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Smart Quality Control for Materials and Spare Parts: Integrating RFID with Etras in EV Manufacturing

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Abstract

This study proposes a smart quality control (QC) framework for managing materials and spare parts in an electric vehicle (EV) manufacturing plant. The framework integrates Radio Frequency Identification (RFID) with the Etras Enterprise Resource Planning (ERP) system to digitalize inspection activities and improve real-time traceability. In parallel, structured Work Instructions (WI) were developed to strengthen workforce capability and reduce human error. A quasi-experimental design with pretest–posttest analysis was applied to 80 QC staff. The results showed that the integrated system reduced inspection errors by 87.18%, decreased processing time, and improved transparency in material flow. Employees trained with WI reported higher accuracy and satisfaction. The findings confirm that smart QC based on RFID–ERP integration offers a scalable model for digitalized quality assurance in advanced manufacturing.

Keywords
RFID Technology, Etras System, Work Instruction (WI), Production Efficiency, Quality Control (QC).

1. Introduction
Electric vehicle (EV) manufacturing requires high precision in managing materials and spare parts to ensure safety and product reliability. Traditional manual inspection often results in errors, incomplete data, and inefficiencies that raise production costs. A leading EV factory in Germany reported frequent non-conforming parts entering the production line, mainly due to limited traceability and outdated quality control practices. To address these challenges, this research introduces a smart QC framework that combines RFID with the Etras (ERP) system to ensure real-time monitoring of materials. The integration reduces reliance on manual inspection and supports transparent inventory management. Furthermore, the study emphasizes the importance of workforce development through clear, visual Work Instructions (WI), enabling QC staff to apply digital tools effectively (Figure 1).

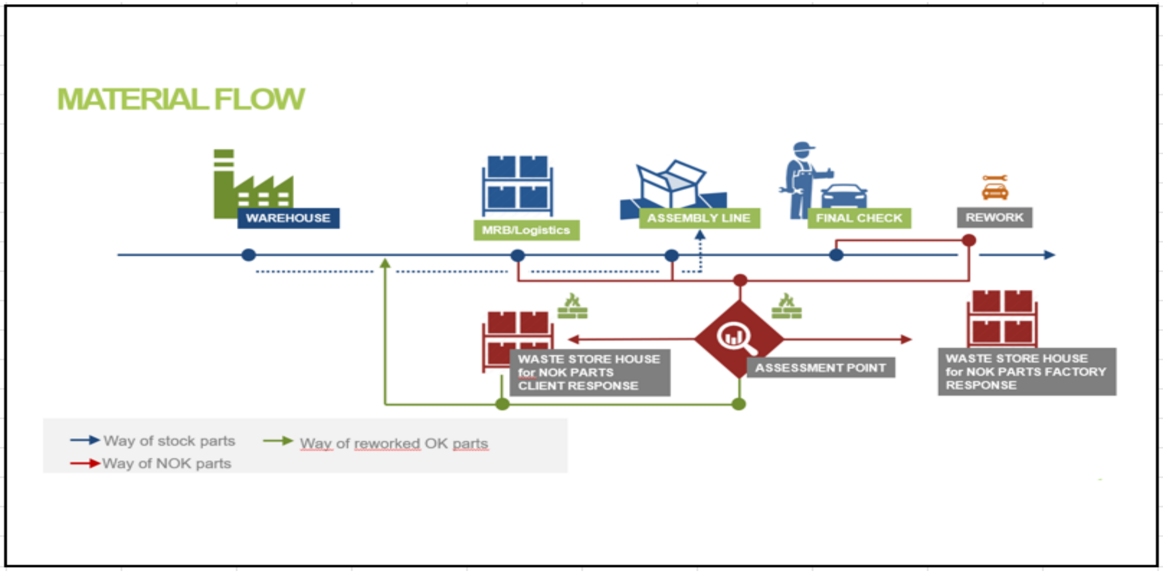


Figure 1. The material flow process from the warehouse to the production line, using red visual symbols to indicate areas designated for the inspection and correction of non-conforming materials.

