td>Bill of Materials</td>
</tr>
<tr>
<td>COPQ</td>
<td>The Cost of Poor Quality</td>
</tr>
<tr>
<td>DRM</td>
<td>Dense Reader Mode</td>
</tr>
<tr>
<td>ETSI</td>
<td>European Telecommunications Standards Institute</td>
</tr>
<tr>
<td>EV</td>
<td>Electric Vehicle</td>
</tr>
<tr>
<td>FCC</td>
<td>Federal Communications Commission</td>
</tr>
<tr>
<td>GA</td>
<td>General Assembly</td>
</tr>
<tr>
<td>HF</td>
<td>High frequency</td>
</tr>
<tr>
<td>HQ</td>
<td>Headquarters</td>
</tr>
<tr>
<td>IoT</td>
<td>Internet of Things</td>
</tr>
<tr>
<td>LF</td>
<td>Low frequency</td>
</tr>
<tr>
<td>LHCP</td>
<td>Left Hand Circularly Polarized</td>
</tr>
<tr>
<td>NC</td>
<td>Non-Conformance</td>
</tr>
<tr>
<td>NFC</td>
<td>Near field communication</td>
</tr>
<tr>
<td>OEM</td>
<td>Original Equipment Manufacturer</td>
</tr>
<tr>
<td>OPEX</td>
<td>Operating Expense</td>
</tr>
<tr>
<td>PLC</td>
<td>Programmable logic controller</td>
</tr>
<tr>
<td>RF</td>
<td>Radio frequency</td>
</tr>
<tr>
<td>RFID</td>
<td>Radio frequency identification</td>
</tr>
<tr>
<td>RHCP</td>
<td>Right Hand Circularly Polarized</td>
</tr>
<tr>
<td>UHF</td>
<td>Ultra-high frequency</td>
</tr>
<tr>
<td>VBA</td>
<td>Visual Basic for Applications</td>
</tr>
<tr>
<td>VIN</td>
<td>Vehicle Identification Number</td>
</tr>
<tr>
<td>VSWR</td>
<td>Voltage Standing Wave Ratio</td>
</tr>
<tr>
<td>WIP</td>
<td>Work in Progress</td>
</tr>
</tbody>
</table>
List of Figures

Figure 5.1: Part identification in station based on RFID [30] ................................................................. 6
Figure 8.1: RFID Coupling Working Principles [39] .................................................................................. 11
Figure 8.2: RFID tag orientation ................................................................................................................ 12
Figure 8.3: UHF RFID antenna polarization [31] ......................................................................................... 13
Figure 10.1: Radiation pattern of Zebra AN440 and AN480 [43] ................................................................. 17
Figure 10.2: CAD model of experimental RFID antenna stand ................................................................. 18
Figure 10.3: Interference of RF with metals and liquids in the automotive assembly ................. 18
Figure 10.4: 27 RFID tag positions for final traceability scan test [44] ................................................... 19
Figure 11.1: Timelines for downtime calculation scenarios ......................................................................... 20
Figure 12.1: RFID part differentiation dual antenna approach exemplified by the windshield [44] .... 25
Figure 12.2: Logic conditions for part identification based on the dual antenna approach .......... 26
Figure 13.1: Part consumption process flowchart pre-main line ............................................................... 27
Figure 14.1: In-station RFID antenna setup 1 heat pump [44] .................................................................. 30
Figure 14.2: Heat pump test 1 plot ............................................................................................................... 31
Figure 14.3: In-station RFID antenna setup 3 heat pump [44] .................................................................. 31
Figure 14.4: Human interference with RFID exemplified on the heat pump [46] ................................. 32
Figure 14.5: Final traceability scan RFID antenna setup 1 [44] ................................................................ 33
Figure 14.6: Chassis and RF waves diffraction [30] .................................................................................. 34
Figure 14.7: Final traceability scan RFID antenna setup 2 [44] ................................................................ 34
Figure 15.1: RFID part identification software design exemplified by driver seat measurement v7 .... 36
List of Tables

Table 4.1: Scan Result Messages...........................................................................................................5
Table 7.1: Comparison of barcode and RFID technologies [36].............................................................9
Table 8.1: Comparison of the 3 main RFID frequency ranges [31] [40]..............................................11
Table 10.1: Experimental Design Hardware.........................................................................................17
Table 14.1: Experiment table for the heat pump ....................................................................................29
Table 16.1: Assumptions for RFID economic feasibility ......................................................................37
Introduction

The Preface of the thesis opens the topic, and the Research Question concludes it by pointing out the main thematic foci. After the thesis introduction, key facts about the company Tesla are presented. Next, the Scanning Operation in General Assembly describes the importance and impact of scanning on a general assembly line. This section also explains why parts need to be identified in the first place and what the challenge with the current method is. Lastly, the RFID Part Consumption Theory section elaborates on the original idea of this thesis and the process flow of this new approach. This chapter provides the necessary information to initiate this topic and links to the State of the Art Technology and Literature Review chapter.
1 Preface

"It's relatively easy to make a prototype but extremely difficult to mass manufacture a vehicle reliably at scale. Even for rocket science, it's probably a factor of 10 harder to design a manufacturing system for a rocket than to design the rocket. For cars it's maybe 100 times harder to design the manufacturing system than the car itself."

Elon Musk

Vehicles are highly complex and technical advanced products that consist of several thousand parts. In addition, the automotive industry experiences increasing global competition and performance goals. At the unveiling of the Model Y in March 2019 Elon Musk stated that designing the production system is “100 times” as hard as designing the car itself [1]. It is such a vast and complex process that tremendous expertise and technology are required to reliably manufacture a vehicle with high quality. Delivering a car with good quality is key to the success of an Original Equipment Manufacturer (OEM), not only in terms of reputation and customer relationship but also when it comes to cost. The Cost of Poor Quality (COPQ) includes categories such as recalls, rework, expediting costs, and inventory shortages, amongst others. An average company loses approximately 20% of its sales due to COPQ [2]. Part of the overall quality is the data quality that is gathered during production. Since there are no legal requirements for all manufacturers, it is the OEM’s choice to keep track of this assembly process and collect the genealogy data of each vehicle [3].

Genealogy is defined as the collection of manufacturing data that describes the product's history. It contains information about the process, tools, torque values, raw materials, resources, equipment, inspection results, dates, quantities, lot numbers, and serial numbers. Having access to strong product genealogy is a powerful asset as it provides advanced traceability, control over consumption, visibility into product life cycle, and activities that have been logged to the product. All this information helps to identify quality concerns before they even occur [4] [5].

One way to record the genealogy data of a car is by scanning the barcode on a component to retrieve the serial number. However, automated identification data capture (AIDC) systems have recently gained relevance and importance. The reason for this is the advancement of the Internet of Things (IoT) and that human interventions are not needed. Thus, it also removes the human error factor. The most common technology for automated data communication is radio frequency identification (RFID) [6].

This thesis evaluates the possibility of utilizing RFID technology to enhance the product genealogy data collection process as well as validity. Hereby, RFID tags are used instead of traditional barcode labels on each part to automate the part identification and consumption in the production process.
2 Tesla

Tesla, Inc. is an American automotive and sustainable energy company with the mission to accelerate the world’s transition to sustainable energy. It was founded in 2003 and Elon Musk is currently serving as the CEO. Tesla offers electric vehicles (EV), solar panels, solar roof tiles, battery energy storage systems, as well as related accessories and services. The company’s headquarters is based in Austin, Texas and according to the Impact Report 2021, there were nearly 100,000 employees [7]. At present, Tesla’s EV product portfolio includes the Model S, Model X, Model 3, and Model Y. Future vehicle products that have already been announced include the Tesla Semi, Cybertruck, Roadster, and Robotaxi. Production facilities for the Tesla vehicles are in Fremont, California; Austin, Texas; Berlin, Germany; and Shanghai, China. Globally, Tesla sold over 936,000 cars in the year 2021. In Q1 2022, the total production volume was 305,407 cars. With a revenue of 16.8 billion dollars in the first quarter of 2022, the company was able to grow 87% year-over-year [8] [9].

3 Scanning Operation in General Assembly

Barcode scanning has been used for many decades in the assembly process. It is the standard procedure to identify a part [10]. Even though it is a simple and very reliable process, it comes along with certain disadvantages. In the automotive assembly process, amongst other things, scanning is utilized to identify the unique serial number of a component. A part number describes the type of part design, whereas a serial number is a unique identifier of one specific part. The serial number of the component, which in this case is also referred to as the child, is consumed to the serial number of the parent [11]. The parent is the next highest entity in the Bill of Materials (BOM). This genealogy data enables an OEM to precisely trace which parts are built into which car. However, manufacturers do not track every part. In general, parts can be classified into one of the three traceability categories [12]:

I. Serial tracked
II. Lot tracked
III. Not tracked

Serial tracked parts maintain traceability through a unique serial number identification with individual part marking. This serial number can be accessible over a label on each part. Lot tracked parts, on the other hand, maintain traceability through a lot/batch number that represents a fixed quantity of homogeneous material, parts, or subsystems that is manufactured during a common production run [13]. Part traceability enables an information flow about the part’s history. It allows, amongst other things, traceability back to raw materials, component serial or batch numbers, process records, inspections, dates, and tests results [14]. Traceability is especially important when it comes to product recalls. According to Töyrylä, it is perhaps the most relevant application of this data [15]. It allows the identification of the product that contains the specific component. This enables an OEM to make selective product recalls [16]. Likewise, good traceability data enhances the response speed to recalls [17]. As a result, comprehensive genealogy data ultimately reduces cost and minimizes the reputational damage to the brand. Product recalls in general are necessary as non-conforming products increase the risk for product liability claims. Besides reducing the risk, genealogy data can be used as a prevention measure. In the event of a product liability claim, traceability data can be utilized as evidence. The data could state that the part was not built into a product and hence is not in circulation [15].
Another reason for scanning during the assembly process is to ensure the right part variant is picked. By scanning a part, not only the serial number is identified, but also the part number. It is specific to the part design. Thus, every part variant has its own part number. The scanned part number is used to verify whether the right part was picked for this car. It is crucial to verify that the right part is selected within the station, as the cost of repair increases as the part goes down the line. The reason for that is as the part gets covered up by other parts, it becomes more difficult to reach. As a result, additional workload is required to access the part and change it.

4 Genealogy Problem Statement

While the scanning operation is an important part of any production process, it is prone to several common errors that could reduce its effectiveness and add time and cost to the overall product being produced. A scan itself is a very robust process, but the entire operation from scanning to assembling a part is not. After the scan happens, it cannot be ensured that the same part that was scanned is also built into the product. Certain scenarios could happen which would prevent the scanned part from being installed. For instance, theoretically, if a part does not fit, the part could be exchanged with another part. Based on this example, physically, one part would be installed, but the system would have recorded the consumption of a different part. Whenever the previously scanned, but not installed, part would be picked and scanned by an operator later, the factory execution software would not accept the part. The scan would fail because the serial number is already consumed by another parent [18]. By analyzing the universal process of manually scanning and installing a part, it becomes clear that the root cause could be versatile. Potential root causes, amongst other things, could be skipping sequences, working ahead, scanning the wrong label, or part interchanges. Regarding the just mentioned root causes and thus the already consumed part error, it is most likely human caused. In general, a complex assembly system can be the origin of human errors [19]. With increasing product complexity, the number of human errors rises as well [20]. Therefore, the already consumed scan result is a common error at any assembly line. If an unacceptable scan is not fixed within the given takt time, this scan warning could cause downtime at the assembly line, as the product should not continue without a scan task being completed. Stopping the line adds visibility, allows operators to solve the problem right when it occurs, and prevents a defective product from proceeding [21]. If, for certain reasons, it would not be possible to fix this scanning issue, the product would have missing genealogy. Thus, the product would be non-conforming. A non-conformance describes the deficiency of fulfilling a required quality characteristic [22]. A manufacturer should quickly respond to non-conformances by containing the product to prevent further use. It is a quality control measure [23] [24]. This in turn would create additional work in the form of correcting the serial number information at a later time.

Hypothetically, if a product with missing genealogy would be in the field, the scope of recalls could increase. If there would be a recall for the unknown part type and the product would be within the specific production period, an OEM recalls those products as well for good measure. This increases the overall recall cost and tarnishes the brand’s reputation [25].