1.1 Research Questions

RQ1: How does the implementation of the RFID–Etras system affect inspection efficiency and defect reduction in electric vehicle (EV) manufacturing?
RQ2: What is the impact of Work Instruction (WI)-based training on QC staff performance, accuracy, and satisfaction?

2. Literature Review

Recent studies highlight digital technologies' role in enhancing quality control (QC) in electric vehicle (EV) manufacturing, focusing on RFID technology, ERP systems, Work Instructions (WI), and AI to boost production efficiency and reduce defects. RFID improves traceability and inventory accuracy, as shown by Ibrahim & Varouqa (2020), Borda et al. (2019), Setyawan et al. (2022, 2024), and Zhang et al. (2020). ERP systems facilitate data integration and decision-making in particular, the Etras system adopted in this study links RFID data with quality inspection and real-time inventory tracking, enhancing process transparency and operational control (Ullah et al., 2020; Pontoha et al., 2024; Kwon et al., 2020). Digital WIs support workforce performance by improving task accuracy and reducing completion time (Eversberg & Lambrecht, 2023; Khan et al., 2023; Salas et al., 2021). AI applications further enable predictive defect detection and process optimization (Jain, 2024; Setyawan et al., 2023; Li & Chen, 2023). Despite these advances, few studies integrate RFID, the Etras ERP system, and WIs into a unified QC framework; this research addresses that gap by proposing a smart QC model that enhances inspection accuracy, production efficiency, and workforce performance.

3. Methods

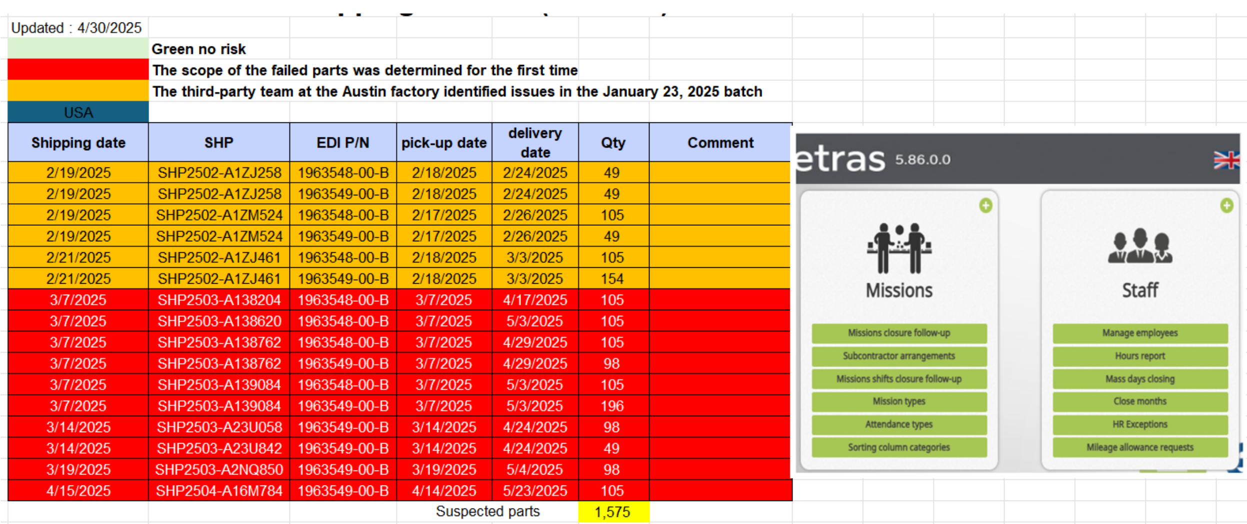
This study employed an applied research framework using a quasi-experimental, one-group pretest–posttest design, which is appropriate for evaluating interventions in a real-world EV manufacturing environment. The research aimed to assess the impact of integrating RFID technology with the Etras ERP system and structured Work Instructions (WI) on inspection efficiency, defect reduction, and QC staff performance. A total of 80 QC staff participated in the study. The sample size was determined based on the practical availability of staff, representativeness of the QC workforce, and sufficient statistical power to detect meaningful changes between pretest and posttest measurements. The quasi-experimental design enabled direct measurement of performance, accuracy, and satisfaction before and after the intervention. The methodology was guided by continuous improvement principles, incorporating both the PDCA cycle and the DMAIC process. Additionally, selected principles from Deming's 14 Points were mapped to these frameworks to support the design, implementation, and evaluation of the quality control improvement process (see Table 1).

Table 1. Linking Deming's Principles with the DMAIC and PDCA Cycles in Research Application.

Deming Principle	**Corresponding Step (PDCA / DMAIC)**	**Practical Application in Research**
Principle 5: Continuously improving the process	Improve (DMAIC) / Act (PDCA)	Review and revise Work Instructions to align with the actual situation
Principle 6: Provide training on the job	Do (PDCA) / Improve (DMAIC)	Conduct employee training on using RFID and the Etras system
Principle 13: Encourage lifelong learning	Control (DMAIC)	Evaluate the effectiveness of Work Instructions after implementation and adjust training approaches
Principle 9: Break down barriers between departments	Analyze (DMAIC)	Interview supervisors to identify coordination issues and adjust the disbursement process
Principle 7: Promote leadership	Define / Analyze	Analyze the role of supervisors in improving warehouse work quality
Principle 3: Reduce reliance on final inspection	Measure / Control	Assess the accuracy of data from the RFID system before it enters the warehouse

3.1 Analysis of Quality Issues in Materials and Spare Parts Using Data from the Etras System

This study examines quality issues related to materials and spare parts by analyzing operational data retrieved from the Etras system.



Updated : 4/30/2025

Green no risk
The scope of the failed parts was determined for the first time
The third-party team at the Austin factory identified issues in the January 23, 2025 batch
USA

Shipping date	SHP	EDI P/N	pick-up date	delivery date	Qty	Comment
2/19/2025	SHP2502-A1ZJ258	1963548-00-B	2/18/2025	2/24/2025	49	
2/19/2025	SHP2502-A1ZJ258	1963549-00-B	2/18/2025	2/24/2025	49	
2/19/2025	SHP2502-A1ZM524	1963548-00-B	2/17/2025	2/26/2025	105	
2/19/2025	SHP2502-A1ZM524	1963549-00-B	2/17/2025	2/26/2025	49	
2/21/2025	SHP2502-A1ZJ461	1963548-00-B	2/18/2025	3/3/2025	105	
2/21/2025	SHP2502-A1ZJ461	1963549-00-B	2/18/2025	3/3/2025	154	
3/7/2025	SHP2503-A138204	1963548-00-B	3/7/2025	4/17/2025	105	
3/7/2025	SHP2503-A138620	1963548-00-B	3/7/2025	5/3/2025	105	
3/7/2025	SHP2503-A138762	1963548-00-B	3/7/2025	4/29/2025	105	
3/7/2025	SHP2503-A138762	1963549-00-B	3/7/2025	4/29/2025	98	
3/7/2025	SHP2503-A139084	1963548-00-B	3/7/2025	5/3/2025	105	
3/7/2025	SHP2503-A139084	1963549-00-B	3/7/2025	5/3/2025	196	
3/14/2025	SHP2503-A23U058	1963549-00-B	3/14/2025	4/24/2025	98	
3/14/2025	SHP2503-A23U842	1963549-00-B	3/14/2025	4/24/2025	49	
3/19/2025	SHP2503-A2NQ850	1963549-00-B	3/19/2025	5/4/2025	98	
4/15/2025	SHP2504-A16M784	1963549-00-B	4/14/2025	5/23/2025	105	
				Suspected parts	1,575	

Figure 2. Etras management system interface with defective spare parts identified on the production line from Supplier A.