Besides the prior described already consumed scan error, there are other potential scan result types. A selection of theoretical scan results is listed in Table 4.1 below. The other scan errors have different root causes than already consumed scan error. Nevertheless, they still could have a significant impact on production, as they would prevent parts from being consumed. This happens for a good reason, as it
add visibility to the process. The result of those potential NOK scans would be additional work, and in the worst case, they could cause downtime or containments.

Table 4.1: Scan Result Messages

<table>
<thead>
<tr>
<th>SCAN RESULT</th>
<th>DESCRIPTION</th>
</tr>
</thead>
<tbody>
<tr>
<td>PART NUMBER IS INCOMPATABLE [26]</td>
<td>Scanned part number does not match the expected part number</td>
</tr>
<tr>
<td>PART CONTAINS NON-CONFORMANCE [27]</td>
<td>There is a non-conformance on the part</td>
</tr>
<tr>
<td>PART SEQUENCE IS INCORRECT [28]</td>
<td>The child is already assigned to a specific parent according to the determined sequence</td>
</tr>
</tbody>
</table>

Apart from that, manually scanning itself can be considered a non-value-adding operation. According to the lean principles, value is added to a product if it can be perceived by the customer, which is not the case for the scanning process [29]. Thus, the time an operator spends on scanning could be reallocated to other tasks. Automating the barcode scanning process is difficult. It requires the barcode to be in the relatively same position every time. This repetitiveness cannot be ensured. Utilizing cameras would increase the scan area barcodes could be detected, but there is still a major disadvantage. For barcodes to be scanned it requires a line-of-sight. This is the greatest limitation of this technology and the reason why this thesis investigates replacing them with RFID tags.

To summarize, there are four main potential problems arising from barcode scanning. They all could either affect the repair overhead, recall activity, productivity, effectiveness, or cost. Those main problems are:

- False genealogy
- No genealogy
- Downtime
- Non-value adding operation

Even though there are no legal requirements for scanning itself, it is a substantial and critical process [3]. Besides transferring part or serial numbers, depending on the part, the consumption process could also transfer further data. Due to its importance and susceptibility to errors, scanning could cause significant downtime. Genealogy data could also be recorded incorrectly and whenever detected it would require an additional workload to fix it. Therefore, this project investigates a new part identification and verification method.

5 RFID Part Consumption Theory

This thesis investigates the possibility of replacing the traditional barcode on a component with an RFID tag to automate and enhance the part identification process in an assembly line. One of the reasons for part identification is to ensure traceability; when a serial tracked part or lot tracked part with individual part marking is scanned, its corresponding serial or lot number is consumed to the parent serial number. Ultimately, genealogy data of a vehicle provides traceability over which part is built into which car. The initial concept of this thesis was to remove part scanning from the assembly process entirely and utilize one “final traceability scan” at the end of the assembly process to consume the children to the
A car completes the assembly process when all necessary work is completed. The idea was that the car drives through an “RFID tunnel” and all RFID tags on the parts are read. This final scan would identify the entire genealogy of the car at once. The reason for scanning at the end of the assembly process is that at this point in time, the car should not be modified anymore. In theory, that would result in perfect genealogy data of the car. However, as certain parts of a vehicle are available in multiple variants, they need to be scanned when assembled to ensure the correct variant is picked. If an incorrect variant would be detected at the end of the assembly line, the workload to fix that is higher compared to fixing it in the station, as work would need to be undertaken in order to reach the part. Another reason supporting scanning in the station is to ensure the parts are released to production and do not require additional inspection. This provides visibility and allows issues to be identified early in the process. As solely the final traceability scan is not applicable, a combination of both, in-station and final scan, is proposed. Hereby, the station scan is the main process, and the final scan serves as verification. The RFID tag replaces the barcode label and instead of an operator manually scanning the label, a fixed antenna automatically identifies the tag. Figure 5.1 illustrates how an RFID tag is placed on a component and a fixed RFID system is identifying the part without any human interaction. From all the potential scan result types that could occur, the RFID solution would only directly address the already consumed scan error. In the subsection Genealogy Problem Statement, potential root causes of this mostly human caused error type are described. The question is whether the implementation of an RFID system could address those scenarios. The potential root cause of skipping sequences, for instance, could be prevented by an RFID system, as the fixed RFID reader combined with the automated identification would detect the correct part. The same applies for the hypothetical scenarios of working ahead and scanning the wrong label. Lastly, the part interchange could not be detected by the RFID in-station system, as it could happen at any time. However, a final traceability scan could discover the part change. Also, the serial number recovery process would be simplified as RFID does not require a line-of-sight. From this theoretical analysis, it can be concluded that the majority of the already consumed scan results could be attributed to human error and addressed with the RFID solution.

It might seem not very beneficial to address only one result type, but already consumed parts are a common error in an assembly line, as they are human caused. Furthermore, there is another concept that would allow addressing all result types. Implementing an RFID gate before the main line that identifies the tags and checks whether the part is consumable, would enable only acceptable parts to make it to the line. Whenever an unacceptable part would be detected, it could either be fixed before it causes an issue, or it could be replaced with another acceptable part. This would theoretically increase the efficiency of the main line and maximize uptime.

Figure 5.1: Part identification in station based on RFID [30]
The implementation of RFID tags instead of barcodes holds the potential for multiple benefits. Firstly, it would remove the non-value-adding operation of manually scanning barcodes. That time can either be saved or contributed to more important tasks that benefit the build process and product quality. Secondly, RFID tags could reduce the potential risk of production holds due to scan non-conformances. If a scan error occurs and could not be fixed within a certain time, it could potentially cause downtime. Finally, by utilizing an additional scan of the entire vehicle after it is completed, in theory, there should not be any discrepancies in the genealogy data. Ultimately, this would significantly reduce time and costs. However, several challenges come along with this technology. The major challenge is the interference of metal and liquids with radio frequencies. Generally speaking, metal diffracts radio waves. Thus, they will not reach the tag or do not transmit back to the antenna. Liquid on the other hand absorbs radio waves [31]. When RFID tags need to be attached to a metal surface, a special tag type is required. These tags cost 10-fold of non-metal RFID tags, which is not favoring their use for this application. Scanning RFID tags through these two substances is highly unlikely. For instance, it is not possible to scan through chassis components. Also, it is not possible to scan through a human body as it consists of 60% water. Therefore, it is part of this thesis to determine where the tag and antenna must be placed, the required reader power, and the necessary equipment to get a read. Besides the technical evaluation, the project includes an assessment of the economic feasibility as the cost per RFID tag exceeds the cost per barcode label by far.

6 Research Questions

The main objective of this project is to determine the technical and economic feasibility of replacing barcodes with RFID tags on components that are identified and installed in an automotive assembly line. The main challenge of the technical implementation is the interference of radio waves with metal and liquids. Cost is the main implementation barrier and disadvantage of this approach. The expense for RFID tags is significantly higher compared to barcode labels and therefore increases the Operating Expense (OPEX). Exploring this new approach, the following three research questions are derived from the high-level scope. Answering them will clarify the overall feasibility and impact of this topic.

I. How to facilitate an automated in-station part identification method based on RFID technology?
II. How is it technically possible to read all RFID tags in a vehicle after it is completely assembled?
III. To what extent is the proposed solution economically feasible?
State of the Art Technology and Literature Review

In this chapter, the state-of-the-art part consumption technologies are reviewed. Included within is a critical summary of the current literature in this research area. The summary analyzes how parts are typically consumed to their parent in an assembly process. Next, the RFID technology, its working principle, and hardware components are studied. Lastly, other research papers are reviewed that investigate the utilization of RFID technology to identify parts in other application fields. This chapter supports the layout of the test series which will be explained in the following chapter.
7 Barcode Scanning in Manufacturing

The first true barcode system in the automotive industry was implemented at General Motors in 1969 [32]. Over the ensuing decades the barcode system has evolved and become progressively popular in production facilities. Most manufacturing facilities globally utilize 1D or 2D barcode systems as part of their part consumption standard. A 1D barcode consists of multiple lines and spaces. It is what most people refer to as a “barcode” and it can only save a few dozen characters. 2D barcodes are commonly known as Data Matrix. This technology encodes data by utilizing patterns of different shapes. Even though 2D barcodes are physically smaller than 1D barcodes, they can store more data [33]. Barcodes are used in many areas of manufacturing such as material handling, Work in Progress (WIP) tracking, and shipping labels. During the general assembly process, a barcode scan triggers a query in the back-end system [34]. Through this process, multiple items are ensured and verified. This includes amongst other things:

- The correct part is installed (type and variant) [26]
- The part installed is acceptable and suitable for use [27]
- The child’s serial number is assigned to the parent (traceability) [28] [35]

Ultimately, this process, and the information captured during this process increases the quality and enables an OEM to keep track of their product genealogy. From an assembly perspective, the disadvantages of the barcode scanning itself are that it requires line-of-sight, and an operator needs to manually scan the barcode with a handheld scanner.

Alternatives to the barcodes which are used in the industry include vision technology, a transfer via the programmable logic controller (PLC), and RFID technology. As vision technology is based on a camera reading a barcode and the PLC is only applicable for a few cases, the comparison in Table 7.1 below focuses on the barcode (1D and 2D) and RFID.

*Table 7.1: Comparison of barcode and RFID technologies [36]*

<table>
<thead>
<tr>
<th>Feature</th>
<th>Barcode</th>
<th>RFID</th>
</tr>
</thead>
<tbody>
<tr>
<td>Require line-of-sight to be read</td>
<td>Yes</td>
<td>No (Except metal and liquids)</td>
</tr>
<tr>
<td>Multiple tag reading</td>
<td>No</td>
<td>Yes (up to thousands)</td>
</tr>
<tr>
<td>Ability to cope with harsh/dirty environments</td>
<td>Low</td>
<td>High</td>
</tr>
<tr>
<td>Distance from reader</td>
<td>Up to 4 m</td>
<td>30 cm to more than 100 m</td>
</tr>
<tr>
<td>Identification of item type</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Ability to identify specific item</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Ability to update stored information</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Amount of data stored</td>
<td>Up to 3 Kb</td>
<td>Up to 128 Kb</td>
</tr>
<tr>
<td>Interference sources</td>
<td>Dirt, physical obstacles</td>
<td>Magnetic fields</td>
</tr>
<tr>
<td>Ability to monitor presence of parts</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Cost</td>
<td>Low</td>
<td>Medium</td>
</tr>
</tbody>
</table>
8 Radio Frequency Identification

One of the key technologies of the fourth industrial revolution is RFID. To fulfill customer demands, the customization and personalization of products, as well as the manufacturing speed must increase. One way to achieve increased output in the face of increasing demand is process automation. Therefore, in most applications, human interaction is required to perform the scan. It is important to discover new use cases for RFID technology to map the physical and digital worlds and solve problems of Industry 4.0 [37].

RFIDs considered predecessor, which is based on the same principle, was first used in 1945. The technology enables contactless data transfer via radio waves and the two main fields of application are object identification and tracking. Any RFID system consists of a tag, antenna, reader, and cable. The detailed specifications of these four hardware components depends greatly on the environment and use case. This chapter will explain the most important parameters that influence the hardware selection [38].