The interface facilitates data retrieval and analysis through key functions, including date range selection, employee filtering, supplier report access, and working hour extraction. However, the current dataset lacks critical information such as the date of part arrival, part expiration date, and the specific type of defect. Based on the data presented in the Figure 2, it was observed that materials and spare parts with quality issues were occasionally mixed into the production line, directly impacting manufacturing efficiency. This led to losses in terms of time, cost, and product quality. Currently, the system has not yet been upgraded with RFID integration in the Etras platform, which means the Etras dataset remains incomplete and may not fully capture all material and spare part movements. These findings highlight the need to develop a quality control system that verifies materials and spare parts prior to entering the production line, aiming to prevent potential issues and enhance overall manufacturing efficiency.

4. Data Collection and Analysis

4.1 Analysis of Root Causes Using a Fishbone Diagram

The fishbone diagram revealed that the primary causes of the quality issues included insufficient inventory checks, lack of standardized training, and delayed feedback loops between QC, supervisor and engineer (Figure 3).

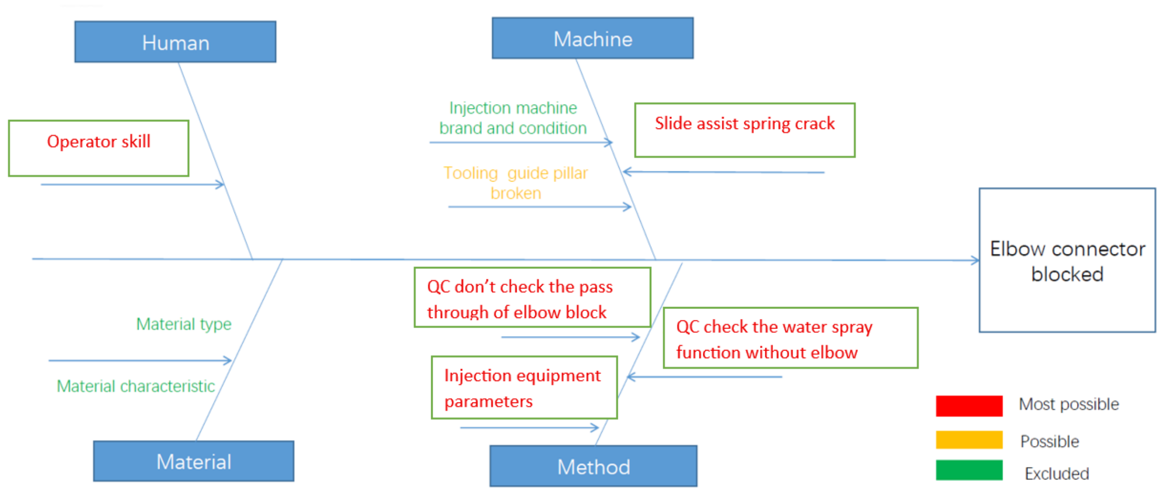


Figure 3. Root cause analysis using a fishbone diagram.