The basic working principle of RFID technology is that the RFID reader continuously sends out radio waves of a particular frequency via an antenna. If an RFID tag is within the range of these radio waves, it transmits feedback which is again picked up by the reader. Typically, there are three frequency ranges used for RFID systems:

- Low frequency (LF) ~ 125 to 134kHz
- High frequency (HF) ~ 13.56 MHz
- Ultra-high frequency (UHF) ~ 860 to 960MHz

A lower frequency band results in a shorter read range even though the actual wave itself is longer. The LF wavelength is around 2400 meters. The reason for the shorter read range is the inductive coupling working principle. This principle uses near-field effects. Hereby, the reader antenna and tag antenna share one magnetic field through which they are coupled, and the energy is transferred. This field is created by the reader and induces the voltage to the coil of the tag. As they have a mutual relationship, a change in current flow by one induces a change in the other and vice versa. In particular, by adjusting the phase, amplitude, or frequency, the reader is modulating the carrier wave which results in a current change in the coil of the tag. The tag, on the other hand, is responding by switching on and off its loads rapidly. This rate of change in the current of the tag also induces a voltage in the reader. Switching on and off the load is known as load modulation. The inductive coupling working principle is displayed in Figure 8.1. At a certain distance to the reader, the intensity of the magnetic field decreases rapidly to such an extent that the energy to power the tag is too low. For LF RFID systems the read range is between contact and 10 centimeters. Also, low frequencies are the only bandwidth able to penetrate metal and liquids. Even though HF RFID systems use magnetic coupling as well, their read range is from near contact to 30 centimeters due to their much shorter wavelength of 22 meters. This frequency can penetrate metals with a lower density such as aluminum to a certain extent. The internationally recognized communication protocol, near field communication (NFC), operates within this frequency spectrum. UHF RFID systems are based on radiative coupling using far-field effects by utilizing a backscatter signal. In contrast to inductive coupling, the electromagnetic waves travel outwards from the reader and never return energy. The small proportion that reaches the antenna of the tag is enough to supply it with power after rectification by diodes. In response, the tag scatters back a fraction of the received energy. This is realized by switching on and off the loads of the antenna, which in turn changes
the reflection characteristics. This change in the tag's effective cross-section makes it either reflect the waves well or poorly, creating a pattern able to transmit data. Therefore, it is also called passive backscatter modulation. This operating principle is displayed in Figure 8.1. The UHF wavelength is approximately 30 centimeters, which allows for a read range of up to 25 meters. Amongst other factors, the frequency influences the tag price as well. On the lower end, UHF tags are the most affordable. They start at roughly $0.09 whereas HF starts at $0.20 and LF at $0.75. The factor affecting the price point the most is quantity. Ordering higher quantities reduces the price even further [39] [31].

The major advantage of this technology over the barcode scanner is that no line-of-sight is required. If the tag is within the range of the radio waves, a signal can be sent back. Another benefit is the possibility to scan multiple tags at the same time. In the past, the tag price used to be the major limitation of this technology. Over time it has come down significantly, however, from tens of dollars to cents. Presently, the key limitation is the interference with metal and liquids. HF and UHF systems are especially limited in the capability to penetrate and sometimes even work around those materials. Metal tends to diffract radio waves whereas liquids absorb them. That leaves the reader with no feedback from the tag and hence no data. Table 8.1 summarizes and compares LF, HF, and UHF RFID ranges and describes their characteristics.

### Table 8.1: Comparison of the 3 main RFID frequency ranges [31] [40]

<table>
<thead>
<tr>
<th>FREQUENCY</th>
<th>LF 125 – 134 KHZ</th>
<th>HF 13.56 MHZ</th>
<th>UHF 860 – 960 MHZ</th>
</tr>
</thead>
<tbody>
<tr>
<td>READ RANGE</td>
<td>0.1 m</td>
<td>0.3 m</td>
<td>25 m</td>
</tr>
<tr>
<td>COST</td>
<td>$$$$</td>
<td>$$</td>
<td>$</td>
</tr>
<tr>
<td>PENETRATION OF MATERIALS</td>
<td>Excellent</td>
<td>To some extent</td>
<td>Poor</td>
</tr>
<tr>
<td>AFFECTED BY WATER &amp; METAL</td>
<td>No</td>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td>ANTENNA</td>
<td>Coil</td>
<td>Coil</td>
<td>Dipole, Slot</td>
</tr>
<tr>
<td>DATA RATE</td>
<td>Slower</td>
<td>Faster</td>
<td></td>
</tr>
<tr>
<td>READING MULTIPLE TAGS</td>
<td>Poor</td>
<td>Good</td>
<td>Very Good</td>
</tr>
</tbody>
</table>

**RFID Tags**

An RFID tag is one of the four main hardware components of an RFID system. Generally speaking, there are two main types of tags, active and passive. The active tag receives its energy from an internal
battery whereas the passive tag receives its energy from the electromagnetic waves of the reader. Passive tags are mainly comprised of an antenna, a microchip, and a substrate. The purpose of the antenna is to receive and send signals. The chip contains certain information and memory banks. Lastly, the substrate holds the pieces together. When it comes to tag types three main types can be identified. Label tags are flexible, paper thin, and offer graphics on their face. Inlays are structured the same, the only difference is that they are transparent and therefore also do not offer graphics. The third type is the hard tag. Usually, they are made from a robust case and consequently are thicker and more robust.

When it comes to tag positioning, three factors have the most impact on the readability. These factors are tag size, orientation, and placement. Tag size influences the read range of the system strongly and the only constraint is the size of the object as it needs to fit dimensionally. This means that a larger tag and thus a larger antenna results in greater performance because more energy can be collected. Orientation considers the three axes pitch, yaw, and roll. They are visualized in Figure 8.2 below. Pitch and yaw are linked to the readability as a modification in their parameters reduces the cross-section of the antenna in relation to the reader and thus the amount of energy the antenna can receive. Only rolling does not influence the readability if a circularly polarized antenna is used. This will be further explained in the paragraph about RFID antennas [31] [41].

**RFID Antenna**

An RFID antenna enables the data exchange between the reader and the tag. Its task is to convert the reader signal into an RF field that transfers the data. Also, it converts the tag response back into a signal for the reader. As for RFID tags, there are several parameters influencing the antenna's read range and readability. The most important parameters will be described, and their relationship elaborated upon below.

- Operating frequency/bandwidth if multiple frequencies
- Reader transmit power
- Coupling technique
- Gain
- Size
- Polarization
- Voltage Standing Wave Ratio (VSWR)
Antenna gain refers to the boost in signal and is expressed in decibels (dB) or other sub-units of decibels in reference to another unit (dBm, dBW, dBi, or dBd). Higher gain results in further-reaching radio frequency (RF) waves. Moreover, higher gain results in a narrower beamwidth. The beamwidth of an RFID antenna is the angle at which most of its power radiates. Thus, gain and beamwidth are closely related [31].

The next parameter is the polarity of the antenna, which is describing the wave's oscillation. Antennas are either linear or circular polarized. Linear polarized antennas oscillate their waves on a horizontal plane. Circular antennas, on the other hand, radiate their waves between horizontal and vertical planes. The geometrical direction of both polarity types is illustrated in Figure 8.3 below. Generally speaking, the polarity of the antenna should be aligned with the one from the tag. Moreover, circularly polarized systems are less sensitive to orientation discrepancies between the antenna and the tag. The read range will be shorter compared to a linear antenna with comparable gain, as the energy is split between two geometrical dimensions [31].

Circular antennas are either left or right-hand polarized. If the electric field vector movement is clockwise, it is Right Hand Circularly Polarized (RHCP). If it is counterclockwise, it is Left Hand Circularly Polarized (LHCP). When more than one antenna is required for one use case, one RHCP and LHCP antenna should be used to avoid any interference [42].

The physical size of the antenna is usually directly related to the reading range. A bigger antenna means more gain and therefore a greater read range. One constraining factor of antenna size is the space available within the area of intended use.

Another major characteristic impacting the read range is the coupling technique and thus the way antenna and the tag are communicating. The two coupling techniques, inductive and radiative, used by near-field and far-field antennas are described at the beginning of this section.

**RFID Reader**

The RFID reader is the brain of an RFID system. It is the entity that is sending out, receiving, and processing the radio waves. There are two main types of readers - fixed and mobile readers. Fixed devices are less flexible in their application but are more powerful. A subset of the fixed reader category is integrated readers. Integrated readers combine the antenna and reader into one unit. In addition to these options, readers can be distinguished in terms of antenna port, power option, and interconnectivity. The exact specification of a reader depends on the use case [31].
**RFID Cable**

Even though this component might seem inconspicuous, the cable between the reader and the antenna is one of the key components of an RFID system. It is responsible for reliable communication between the two entities. Cable length, thickness/insulation rating, and connector types are the three main factors impacting the cable’s ability to transfer energy.

A cable’s insulation rating depends on its length and thickness. The cable length should be as short as possible due to power loss as a result of the material resistance. To counteract the power loss the thickness can be increased. This, in turn, makes the cable more rigid, less flexible, and thus harder to install or run through a conduit. To summarize, a well-insulated cable loses less power, and the higher the insulation rating, the thicker the cable. A cable’s connector types are determined by the connectors on the reader and antenna [31] [41].

**9 RFID Application in Manufacturing**

The research paper “RFID driven robotic assembly for random mix manufacturing” describes how a passive RFID tag identifies a part in a station. Prior to this use, a vision system was identifying the part based on its shape. However, vision detection is limited when it comes to identifying the material of the part, which is why the RFID solution was tested. One can conclude from the article that it is possible to identify a part in an assembly line with an RFID tag. In their paper, the authors also highlight the technical issues of the interferences between the electromagnetic fields from the equipment with the RFID field. Another issue described is the limited readability due to the tag orientation. The paper, however, provides only limited information about the test setup and the hardware used. Within this master’s thesis, a similar procedure will be researched. A value-adding aspect that this thesis provides is details about the equipment. Distinguishing factors are the test setup. In the testing environment used for this thesis, the reading distance and the surrounding noise will be greater. Another takeaway from this paper is that when setting up an RFID system in a production environment, the surrounding sources of interference need to be considered [36].
Methodology

The methods used for the empirical research conducted within this thesis can be divided into two main sections - RFID Experimental Design and Line Impact of Scanning. Hereby, the focus lies in the theoretical development of methods to answer the research questions. Overall, this chapter determines all methods used in the Results and Analysis chapter. The chapter RFID Experimental Design uses primary data that was collected when executing the proof of concept. It describes the entire test setup and execution process. Lastly, the Line Impact of Scanning section elaborates on the methodology to evaluate potential scan caused downtime, which is used for the economic feasibility assessment.
10 RFID Experimental Design

This section focuses on the experimental design of the RFID system testing. To verify the technical feasibility, the execution of a proof of concept in the form of a practical test is required. The Hardware, In-Station Experiment Setup, and Final Traceability Scan Setup sections elaborate in detail what equipment was used and how the experiments were conducted. The in-station experiments were conducted from July 16, 2022, to August 13, 2022. The testing for the final traceability scan was executed from August 1, 2022, to August 5, 2022.

Examined Parts

To test and validate whether RFID tags can be utilized instead of barcode labels on individual items, a limited number of parts needed to be determined. It would not be feasible to perform the test procedure for every part with a barcode. Therefore, the investigation and series of tests were limited to 26 items. These parts were chosen because they reflect a great variety in terms of size, complexity, and material, which increases the confidence that this method is applicable to most parts. The part list contains, amongst other things, the parent, engineering and manufacturing part number, description, the station where the label is applied and consumed, and material. It is attached in Appendix A.

Hardware

Based on the literature review from the Radio Frequency Identification section, the hardware for this project was selected. As the reading distance is approximately 6.5 to 13 feet (two to four meters), the ultra-high frequency is the only applicable frequency range for this case. Furthermore, these tags are the least expensive, and it has a great capability to read multiple tags. When it comes to active or passive tags, the choice falls clearly on passive tags. Not only are they much smaller and lighter in weight, but also substantially less expensive. The price per tag is the key criteria when it comes to the implementation of this project. Multiple tags would be added to the vehicle which increases cost without adding any value for the customer. Therefore, the cost per tag needs to be as low as possible.

To verify the technical feasibility of an RFID system it needs to be tested. The reason for this is the many interfering sources by which radio waves are affected. Therefore, a selection of different RFID hardware components was made to enable more flexibility when testing. Also, a variety in hardware will increase the likelihood of achieving a read. Table 10.1 states the reader and antenna hardware components utilized within the framework of this thesis. The selection of passive RFID tags used within this experiment is listed in Appendix E. Further accessories that are required to run the RFID system are documented in Appendix F.
### Table 10.1: Experimental Design Hardware

<table>
<thead>
<tr>
<th>Item Number</th>
<th>Picture</th>
<th>Description</th>
<th>Qty</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reader and Antennas</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>FX9600-82320A50-US</td>
<td><img src="image" alt="FX9600" /></td>
<td>FX9600, FIXED RFID READER, 8-PORT, POE, US ONLY (Data sheet in Appendix B)</td>
<td>2</td>
</tr>
<tr>
<td>AN440-CPDFQ915WR</td>
<td><img src="image" alt="AN440" /></td>
<td>High Performance Dual Antenna for Indoor and Outdoor use, White Color, Size inches: 22.6 x 10.2 x 1.32</td>
<td>1</td>
</tr>
<tr>
<td>AN480-CL66100WR</td>
<td><img src="image" alt="AN480" /></td>
<td>Antenna, 1 Port, General Purpose, Wide-Band-Left, Pig-Tail, Left-Hand Circular Polarization, RoHS. Worldwide</td>
<td>1</td>
</tr>
<tr>
<td>AN480-CR66100WR</td>
<td><img src="image" alt="AN480" /></td>
<td>Antenna, 1 Port, General Purpose, Wide-Band-Right, Pig-Tail, Right Hand Circular Polarization, RoHS. Worldwide</td>
<td>1</td>
</tr>
</tbody>
</table>

For the reasons explained in the chapter Proposed RFID Approach, two FX9600 RFID readers are used for the testing. The utilized demo equipment is not able to separate the signal from each antenna. Therefore, the setup uses two readers recording separate raw data to separate computers. To analyze and evaluate the data, it needs to be processed and merged. This is done by a VBA code. The code transforms the raw data into reads per tenth of a second for each tag and antenna.

All antennas are intended for the US market and their frequency band aligns with the Federal Communications Commission (FCC) standards. Figure 10.1 shows the radiation patterns of the Zebra AN440 (LHCP) and AN480 antennas. With 20 dB the AN440 has a great front-to-back ratio. Also, the AN440 has more power. On the other hand, the AN480 has a higher axial ratio of 1.5 dB. Appendix C contains the Zebra data sheet with all the specifications about the AN480. In Appendix D is the datasheet of the AN440 antenna. It also includes the radiation patterns for the RHCP version.

![Figure 10.1: Radiation pattern of Zebra AN440 and AN480](image)
10.1 In-Station Experiment Setup

The in-station experiment serves as the proof of concept to validate the technical feasibility of this concept at the assembly line. Within the experiment, the various hardware from the previous paragraph is tested. To document and reproduce the test results, the antenna needs to be positioned on a stand. This stand was designed to hold any antenna variant and to be adjustable in height. A fixed mount in a station is not feasible. Figure 10.2 displays the antenna stand. The height is adjustable between 6.5 and 11.5 feet (2 to 3.5 meters). The antenna is mounted to the stand with the mounting bracket stated in Appendix F.

For the in-station part identification testing, the standard assembly procedure is replicated. Hereby, different label types are applied to the part to determine the best solution. Also, different tag positions on the part itself are tested. It remains a priority to place the labels on non-metal spots in order to enable the usage of the less costly RFID tags. If a standard RFID label is placed on a metal surface, the RF waves get diffracted, leaving the tag without power. Next, the antenna will be placed at a location where it does not block any other equipment and the line-of-sight is not blocked by metal or liquids (operator). All the knowledge of the previous chapter is applied here. The first attempts and starting points are based on this information. The assembly procedure will be executed and recorded at least 10 times to verify the RFID system is able to read the tag reliably and increase the validity of the experiment. The earlier described challenges of RF and certain materials are exemplified in Figure 10.3 below.
10.2 Final Traceability Scan Setup

The objective of the final traceability scan testing is to determine the technical feasibility of reading the RFID tags on the selected components after a car is entirely assembled. The challenge here is the interference of radio waves with metal. Since the chassis of a vehicle is made of metal, it limits the areas where it is possible to read the tags. The setup includes a Tesla Model Y with RFID tags placed on the 26 components. To apply the RFID labels to strategically selected positions, the vehicle was partially disassembled to reach those parts. The vehicle was then returned to its original condition, to simulate a completed car. In addition to evaluating the technical feasibility, this experiment determines the best antenna positions to read all the RFID tags placed in the vehicle. In total 27 tags were placed in the test vehicle. The number deviates from the 26 determined parts because certain repetitive parts were skipped, and other parts received two labels. For example, only the left front knuckle received an RFID tag because if it is possible to read this knuckle, it is also possible to read the knuckle on the right side. The reason why certain parts have two labels is to test different labels and positions on the part. Since parts underneath the car require it to be on a car lift to apply the labels, for efficiency all the RFID labels are placed at the same time. The 27 RFID tag positions for the final scan test are displayed in Figure 10.4 below.

![Figure 10.4: 27 RFID tag positions for final traceability scan test [44]](image)

Pictures of the precise tag locations on the real test vehicle are attached in Appendix H.

11 Line Impact of Scanning

This section describes an approach to quantify the impact of scan results on a production line and its output capability. Specifically for this thesis, a methodology was developed to calculate the potential downtime caused by scan warnings in a production line. It is a generic approach that could be applied to most assembly lines. The necessary information would be pulled through a machine-generated data analysis software from the central database. Next, the data would be processed by a Visual Basic for Applications (VBA) code in Excel to calculate the potential downtime. The code is attached in Appendix G.
To address and quantify scan results, this approach was developed. The downtime determination process is as follows. By taking the timestamp a car entered the station and adding the respective takt time for this line, the timestamp when the car should leave the station is calculated. The period between those two timestamps equals the time frame to complete all tasks in this station. Whenever there is a NOK scan followed by an OK scan, the events are recorded. If those two scans happened within the time frame a car is given to complete all tasks in one station, no downtime was caused by this scan error. This case is illustrated in the first timeline of Figure 11.1. However, if the second, acceptable scan happened after the timestamp a car should be completed, this particular scan error caused downtime. The reason behind this is a car cannot leave a station before all assigned tasks for this station are completed. Thus, if a scan is not successfully completed, the car will reach a temporary stop. If a VIN exceeds the given time, it is also referred to as an overcycle. The downtime caused equals the period between the time a vehicle overcycles and the time of the OK scan. This scenario is displayed by the second timeline in Figure 11.1. The third case is referred to as overcycled scan error. If the NOK and OK scan occur after a car should be completed, the code only accounts for the time between those two events. The reason behind this logic is that the time between overcycle and NOK scan is not due to the scan error, as it could be due to a part shortage for example. The timeline of this instance is stated in Figure 11.1. If there would be no OK scan time recorded, the code would check for a containment. As obtained from the literature review, if there would be a non-conformance because of a scan warning that couldn’t be fixed, the product would be contained. If this case would occur, the code would take the timestamp of containment to calculate the theoretical impact. To summarize, an NOK scan is the trigger for the calculation. Solely an OK scan after a vehicle overcycles is neglected because it is not related to scan errors. The OK scan in the figure below is representative of an OK scan or a containment. Hence, the respective timestamp is used for the downtime calculation. Finally, the code sums up the downtime caused by scan errors as well as other information.

**Figure 11.1: Timelines for downtime calculation scenarios**
In this paragraph, certain aspects of the calculation are explained in more detail. The behavior in those scenarios is described based on the code. To identify the scan errors, the VBA code is looking for scan events where the result does not equal “pass”. The respective code section is the following.

```
“For i = 2 To r
If Worksheets("Scans").Cells(i, 6).Value <> "pass" Then
Set rgSource = Worksheets("Scans").Range(Sheets("Scans").Cells(i, 1), Sheets("Scans").Cells(i, 6))
Set rgDestination = Worksheets("Main").Range("A" & Rows.Count).End(xlUp).Offset(1, 0)
rgSource.Copy
rgDestination.PasteSpecial xlPasteValues
End If
Next”
```

Next, scan error event duplicates are removed. Multiple scan results for the same scan task related to the same job could occur. The reason behind this is if the same part number would be scanned multiple times. Thus, there would be multiple events for the same vehicle which would wrongly increase the downtime. An event is removed if there is a duplicate of the same VIN. To get the timestamp of when the scan operation is marked as finished, the three previously described options are investigated. They are also referred to as OK events. Continuing, the time a car enters the station in which the error occurred in, gets added. The two conditions for that are matching VINs and station names. To calculate the time when all the work should be completed in the station, the program adds the respective takt time of the line to the timestamp when the car entered the station. Following, the VBA script evaluates which of the three options for an OK event are available. In the code this is realized by running a loop for every line and assigning the variable q with the respective time. If the script cannot find an event, q equals zero.

```
“If Worksheets("Main").Cells(i, 12) <> "" Then
q = Worksheets("Main").Cells(i, 12)
ElseIf Worksheets("Main").Cells(i, 10) <> "" Then
q = Worksheets("Main").Cells(i, 10)
ElseIf Worksheets("Main").Cells(i, 11) <> "" Then
q = Worksheets("Main").Cells(i, 11)
Else: q = 0
End If”
```

After determining the timestamp that marks the OK event, the code selects the appropriate method to calculate the downtime displayed in Figure 11.1. If the scan is not completed within the takt time, the vehicle would reach a temporary stop. Thus, the scan error would create downtime. First, the code checks if any OK event is recorded. Next, the script checks if the NOK scan happened after the job overcycled, the OK event is greater than the time a car overcycles, and the OK event happened after the NOK event. This is referred to as an overcycled scan error. If this is not the case, the script checks if it is a downtime scan error. Hereby, the code evaluates if the OK event occurs after the time a job should be completed. If none of the scenarios are true, it is a no downtime scan error, and no downtime is recorded. This means the NOK scan and OK event occurred before the vehicle overcycled. The VBA section is as follows:

```
“If q = 0 Then
    Worksheets("Main").Cells(i, 14) = "No OK Event"
ElseIf Worksheets("Main").Cells(i, 7) > Worksheets("Main").Cells(i, 13) And q >
    Worksheets("Main").Cells(i, 13) And q > Worksheets("Main").Cells(i, 7) Then
```

---

**Methodology**

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Lastly, the results are visualized in form of a dashboard. The described line impact calculation approach is solely looking at downtime events. Although this method is very conservative and does not include certain scenarios, the potential impact of scanning becomes clear. An example of a scenario which is not considered, could be a NOK scan with an OK event right before the car would overcycle. After the OK event, there could still be work that needs to be performed, such as torquing down the joints of the scanned part for instance. Thus, theoretically, the car would still overcycle, stop the line, and cause downtime. Since the code only checks for OK events after a car overcycles this scenario is not included.

The reason the code is not adding those events is that it cannot be said with certainty that whatever happens after the OK scan event until the vehicle leaves the station is related to the scan result. A further point that must be emphasized is that the code does not consider the time and effort allocated towards fixing scan warnings that are resolved within the takt time. It does not reflect the potential loss of productivity because labor input is wasted on fixing scan warnings rather than contributing to value-adding tasks. Nevertheless, it is a first approach to quantify the overall impact of scanning at any production facility.
Proposed RFID Approach

This chapter elaborates on the approach for part identification and verification based on RFID technology proposed by this thesis. It is a new method for the automotive industry and can mainly be divided into two parts. The first part focuses on a specific method to verify that the correct part is identified during the in-station assembly process. This is described in the section Methods for Accurate Part Differentiation. The second part describes the proposed process flow of an RFID system. It takes the entire process from part delivery to final traceability scan verification into account. This section is called Process Flow of the RFID System.
12 Methods for Accurate Part Differentiation

One of the main challenges of the in-station RFID part identification is to accurately determine the part that is installed into the vehicle. Given the radiation patterns of UHF RFID antennas in the RFID Experimental Design section, it becomes clear that depending on the power, the antennas may not only identify the intended part but also other parts in the vicinity. To narrow down the beamwidth, the power implied by the reader needs to be reduced. This in turn reduces the penetration capability of the RF waves. Now, it may be problematic to read the desired part, as the tag may be either at an unfavorable angle to the antenna, or only a very limited RF wave strength reaches the tag due to the diffractions caused by the metal of the chassis. Therefore, the reader power should not be reduced significantly. This thesis proposes two methods to solve this problem. The first one is to base the decision on the signal strength recorded by the reader. The second one is to place additional antennas at the lineside storage to detect the parts stored in that space.

The first proposed method evaluates the recorded data and bases the decision-making on the signal strength. The signal strength in this thesis is expressed by the reads per second recorded by the reader. The higher the reads per second the better the part can be identified. This is the case if the tag is at a favorable angle and close to the antenna. Generally speaking, the idea is to determine the installed part based on the greatest reads per second of a tag, which is most likely the tag closest to the antenna. For certain application fields, this method works, however, it is not always true. There could be a scenario where a part stored lineside is detected by the antenna and has a greater read rate than the part installed. The reason for that is the diffractions caused by the metal of the vehicle body. Furthermore, it is not always true that the RFID antenna is closest to the installed part, which then would cause a false part identification. Thus, the most reliable method is the dual antenna approach.