4.2 Operational implementation in accordance with the DMAIC approach

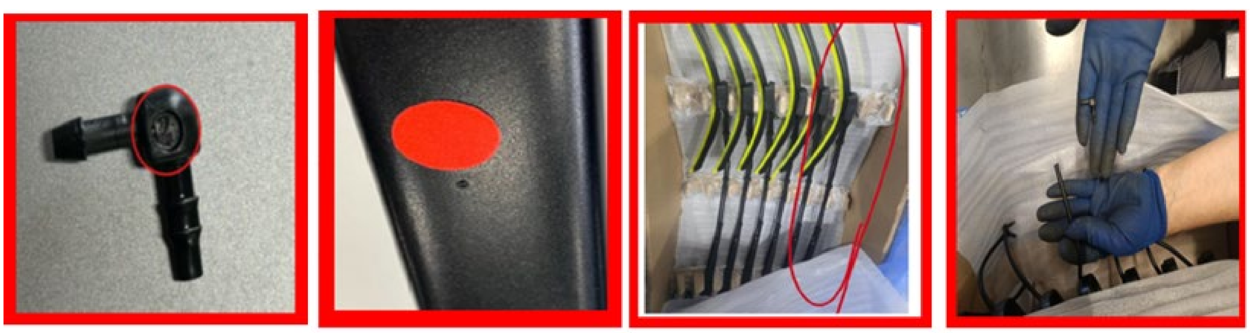


Figure 4. Types of non-conforming parts detected from Supplier A

1) Define: Elbow connector blocked, causing non-spray (Table 2 and Figure 4).

Table 2. Inspection identified 1,575 parts that did not comply with specifications, representing a breach of quality requirements.

What:	1963XXX-00-B WIPER ARM&BLADE ASSY PS LHD. Wiper Arm/ Blade Assy with non-conforming part detected:
When：	3/25/2025
Where：	GF
Who:	SQA GF

Why it is a problem:	Elbow connector blocked, causing non-spray issue (Cavity no.2)
How many:	1,575 ea

2) Measure

Table 3. A defect rate of 52.5% was found in connectors due to blockages at joint No. 2 on the assembly line.

Quantity of Defective Units (pc)	Defect Rate = (Number of defective items ÷ Total number of inspected items) × 100	Area of Defect	Origin of the part	Type of Defect	Date Found
1,575	(1575÷3000)x100=52.5%	Connector	Assembly Line	A blockage occurred at joint No. 2, preventing the spray function from operating	3/25/2025

From Table 3 presents a summary of a defect identified during the production process. Out of 3,000 inspected units, 1,575 were found to be defective, resulting in a defect rate of 52.5%, which significantly exceeds the acceptable threshold of ±10%.The defect was localized in the connector area, with the root cause traced to a blockage at joint No. 2, which prevented the spray function from operating correctly. All defective parts originated from the assembly line, and the issue was first detected on March 25, 2025.This measurement highlights a critical quality issue requiring immediate root cause analysis and corrective action to prevent recurrence and reduce production losses.

3) Analysis

An air pressure test was conducted at 60 kPa to detect cavity blockages. Parts exhibiting pressure readings of ≥34 kPa were classified as non-conforming (NOK). This procedure enabled systematic identification of blocked connectors (Figure 5).

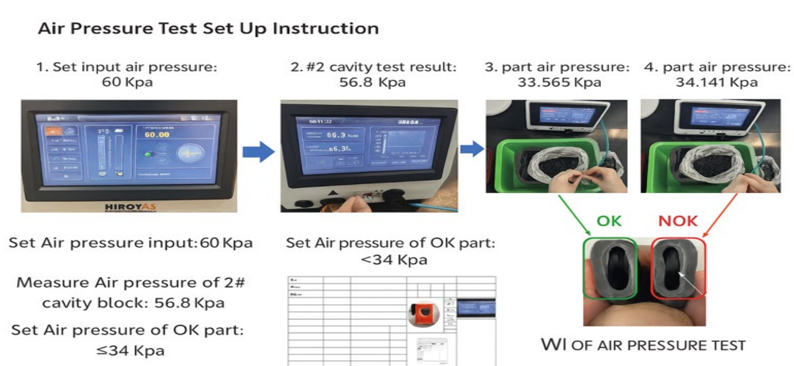


Figure 5. Show the operation without a clear Work Instruction.

5. Summary of improvements and recommendations

5.1 Improve

Process improvement through the installation of RFID technology, enabling the scanning of RFID tags into the Etras system (Figure 6).