The dual antenna approach utilizes additional antennas to detect the parts stored lineside. To tie this to the previous problem definition, whenever the main antenna detects multiple parts, the lineside antenna is utilized to confirm what part is installed in the vehicle. Based on logic, the actual installed part can be determined, by confirming that its signal is not picked up by the lineside antenna. In turn, following the same logic, parts detected by the main antenna but actually stored lineside are also detected by the lineside antenna. This means they are not installed into the vehicle. Since the parts stored lineside are well accessible for RF waves, the required power and therefore also the beamwidth can be reduced. This is important because the lineside antennas should only detect the lineside parts. The described dual-antenna approach is exemplified in Figure 12.1.
The dual antenna approach also requires a certain logic to identify the part installed into the vehicle. This thesis proposes the following method to ensure the right part is identified. All the signals from the RFID tags are calculated to a moving average of 50 points. Since one measurement point represents a tenth of a second, 50 points represent a period of five seconds. The reason for using a moving average function is to smooth out fluctuations of the measurement data and to highlight the overall direction.

There are three conditions that need to be fulfilled for a part identification with confidence. First, the read rate needs to surpass a certain threshold. Second, if there is another signal from a different tag detected by the main antenna, it either needs to be below a certain percentage of the initial tag or the lineside antenna needs to detect a certain signal strength from this tag. This ensures that if another tag is picked up by the main antenna and at the same time surpasses the lineside threshold detected by the lineside antenna, it is certain that the part is still in the storage and not installed. The third condition ensures that the seemingly detected part is not in the lineside storage and thus not detected by its antenna. To achieve this the signal strength detected by the lineside antenna needs to be below a certain threshold. However, as the signals represent the moving average over five seconds, the part can still be detected even though it is already installed. Especially for applications where the lineside storage is close to the vehicle, this is the case, because the time between detection by the main antenna and the cessation of detection by the lineside antenna is very little. Thus, there is an alternative condition. The signal needs to be either below the mentioned threshold or it must decrease. The flow chart visualizing this logic is displayed in Figure 12.2. If all three conditions are fulfilled the part identification is true.

The values stated in this paragraph and in Figure 12.2 serve as a guideline for implementation. However, those values need to be adjusted on a case-by-case basis, as every part, environment, and source of interference is different.
13 Process Flow of the RFID System

Based on the research conducted within this thesis, a process flow of the entire part identification and consumption process based on RFID technology was determined. The proposed process is divided into three areas. The first one is the pre-main line area. It deals with the prevention measure of stopping NOK parts from reaching the main line. The second one is at the main line, which handles the part identification in a station. Lastly, the third area is the final traceability identification. It describes the process flow to read the tags and verify the genealogy data after the car is assembled.

The pre-main line identification focuses on the prevention of NOK parts making it to the line and potentially causing downtime. As the RFID technology in a station can solely prevent already consumed scan warnings, this enables to address every scan result. Before a part is delivered to the main line and stored lineside, it passes through an RFID gate. Hereby, the RFID tags on the parts are read. If there is a NOK part, it can either be removed or fixed before delivering it to the station. The pre-main line
process is illustrated in Figure 13.1 below. Alternatively, the previously described lineside antennas could also read the parts that are stored lineside in advance and report those errors. This means the additional RFID gate would not be required.

When a part is picked up for assembly from the lineside storage, the suggested process looks as follows. The RFID reader identifies the part that is brought to the vehicle before it is physically installed to verify the right part is picked and there is no containment on the part. If this part check were to fail, appropriate steps would be taken. If the initial read would have passed and all the tasks assigned in this station are complete, the part is identified again before it is finally consumed in the system. The reason for the second read is to verify the same part is still built into the car when it moves to the next station. It could be that a part is swapped during the assembly process. When this identification process is completed, the child is consumed to the parent in the factory execution software and the in-station consumption is done.

After all the work on a vehicle is completed, it changes states from WIP to complete. Since no more work should be performed on the vehicle, a final traceability RFID read should allow confirming the accurate genealogy. If there is a discrepancy with the data recorded earlier, the individual case would be investigated. If not, a vehicle with 100% correct genealogy leaves the factory. The flow chart of the entire RFID process flow is attached in Appendix I.
V Results and Analysis

The methods and experiments elaborated in the previous chapter III are applied and executed to answer the research questions. Hereby, the section RFID Experiment Evaluation assesses the results of the testing conducted at the assembly line and when the vehicle is completely assembled. Next, the part differentiation method earlier proposed by this thesis is applied to the measurements. The objective is to evaluate if and how well the logic works. Lastly, the Economic Feasibility section states if replacing the barcode with an RFID tag is reasonable from a financial perspective.
Results and Analysis

14 RFID Experiment Evaluation

Within this section, the entire series of experiments conducted to answer the research question regarding the technical feasibility is stated. First, the in-station testing is documented. In total 498 experiments were conducted. Next, the final traceability scan experiment is summarized.

14.1 In-Station Results

The data set of the in-station testing is a result of comprehensive data collection due to the number of tests performed for each part and the total number of parts investigated. Therefore, this section focuses on one specific example to explain the results in detail. The exemplary part is the heat pump. Lastly, the conclusive findings of the entire test series summarize the experiment. The following Table 14.1 summarizes and provides an overview of all the tests performed with the heat pump. All stated gain figures represent the reader output power, which does not include cable losses.

<table>
<thead>
<tr>
<th>RFID TAG</th>
<th>TAG PART NUMBER</th>
<th>A1 GAIN</th>
<th>A2 GAIN</th>
<th>TAG POSITION</th>
<th>SETUP</th>
<th>TEST #</th>
</tr>
</thead>
<tbody>
<tr>
<td>10036991</td>
<td>1</td>
<td>30 dB</td>
<td>28 dB</td>
<td>1</td>
<td>1</td>
<td>v1 – v6</td>
</tr>
<tr>
<td>10036991</td>
<td>1</td>
<td>30 dB</td>
<td>25 dB</td>
<td>1</td>
<td>1</td>
<td>v7 – v11</td>
</tr>
<tr>
<td>10036991</td>
<td>1</td>
<td>30 dB</td>
<td>28 dB</td>
<td>1</td>
<td>2</td>
<td>v12 – v17</td>
</tr>
<tr>
<td>10036991</td>
<td>1</td>
<td>30 dB</td>
<td>28 dB</td>
<td>1</td>
<td>3</td>
<td>v18 – v23</td>
</tr>
</tbody>
</table>

The following results are from the in-station testing of the heat pump. It is a subassembly consisting of multiple parts. Many of the parts are made from metal, so they are not suitable for attaching the RFID tag. Other parts of the sub-assembly are made from synthetic material but contain liquids, which is also not ideal. A synthetic bracket of a sub-part, therefore, seems the most suitable location for the RFID label application. The main objective of the RFID label selection is cost. Thus, the Zebra label 10036023 is the ideal choice, given its low cost. Unfortunately, due to the physical dimensions of the label it does not fit on the bracket, which is why a smaller label is selected. With a catalog price of $0.138 the Zebra label 10036991 is the best choice [45].

In total, three different in-station setups were tested. They were adjusted step-by-step based on observations during the testing. The first setup is displayed in Figure 14.1. It also includes the technical dimensions. The main antenna facing the vehicle operates with a gain of 30 dB and the second antenna detecting the lineside storage operates with a gain of 28 dB. Both antennas are Zebra AN480.
Cumulatively, the assembly procedure was executed and recorded six times with these settings. Figure 14.2 below shows the plot of the read rate over time from the first measurement. The dotted lines represent the parts detected by the lineside antenna. Full lines embody parts identified by the main antenna. The color of the lines helps to distinguish between individual parts. The same color stands for the same part. Immediately after starting the measurement, the intended part is picked. This is made clear by the fact that the solid red line rises while at the same time the dotted red line’s values become less. This indicates that a part was picked from the lineside storage and physically brought to the car. After the part is installed, its main antenna reads stay at around a certain level while its lineside signal remains almost zero. The other lineside parts represented by the two dotted gray lines remain at a constant level during the measurement. It means the lineside antenna is detecting the parts while the main antenna is not. Thus, the parts remained lineside and were never brought close to the vehicle.

When comparing the fluctuations of the installed part and the lineside parts a difference is noticeable. Since both signals are exposed to influences from the environment, this cannot be the cause. It is most likely that the volatility is due to the operator’s movement as well as the diffractions of a moving metal equipment within the radiation pattern of the main antenna. Another potential cause for the fluctuations could be the RFID reader settings. If Dense Reader Mode (DRM) is activated, the reader checks the channels it plans to utilize first, before emitting a signal. If it is used by another reader, it skips to the next channel to avoid any interference. This can cause fluctuations in the data especially since the two readers in this setup operate close to each other. Those interfering sources are not avoidable in a production environment. However, the deviation strength is still within an acceptable range. Overall, the trajectories of the six measurements are similar. It can be concluded a read of this part in the station is technically feasible with this configuration.
At around 15:52:02, 15:52:12, and 15:52:25 the line side antenna still detected the installed part for a short time. It is only a very weak signal; nevertheless, the lineside antenna strength was reduced from 28 dB to 25 dB. The assembly process was repeated another five times. With the reduced lineside antenna strength, the signal become weaker but did not disappear entirely. As this minor signal is not an issue for the part identification process and the proposed logic, this investigation is not further pursued.

Experiments 12 to 17 were performed with setup 2. It is the same as setup 1, with the only difference being the height of the lineside antenna. In setup 1, the lineside antenna is set at a height where an operator walking lineside would block the RF waves. Thus, the antenna height was increased to 104 inches (2.64 meters). With this setup, it was also possible to identify the part every time and the plots look similar to the results from the previous experiments.

The last six experiments were executed with setup 3. Figure 14.3 displays the technical dimension of the antenna setup. This setup picks up the signal from the installed part from a different angle. The purpose is to demonstrate that multiple angles can work and the flexibility of the system. This is important for the consideration of a moving line. The challenge of a moving line is further explained below.
Appendix J displays the plot of the RFID heat pump in-station measurement 21. Two main anomalies are visible that are different compared to the previous plots. The two parts stored in the lineside buffer have a different read rate. With the previous setups, they were almost the same. This leads to the conclusion that one part can be detected significantly better. The second noteworthy occurrence is the trough at 17:53:35. It is noticeable in different strengths across all the measurements. After analyzing the experimental setup, this anomaly is due to the diffractions caused by a moving assembly equipment made from metal in that station. During the installation process of the heat pump, a metal arm of other equipment happens to be very close to the main antenna causing the diffractions of the RF waves. The antenna should be lowered by a couple of inches to reduce the effect. To conclude, when installing an RFID system in a station, the already installed equipment must be considered.

To demonstrate one of the challenges with the RFID technology, certain error scenarios were simulated. In the following case, an operator training with another operator is showcased. Figure 14.4 illustrates the situation. The red operator is assembling the heat pump to the vehicle. The second employee (blue) stands at the indicated position. Since about 60% of a human’s body is water, the second operator standing between the RFID antenna and the RFID tag is absorbing the RF waves. Thus, the system is not able to detect the part anymore. Even though the blue operator is not supposed to be there, it is a likely scenario that could happen at any assembly line. A potential solution would be to add a second antenna. It would be a redundant layer in case the line-of-sight from one antenna is blocked.

![Figure 14.4: Human interference with RFID exemplified on the heat pump [46]](image)

In total, 17 out of the 26 selected parts were tested in their respective in-station environment. It was not possible to test every part due to the immense time effort to test one part and the experimental time constraints. Also, certain parts were not available due to the production schedule. Out of the 17 tested parts, it was possible to identify every single one under at least one setup. Out of the 26 parts, 24 have a location where a non-metal tag can be applied. Only two parts require a more expensive on-metal tag as they consist entirely of metal. To conclude, it is possible to identify every part accurately in their station. However, every single part needs its own setup adjusted to the environment in which it is assembled. There is not one out-of-the-box solution that suits every individual application. Although the experiments were performed on a real production line, they were performed during production breaks. Thus, the environmental influence on the RFID system is low. Under high-volume production conditions, the number of employees working on a production line and the equipment in use is a multiple higher, creating additional potential sources of interference. The second major limitation of
the stated test results is the line movement configuration. All tests were performed in an environment that simulates a stopping line, where a car enters the station, stops at a dedicated position, and only after all the work is completed moves to the next station. Most automotive production lines, however, operate with a continuous moving line. The potential challenge of this could be that certain body parts or equipment like a lifting assist for instance could diffract the RF waves and prevent the part identification. A potential solution could be to set up more than one main antenna to cover a broader area of the station and take over whenever one antenna is blocked. This redundant system needs to be further tested.

14.2 Final Traceability Scan Results
Ultimately, the final scan validates the already recorded genealogy of the vehicle. In order to carry this out, the vehicle’s individual components with the RFID tags need to be identified. The challenge hereby is the interference of RF waves and metal. It is not possible to scan a tag through metal. Thus, the RFID labels and antennas need to be placed in strategic positions to get around the metal body parts. The objective is to find these positions and prove that all tags can be read.

After all the labels were placed in the test vehicle, the antenna setup was determined. The first setup is based on the knowledge obtained from the literature review. Hereby, the main considerations are regarding the radiation patterns and material penetration constraints. The first setup utilizes three antennas. One Zebra AN480 facing straight down from the top of the vehicle and another underneath the front of the car. The third antenna is a Zebra AN440 radiating RF waves from the right side of the car. The technical dimensions of the antenna locations can be taken from Figure 14.5. The reason for the antenna locations is to capture the vehicle holistically. All three antennas were operated with the maximum reader power of 30 dB the FX9600 offers.

![Antenna Setup Diagram](image)

*Figure 14.5: Final traceability scan RFID antenna setup 1 [44]*

The results from the test with the first setup state that 23 out of the 27 tags are read. In conclusion, with this setup it is not possible to read all the parts. The four parts that are not detected by this setup are rear frame labels 1 and 2, Battery label 2, and rear knuckle label 2. One reason for this could be that the interference due to the metal in the rear is too great. More likely though is the lack of RF power in the rear. All the missed parts are in the rear of the car. Thus, it can be concluded, that those parts are not detected due to the lack of RF strength as there is no antenna in the rear. Theoretically, if the car would drive or move in any way over the antenna this setup could capture all the parts. However, this cannot
be confirmed with certainty by the test carried out. Figure 14.6 exemplifies how the metal diffracts the RF waves and thus why the top antenna is not able to detect the parts underneath the car. The vehicle body including the front underbody, rear underbody, and battery, act like a shield and shear off the underside of the car.

![Figure 14.6: Chassis and RF waves diffraction](image)

Thereupon, a new setup is tested. This time the Zebra AN440 is facing straight down from the top of the vehicle and both AN480s are underneath the car. One is in the front and the other one in the rear of the car. Based on the findings from the previous experiment the entire car should be covered. The technical dimensions of the antennas of the second setup are stated in Figure 14.7. As in the previous tests, all three antennas are operated with maximum power.

![Figure 14.7: Final traceability scan RFID antenna setup 2](image)

With the above stated setup, it is possible to read all 27 RFID labels in the car. It took less than six seconds to read every part at least once. To verify the robustness of this setup the test was repeated 10 times. Every time it was possible to identify all the parts. The only difference between the tests is the number of reads per part and thus the time it takes to read every part at least once. The reason for these deviations could be ambient frequencies from the environment, electromagnetic fields from wirings, certain RF reflections, other RFID systems in the factory, or the reader operating logic. Nevertheless, they are minor deviations and should not pose an issue. For this setup, there is also the possibility that if the car drives over the antenna only one antenna would be required underneath the car.

One limitation of the conducted final verification scan test is the consideration of interference with other cars. If this would be implemented in the production environment of an automotive manufacturer, there would be a vehicle driving through the final traceability scan frequently with a car waiting behind it.
and another one waiting after the scan station. This could cause possible mix-ups as the RFID antennas could detect parts from one of the other cars instead of the one currently tested. It might be possible to solve this challenge by utilizing the signal strength. The other cars before and after the scan station are further away and should have a lower read rate. However, a certain level of uncertainty remains. Another potential solution could be a particular station design. The supposed RFID disadvantages of interference with metal could be used as an advantage. The car could drive into an enclosed metal container with a rolling gate to perform the test. This would prevent RF waves from reaching other vehicles.

15 Software Design Application

To evaluate the proposed Methods for Accurate Part Differentiation, they are applied to the measurements and their feasibility is assessed. Figure 15.1 below shows measurement seven of the driver seat experiment. The lines again represent the moving average over 50 measurement points. Full lines are recorded by the main antenna whereas dotted lines represent parts identified by the lineside antenna. The red fine dotted line constitutes the threshold 1 line, which must be exceeded by the signal of the installed part. This occurs at approximately 19:40:48 when the blue line crosses the threshold line. Thus, the first condition is fulfilled. Moreover, the second condition must be true, which is that either no other part is within the +/-70% range of the supposedly installed part, or if there is another part detected by the main antenna, its lineside antenna signal need to surpass the threshold 2. For now, threshold 2 is set to 20 reads per tenth of a second. This signal strength should be sufficient to ensure that a part is lineside and not in the vehicle. In the graph, it is visible that the main antenna is detecting another part intermittently, but none of the signals is violating one of the conditions. The third and final condition is ensuring that the reportedly installed part is no longer detected by the lineside antenna. This means either the signal received from the lineside antenna is decreasing or is lower than threshold 3. As the lines represent a moving average, the signal does not drop instantly after the part is picked from the storage, it slowly decreases. From a logical perspective, however, the part cannot be detected in both areas. Thus, it either decreases or is lower than the threshold. The threshold 3 value is currently set to two. It cannot be zero as intermittently a very low signal, probably due to reflections, is detected. In the figure below, the green highlighted background indicates whether those three conditions are fulfilled, and based on the logic a part is considered as identified.
Results and Analysis

Appendix L contains the plot of the driver seat measurement v14. When conducting this measurement, a potential failure mode was simulated. After installing the part, another part of the same type was installed in addition. At 20:40:51 it was detected the first time when it was carried to the vehicle, leading to the software design rejecting a positive identification. Next, at 20:05:21 the additional part was finally installed which again resulted in an unsuccessful identification. If this scenario would occur in a production environment, the consumption would not be possible. The best solution here would be to inform the operator by populating a message on the production screen saying that two parts have been detected, and that the operator should check and remove one from the vehicle.

Another potential scenario could be that one part is installed, but then, for certain reasons, the part is exchanged and another part is installed. This scenario is replicated in the driver seat measurement v17 stated in Appendix M. For the part identification itself the same logic is applied. The only difference is that when the parts are swapped the priority focus part is the new one. Since the consumption logic states that the last detected child, after all tasks are completed in this specific station, is consumed to the part, this scenario would not be problematic.

The logic given is intended to serve as a starting point for this topic. For industrial applications, further development and testing are required. Also, the given thresholds and percentages are based on the results of the conducted experiments. They need to be adjusted on a case-by-case basis, as it seems there is no universal solution that fits every situation. The reasons for that are the different signal strengths caused by the RFID setup and the interference within each environment. As an implementation strategy, this thesis suggests running further trials during full production hours to record more data. Thereupon, the data must be analyzed, and the logic applied to verify its feasibility.
16 Economic Feasibility

To evaluate the economic feasibility and determine the tangible business value for an OEM, the following study is conducted. As already stated before, the additional cost of the RFID tag is the greatest challenge of this approach. Therefore, this section is crucial to better understand its implementation feasibility. The economic feasibility study examines five main aspects, which are:

- Additional uptime profits
- Manual scanning operation cost savings
- Repair cost savings
- Additional cost of RFID tags
- Initial hardware and setup costs

Each area is evaluated separately. Finally, all factors are considered as a whole in order to answer the research question. For the sake of simplicity, certain assumptions have been made. Furthermore, to protect Tesla’s proprietary information, actual production numbers are replaced with public figures of another manufacturer from an open source. The only purpose is to represent the calculations and the value of an RFID system. Thus, the presented values are for demonstration purposes only and do not reflect any factual information regarding Tesla’s production. All the values for the cost calculation are stated in Table 16.1 below.

*Table 16.1: Assumptions for RFID economic feasibility*

<table>
<thead>
<tr>
<th>Assumptions and exemplary production numbers</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Production days (per year)</td>
<td>350</td>
</tr>
<tr>
<td>Percent of faults that can be addressed with RFID</td>
<td>90%</td>
</tr>
<tr>
<td>Average time for scanning operation</td>
<td>4s [34]</td>
</tr>
<tr>
<td>Cost of labor (per hour)</td>
<td>$30</td>
</tr>
<tr>
<td>RFID tags (per car)</td>
<td>15</td>
</tr>
<tr>
<td>Average cost of RFID tag</td>
<td>$0.1</td>
</tr>
<tr>
<td>Downtime (per day)</td>
<td>35min [47]</td>
</tr>
<tr>
<td>Percentage of scan related downtime</td>
<td>5%</td>
</tr>
<tr>
<td>Downtime profit loss (per min)</td>
<td>$50,000 [48]</td>
</tr>
<tr>
<td>Takt time</td>
<td>15s [47]</td>
</tr>
<tr>
<td>Cars produced (per day)</td>
<td>18,526 [47]</td>
</tr>
<tr>
<td>Average percentage of defective units</td>
<td>0.55% [47]</td>
</tr>
<tr>
<td>Containments (per day)</td>
<td>102 [47]</td>
</tr>
<tr>
<td>Average time to fix a containment</td>
<td>30 min</td>
</tr>
</tbody>
</table>

**Additional Uptime Profits**

The additional uptime profits are based on the profit loss an OEM experiences due to scan errors, which could be turned into additional profit. One way to calculate this figure is multiplying the downtime per day with the percentage of scan related downtime, the cost per minute downtime, the percentage of faults that can be addressed with RFID, and the production days per year:
Alternatively, and for a more accurate result, the downtime due to scan warnings per line could be calculated with the method explained in the Line Impact of Scanning section. Next, all the downtime could be converted into downtime in the final line by using conversion factors. To get the factor from marriage to the final line, for instance, the starving time of the marriage line was divided by the sum of starving time and downtime of the marriage line. After the downtime is converted to downtime to final line, this time can be used to calculate the vehicle output loss by dividing in with the takt time in final line. Thereupon, the loss of vehicle output can be multiplied with the profit per car and the percentage of problems that can be addressed by RFID.

This figure is solely based on the loss due to products not being sold. It does not account, for instance, for lost productivity during downtime. Because during a downtime event, a manufacturer is not only producing to their potential, but also must pay idle operators.

**Manual scanning operation cost savings**

The next aspect of the economic feasibility is the cost of the manual scanning operation. The costs for this estimate are calculated by multiplying the average time per scan with the cost of labor per second with the number of scans per car and the number of cars per year produced. Based on the exemplary numbers from the Table 16.1 the following results:

\[
\frac{35\text{min}}{\text{day}} \times 0.05 \times \frac{$50,000}{\text{min}} \times 0.9 \times \frac{350\text{days}}{\text{year}} = $27.6\text{M/year}
\]

**Repair cost savings**

If a non-conformance occurs the vehicle needs to be contained. The repair cost for an OEM includes the labor to recover the serial number and update the genealogy data in the system. The figure is calculated by multiplying the number of containments with the average time to fix such an issue and the labor costs. It is assumed that out of the exemplary 102 containments per day, 5% are caused by scan errors, which results in 5.1 containments per day due to scans.

\[
\frac{30\text{min}}{\text{failure}} \times \frac{5.1\text{containments}}{\text{day}} \times \frac{350\text{days}}{\text{year}} \times \frac{$30}{60\text{min}} = $26.775/\text{year}
\]

**Additional cost of RFID tags**

To take the cost of RFID tags into account the average price for the RFID tag is multiplied by the number of tags per car and the number of cars produced per year. Based on the fictional numbers the following results:

\[
\frac{$0.1}{\text{tag}} \times \frac{15\text{tags}}{\text{car}} \times \frac{18,526\text{cars}}{\text{day}} \times \frac{350\text{days}}{\text{year}} = $9.7\text{M/year}
\]
Initial hardware and setup costs

An RFID reader costs approximately $1,400 USD, the antenna approximately $300 USD, and other accessories are around $200 USD. Based on the previous calculation of the other aspects, the initial hardware costs are very small compared to the other costs. However, a major factor that is not estimated, is the setup cost. For an RFID system to take over the manual part identification in an assembly line, comprehensive integration software needs to be developed. The previous section Software Design Application briefly touches on the subject, but to integrate this technology reliably and entirely into a production environment, substantial efforts must be undertaken which are not explored in the remit of this thesis.

When adding up the additional profit due to uptime, the cost saving of the manual operation, and the cost saving for repair, and subtracting the additional cost for RFID tags, the potential profit is still significant in this example. From the estimated calculations described above, it can also be concluded that the two major contributors are the additional uptime and RFID tag costs. Nonetheless, the manual scanning operation cost saving is also noticeable. However, these figures do not account for the initial setup and hardware cost. As described earlier, the development cost for the integration of the RFID data may be substantial but was not investigated as a part of this thesis. The initial hardware cost is most likely offset with the initial hardware cost for handheld scanners. It will be slightly higher but in relation to the other costs, it is not significant. It must be noted that this is only a rough estimate to achieve an initial representation of the total costs. Overall, the economic feasibility is high because the additional uptime offers great potential for a manufacturer. As the numbers above demonstrate, the value that an RFID part identification system can add is greater than the additional costs that would be incurred.
VI Conclusion and Future Research

In a final part, the entire topic is viewed holistically and summarized. Hereby, the focus is on the proposed RFID method, the conducted experiments, their findings, and their impact on a production line. Thereupon the limitations already pointed out in the Results and Analysis chapter are outlined, assessed, and additional measures suggested. Furthermore, it reviews the industrial implementation feasibility for a production line. This final chapter completes the thesis by highlighting future work on this topic and emphasizing additional application potential by utilizing the RFID tags of the individual components.
Thesis Conclusion

This research aimed to investigate several aspects of an RFID part identification system that automates and enhances the genealogy data-capturing process of an assembly line. Scanning is a common process used in almost every assembly line. It is a non-value-adding process, prone to error, and has not changed in decades. Thus, the proposed method based on RFID technology is an innovative approach that offers multiple benefits.

With a handheld scanning process, it is not possible to ensure the scanned part is the one built into the vehicle. This leaves the potential for human error to affect the vehicle genealogy data, which poses an enormous risk for an OEM, as it would lead to a lack of data integrity. Consequently, the lack of confidence could increase the number of containments and ultimately the scope of recall which would increase costs and harms the brand’s reputation. In addition to the genealogy impact, scanning also directly affects the assembly line output. To ensure high product quality, a scan non-conformance is made visible in the station right when it happens. The downside hereby is the lost production time. Also, as pointed out before, scanning is a non-value-adding process. Due to those and more reasons, this thesis proposes and investigates a new option, based on RFID. This technology already finds several applications in the industry, but not yet as proposed here.

Compared to other technologies for part identification, the advantage of RFID evidently is that no line-of-sight is required to read the information of the tag. The barcode scanner requires a direct line-of-sight to the barcode. Therefore, having fixed barcode scanners or cameras in the station to scan the barcode is not feasible as the operator would need to point the barcode towards the device. It could be a solution for certain parts that are always handled in the same manner and placed at a well-accessible location. One could argue that barcode scanning gloves could be a better alternative, however, they still do not ensure the scanned part is the part finally built into the car. A barcode scanning system combined with motion tracking is most likely not feasible due to the enormous efforts it would take to establish a reliable motion tracking software. Lastly, it must be pointed out that the final traceability verification would not be feasible with any of these solutions.

Within this thesis conducted research shows that it is technically feasible to replace barcodes with RFID tags on individual parts and identify them in the station they are assembled. For all the tested parts, there was at least one setup that enabled reading the part while being installed. Also, the experiments showed that it is difficult to find a non-metal spot on every part enabling a reliable read. For all parts besides two, there was a location on the part where the less expensive non-metal RFID tag could be placed. The major challenge of the in-station part identification, however, is to accurately detect the part that is installed and not one of the parts stored lineside. Despite the fact that RFID enables one to calculate the distance to a tag by measuring the time it took for a signal to arrive, it cannot be determined with certainty as there are many sources of interference at an assembly line. This could cause it to falsely appear as if another part is installed. Therefore, the dual antenna approach is suggested by this thesis. It increases the certainty about the installed part’s serial number and gives the system visibility of the parts in the station. All the parts tested with this method were successful, demonstrating the method’s potential. Nevertheless, further research and experiments are required to improve the part identification, make it a robust procedure, and discover other failure modes. In addition to that, substantial efforts must be directed toward software development. Overall, the experiments also showed that every setup needs to be adjusted to the environment of the station and the location the part is installed. There is no out-of-
the-box solution. Every station is different in terms of layout, equipment, and processes, which all can interfere with the RFID system. It may take several minor adjustments until the best positions are determined. In this regard, a major limitation of the conducted experiments is the line movement configuration. All the experiments were executed under a stopping line configuration. High-volume automotive production lines, however, are often continuous moving lines, as it offers certain benefits. In the case of a constantly moving line, the part to be detected is not always at the same position. Therefore, further testing with a continuous moving line is required as this makes an RFID introduction more complex.

Besides the in-station identification, the technical feasibility of “scanning” the entire car after it is completely assembled was investigated. This is the ultimate goal, as it enables an OEM to verify what parts are installed before the car goes to a customer. This superior method proposed by this thesis would offer strong confidence in the integrity of the genealogy data, because at this point the car is not modified anymore. Thus, the recorded data by the final traceability scan represent what is effectively installed into the vehicle. The experiments show that it is possible to identify all within this thesis tested parts. Moreover, based on the findings, it is likely that most of the parts in a vehicle can be identified. The only question is if they need a costly metal tag which would reduce the economic feasibility. Part identification is possible because certain parts of the vehicle are not made from metal, allowing the RF waves to penetrate them and reach the installed tags. For instance, the panorama roof, the front bumper, and the aero shields underneath the car enable the RF waves to radiate through them. Otherwise, this approach would not work as it is not possible to penetrate a hood or battery pack for example.

Overall, in every assembly line, scanning has a noticeable impact on the production output. Every scanning process is prone to error, potentially causing quality issues and slowing down production. The proposed method to determine the impact of scan errors shows the potential loss caused by downtime. This data is used to quantify the economic impact. The exemplary calculations state that the scan caused downtime has the biggest economic impact. The cost of the manual scanning operation is still noticeable, but the cost of repair compared to the additional profit potential due to more uptime is almost negligible. As mentioned before, one of the greatest challenges of the proposed RFID method is the additional cost because of the more expensive RFID labels compared to barcode labels. Nevertheless, the research states that it is profitable as the potential profits are greater than the additional cost for the labels. In this regard, it must be stated that those costs are operational expenses and do not take, amongst other things, the initial cost for hardware procurement and software development into account. To conclude the answer to the third research question, the economic feasibility is very likely but must be individually determined by the manufacturer. The elimination of manual scanning alone can, on average, save 3.3 cents of labor cost per scan. Taking into account that labor costs will further increase in the future, this factor will gain relevance. This still leaves a delta of 6.7 cents considering the additional cost of approximately 10 cents per RFID tag. This difference should be motivated by either the potential repair costs or the potential vehicle output losses due to scan-caused downtime. Considering a perfect production line, without any scan error, the price per RFID tag should be less than 3.3 cents to have an economic benefit. It must be pointed out, that this is solely based on economic aspects and therefore does not value the potential quality advantages or ease for the operators by removing the manual scanning operation.
Based on the relatively high price per tag, it might be feasible to replace only certain barcode labels. The criteria for it could be a compromise between safety critical parts and error high hitters having the greatest impact on production. As the Pareto rule states, 80% of the errors can be addressed by eliminating only 20% of the causes. Therefore, this approach could be effective. On the other hand, only partially implementing the RFID system in a production line creates further complications, as the part identification is now done in some stations with RFID and in others with barcodes. From a manufacturing engineering perspective, it would ease the implementation besides also having the advantage that no more time needs to be accounted for this operation as it is now automated. To strengthen the economic feasibility of replacing barcodes with RFID labels, all scan errors should be addressed, not only the already consumed error. That could be done by using the lineside antennas to add visibility by highlighting parts that are not ready for consumption. This would stop NOK parts from reaching the line, decrease the potential scan-caused downtime, and therefore boost the line efficiency. The principle is further explained in the future work section down below.

The proposed RFID part identification method for an automotive assembly line offers great benefits from an economic as well as quality perspective. This thesis contributes an innovative method and demonstrates the technical feasibility contrary to many initial doubts and third-party opinions. The stated results within this master’s thesis prove that it is worthwhile pursuing this method and working on an industrial implementation.

**Outlook on Future Research**

For future applications of the RFID part identification in assembly lines, more testing and development is necessary. Since the tests are a first proof-of-concept, further tests have to be performed. Selecting a part that is likely to succeed and has a high error rate would be a good starting point for a manufacturer. The RFID equipment should be installed in its station under a permanent configuration. As a starting point, the RFID output data should be separately collected during full production hours. This data can then be used to evaluate and work on the software implementation without interfering the current production. Furthermore, future work should be dedicated to testing the RFID in-station setup with a moving line configuration. This adds more complexity to the system as the assembled part is not always in the same position. Thus, the RF antenna setup needs to be adjusted or additional antennas need to be added to cover a broader area. Its technical feasibility needs to be proved again.

Additional future work that should be investigated, is utilizing the RFID tags on the individual parts for more purposes to maximize efficiency. As pointed out before, the lineside antennas could be used to identify any containments on parts before they make it to the vehicle and cause downtime. Whenever a non-consumable part is detected, the system could send out an alert and notify the operator. This additional visibility in the process still would not stop the error from occurring in the first place, but it would stop NOK parts from reaching the line and therefore increase the main line efficiency. If those errors shall be detected at an earlier point in time, an RFID gate could be a remedy. It could read the part when it passes the gate and send an alert right away. If a forklift is used to transport the parts, an RFID reader could also be applied to the forklift itself to detect any non-conformance. Moreover, the RFID tags could be used for logistical purposes. They could help manage the line side storage as it allows for an accurate storage part count. Thus, it could streamline the material flow by sending an
Conclusion and Future Research

order exactly when needed. Furthermore, it could create an automatic emergency part request when the stock is at a critically low level, and they need supplies immediately. By maximizing the utilization of the RFID tags on individual parts, the economic feasibility rises.

Another future work topic that needs to be addressed is an investigation of any interference of RFID tags with sensors or other electronics within the vehicle. Since the tags are passive and powered by the RF waves they receive, it seems implausible. Nevertheless, this should further be investigated to avoid any quality issues.

As the IoT grows considerably, the amount and sensitivity of the data increases. Therefore, the topic of data security is more important than ever, this topic should be further investigated in relation to RFID. Concerns could be expressed that the RFID tags in the vehicle could be read by third parties. In this case there is the option to encrypt the information before it is written to the tag. This is another topic of potential future research.

Lastly, future research should investigate the option of embedding the RFID tags within the part itself. This would remove the necessity of placing a label on the part during the assembly process. The investigation should evaluate whether label placing has an impact on the data integrity as well as if the benefits of embedding the RFID tag outweigh the additional production costs of the integration process.

Depending on the future dedication towards this topic, the industrial application is decided. The findings of this research show that replacing a barcode label on an individual part with an RFID tag is a promising approach to automate the part identification process and enhance the vehicle’s genealogy data integrity.
Bibliography


Appendix

List of Appendices

Appendix A: (Confidential) Experimental Part List............................................................... XV
Appendix B: Zebra FX9600 Reader Data Sheet [49]............................................................... XVII
Appendix C: Zebra AN480 Antenna Data Sheet [43]........................................................... XVIII
Appendix D: Zebra AN440 Antenna Data Sheet [43]............................................................ XIX
Appendix E: RFID Tags Selection.......................................................................................... XX
Appendix F: RFID Testing Accessories................................................................................ XXI
Appendix G: (Confidential) VBA Code Downtime Calculation.............................................. XXII
Appendix H: (Confidential) 27 RFID Tag Locations for Final Traceability Test...................... XXX
Appendix I: Process Flow for RFID Part Identification.......................................................... XXXI
Appendix J: Heat Pump Test 21 Plot...................................................................................... XXXIII
Appendix K: Heat Pump Test 10 Plot Showcasing an Operator Blocking Line-of-Sight........... XXXIV
Appendix L: RFID software design exemplified by Driver Seat measurement v14.............. XXXV
Appendix M: RFID software design exemplified by Driver Seat measurement v17.............. XXXVI
**Appendix B: Zebra FX9600 Reader Data Sheet [49]**

**PRODUCT SPEC SHEET**  
FX9600 FIXED UHF RFID READER

### Specifications

#### Physical Characteristics

- **Dimensions:** 170 x 110 x 125 mm, W x D x H  
- **Weight:** Approx. 4.4 lbs/2kg
- **Housing Material:** Die-cast aluminum, meets IP53 standards
- **Graffiti Indicators:** Multiple: LED, Power, Activity, Status and Applications

#### RFID Characteristics

- **Max Receive Sensitivity:** -81 dBm (RSSI)
- **Air Protocols:** ISO15693-00 (ITC Class 1 Gen 2 v2)
- **Frequency (UHF Band):** 860-960 MHz, 902-928 MHz, 865-868 MHz
- **(UHF Band):** 51.10 MBps, 24/7 External DC
- **Power Supply:** 13.5 VDC, 12 VDC, 24 VDC

#### Connectivity

- **Communications:** 10/100 Base Ethernet (RJ45), USB Host, and USB Type A and B, Serial (DB9)
- **Generals Purpose I/O:** 4 Inputs, 4 Outputs, optically isolated (Terminal Block)
- **Power Supply:** F/83 (EU2, UK)
- **Antennas Ports:** FG900A-R, Flexible Antenna ports, Reverse Polarity (N)  

#### Environmental

- **Operating Temp.:** -4°F to +131°F (-20 to +55°C)
- **Storage Temp.:** -40°F to +158°F (-40 to +70°C)
- **Humidity:** 5-95% non-condensing
- **Sealing:** IP53

#### Hardware, OS and Firmware Management

- **Processor:** Texas Instruments AMR5516 (55 MHz)
- **Memory:** Flash 512 MB, DRAM 256 MB
- **Operating System:** Linux
- **Firmware Upgrade:** Web-based and remote firmware upgrade capabilities

#### Management/Protocols

- **Management/Protocols:** RM 1.7, with XML, over HTTP/HTTPS and SNMP (v1, v2, v3)
- **Network Services:** DHCP, HTTP, FTP, SSH, Telnet, FTP, SMTP, NTP
- **Network Stack:** IPv4 and IPv6
- **Security:** Transport Layer Security Version 1.2, IPS 340
- **API Support:** Host Applications – .NET, C, Java, EMX; Embedded Applications – C and Java SDK

#### Regulatory Compliance

<table>
<thead>
<tr>
<th>Safety</th>
<th>UL 60950-1, UL 2043, IC-ES 0501, EN 60950-1</th>
</tr>
</thead>
<tbody>
<tr>
<td>RF/MPE</td>
<td>FCC Part 15, IC-ES 0501, EN 300 220, ICES-003</td>
</tr>
<tr>
<td>SA/NPRE</td>
<td>FCC 47 CFR Part 15, IC-ES 0501, EN 300 220</td>
</tr>
</tbody>
</table>

#### Environmental Compliance

- **Warranty:** 3 years

#### Markets and Applications

- **Warehousing**
- **Transportation and Logistics**
- **Manufacturing**
- **Retail**
- **Government**

#### Recommended Services

- **Support Services:** Zebra OneCare® On-Site System Support
- **Advanced Services:** Zebra Design and Deployment Services

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**Footnotes**

- Configurations without a USB hub require an external USB hub for full USB functionality.
- Specifications are subject to change without notice.

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**ZEBRA TECHNOLOGIES**
Appendix C: Zebra AN480 Antenna Data Sheet [43]

BROCHURE
ZEBRA UHF RFID ANTENNAS

Zebra AN480
Wide-Band RFID Antenna

High-performance, wide-band antenna for worldwide use

The AN480 single port antenna offers maximum performance and flexibility. The low axial ratio is nearly 50 percent lower than typical competitive devices, delivering a more uniform gain — and better performance. The wide frequency range enables this antenna to be utilized in worldwide deployments, providing cost efficiencies and a simplified RFID infrastructure. The AN480 can be installed throughout the enterprise in manufacturing and warehouse floor environments, or any dock door receiving application. As with all Zebra antennas, the AN480 uses Zebra’s standard mounting bracket — mounting the antenna for the first time or upgrading an existing Zebra antenna with the AN480 is fast and easy.

AN480 Specifications

<table>
<thead>
<tr>
<th>SPECIFICATION</th>
<th>VALUE</th>
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<tbody>
<tr>
<td>Gain</td>
<td>6.0 dB</td>
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<tr>
<td>Front to Back Ratio</td>
<td>18 dB</td>
</tr>
<tr>
<td>3 dB Beam Width</td>
<td>65° in both planes</td>
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<tr>
<td>Maximum Power</td>
<td>2 Watts</td>
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<tr>
<td>Axial Ratio</td>
<td>1.5 dB typical</td>
</tr>
<tr>
<td>Operating Temperature</td>
<td>-25°C to +70°C</td>
</tr>
<tr>
<td>Storage Temperature</td>
<td>-40°C to +60°C</td>
</tr>
<tr>
<td>IP Rating</td>
<td>IP64</td>
</tr>
<tr>
<td>Vibration</td>
<td>B Grade series</td>
</tr>
<tr>
<td>Humidity</td>
<td>B Grade series</td>
</tr>
</tbody>
</table>

TAA Compliance: No

Types of Markets:
- Retail
- Enterprise/Office
- Hospitality
- Healthcare

Applications:
- Point-of-Sale
- Checkpoints
- Kiosks
Appendix D: Zebra AN440 Antenna Data Sheet [43]

Zebra AN440
Dual-Element RFID Antenna

Large area coverage for high-capacity, high throughput environments

The AN440 RFID antenna gives you a wide read field and high-speed RF signal conversion, so data capture is fast and accurate, even in expansive, high-demand environments. The AN440 is easy to mount on ceilings and walls, and its rugged housing is at home in both customer-facing and industrial settings. You can achieve superior read zones around stockroom shelves, warehouse doorways, and dock platforms — anywhere boxes and pallets are moving in and out of your facility. Your workflow keeps flowing, your inventory count stays accurate, and your productivity can reach new heights.

AN440 Specifications

<table>
<thead>
<tr>
<th>PHYSICAL CHARACTERISTICS</th>
<th></th>
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<tbody>
<tr>
<td>Polarization</td>
<td>RHCP/LHCP</td>
</tr>
<tr>
<td>Dimensions</td>
<td>575.1 mm x 259.1 mm x 33.2 mm</td>
</tr>
<tr>
<td>Connector</td>
<td>Right Angle Female</td>
</tr>
<tr>
<td>Connector Location</td>
<td>Rear</td>
</tr>
<tr>
<td>Measuring Optics</td>
<td>Mounting stud provided</td>
</tr>
<tr>
<td>Weight</td>
<td>7.0 lbs/3.2 kg</td>
</tr>
<tr>
<td>Casing/Materials</td>
<td>UV Stable ABS</td>
</tr>
<tr>
<td>Frequency Range</td>
<td>EU: 865 – 866 MHz</td>
</tr>
<tr>
<td>Case SWR (Return Loss)</td>
<td>1.22:1</td>
</tr>
<tr>
<td>Gain</td>
<td>US/Canada: 6.2 dBi</td>
</tr>
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</table>

Front to Back Ratio: 20 dB
3 dB Beam Width: 70° in both planes
Maximum Power: 10 Watts
Axial Ratio: 1:1 typical
Operating Temperature: +40° to +70°C (40° to 158°F)
Storage Temperature: +40° to +85°C (109° to 185°F)
IP Rating: IP67
Vibration: MIL-STD-810G, Method 516.5, Procedure II – Aggravated, 3G; 4055±50 Hz, 0.5 g, one hour in each of two axes, random vibration
Humidity: 3G; 4055±50 Hz, 95% relative humidity

TAA Compliance: No

Vertical Markets:
- Retail
- Enterprise
- Hospitality
- Healthcare
- Transportation & Logistics
- Manufacturing

Applications:
- Point-of-Sale
- Conveyor belts
- Check points
- Highways

*Limited for US
### Appendix E: RFID Tags Selection

<table>
<thead>
<tr>
<th>Item Number</th>
<th>Picture</th>
<th>Description</th>
<th>Qty</th>
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</thead>
<tbody>
<tr>
<td><strong>Passive RFID Tags</strong></td>
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<td></td>
</tr>
<tr>
<td>Zebra - 10036023</td>
<td><img src="image1.png" alt="Image" /></td>
<td>BT0573 / UCODE 8 / Z-Perform 1500T (3 x 1 in.)</td>
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</tr>
<tr>
<td>Zebra - 10036818</td>
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<td>ZBR2000 / UCODE 8 / PolyPro 3000T (3.875 x 0.45 in.)</td>
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<tr>
<td>Zebra - 10036991</td>
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<td>BT781 / UCODE 8 / PolyPro 3000T (1.75 x 0.75 in.)</td>
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<tr>
<td>Zebra - 10026450</td>
<td><img src="image4.png" alt="Image" /></td>
<td>BT349 / Monza R6-P / PolyPro 3000T (1.75 x 0.75 in.)</td>
<td>30</td>
</tr>
<tr>
<td>Zebra - 10026649</td>
<td><img src="image5.png" alt="Image" /></td>
<td>ZBR2000 / UCODE 8 / Z-Perform 1500T (4 x 6 in.)</td>
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<tr>
<td>Zebra - 10036110</td>
<td><img src="image6.png" alt="Image" /></td>
<td>EOS-200 / UCODE 8 / Z-Ultimate 4000T (3 x 0.55 in.)</td>
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<tr>
<td>Zebra - 10036485</td>
<td><img src="image7.png" alt="Image" /></td>
<td>EOS-200 / UCODE 8 / PolyPro 3000T (0.94 x 0.55 in.)</td>
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<tr>
<td>Zebra - 10026781</td>
<td><img src="image8.png" alt="Image" /></td>
<td>BT577 / Monza R6-P / Z-Ultimate 4000T (2.67 x 1 in.)</td>
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<tr>
<td>Zebra - 10026763</td>
<td><img src="image9.png" alt="Image" /></td>
<td>Silverline Micro II FCC / Monza R6P / Polyester (1.77 x 0.51 in.)</td>
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### Appendix F: RFID Testing Accessories

<table>
<thead>
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<th>Item Number</th>
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<tbody>
<tr>
<td>CBLRD-1B4003600R</td>
<td><img src="image.png" alt="Cable" /></td>
<td>Cable, 30 feet LMR 240 antenna cable for FX9600 use</td>
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<tr>
<td>PWR-BGA24V78W1WW</td>
<td><img src="image.png" alt="Power Supply" /></td>
<td>Cable, Level VI AC/DC Power Supply Brick w/Captive DC Cable. AC Input: 100-240V, 1.4ADC Output: 24V, 3.25A, 78W, -20 to +55 degrees C. Requires: Country specific grounded AC line cord 48.36</td>
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<tr>
<td>23844-00-00R</td>
<td><img src="image.png" alt="Cord" /></td>
<td>Cable, AC line cord, 7.5 feet long, grounded, three wire. Associated Country: US</td>
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<tr>
<td>BRKT-70661-01R</td>
<td><img src="image.png" alt="Antenna" /></td>
<td>Antenna, Standard Mount for AN400 and AN480 Antenna</td>
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<tr>
<td>9NY-6AS10-50L</td>
<td><img src="image.png" alt="Ethernet Cable" /></td>
<td>Ethernet Cable, 50 feet / 15.2 meters, CMR 75C E146107-F</td>
<td>2</td>
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</tbody>
</table>
Appendix I: Process Flow for RFID Part Identification
Appendix I: Process Flow for RFID Part Identification
Appendix K: Heat Pump Test 10 Plot Showcasing an Operator Blocking Line-of-Sight
Appendix L: RFID software design exemplified by Driver Seat measurement v14