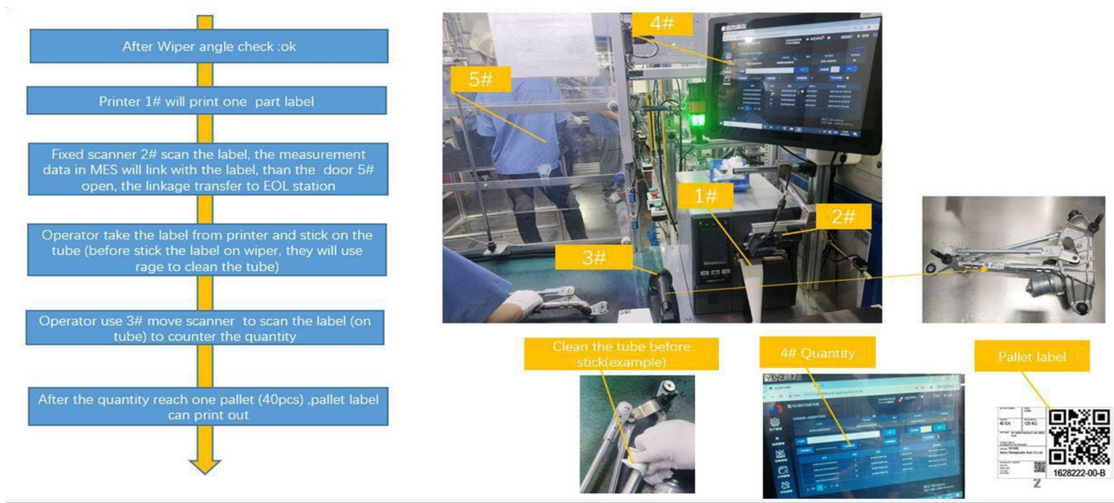


Figure 6. The spare part inspection process involves RFID technology, with designated scanning points clearly defined throughout each stage of the workflow.

RFID Installation Procedure for Scanning RFID Tags into the Etras System as follows.
1. Install RFID tags on each type of spare part to enable real-time tracking of location and quantity.
2. Connect the data to the Etras system to allow automatic and accurate inventory status monitoring.
3. Configure RFID tags to indicate the production date and expiration date of each item.
4. Scanning the RFID tags on a spare part allows verification of proper quality control procedures.
5.Once scanned, the item is entered into the system and displayed as shown in Table 4.

Table 4. All material data entered into the system will be updated in real time and can be traced back for verification.

Label Information	Version	Delivery Date	Ship NO.	Arrive Date	Expiry Date
GBGPB202504160004,1963548-00-B,20250416001	返工主刮臂-B	4/30/2025	SHP2503-A55N798	5/28/2025	5/28/2027
GBGPB202504160005,1963548-00-B,20250416001	返工主刮臂-B	4/30/2025	SHP2503-A55N798	5/28/2025	5/28/2027
GBGPB202504160006,1963548-00-B,20250416001	返工主刮臂-B	4/30/2025	SHP2503-A55N798	5/28/2025	5/28/2027
GBGPB202504160009,1963548-00-B,20250416001	返工主刮臂-B	4/30/2025	SHP2503-A55N798	5/28/2025	5/28/2027
GBGPB202504160011,1963548-00-B,20250416001	返工主刮臂-B	4/30/2025	SHP2503-A55N798	5/28/2025	5/28/2027
GBGPB202504160012,1963548-00-B,20250416001	返工主刮臂-B	4/30/2025	SHP2503-A55N798	5/28/2025	5/28/2027
GBGPB202504160022,1963548-00-B,20250416001	返工主刮臂-B	4/30/2025	SHP2503-A55N798	5/28/2025	5/28/2027
GBGPB202504160023,1963548-00-B,20250416001	返工主刮臂-B	4/30/2025	SHP2503-A55N798	5/28/2025	5/28/2027
GBGPB202504160024,1963548-00-B,20250416001	返工主刮臂-B	4/30/2025	SHP2503-A55N798	5/28/2025	5/28/2027
GBGPB202504160025,1963548-00-B,20250416001	返工主刮臂-B	4/30/2025	SHP2503-A55N798	5/28/2025	5/28/2027
GBGPB202504160026,1963548-00-B,20250416001	返工主刮臂-B	4/30/2025	SHP2503-A55N798	5/28/2025	5/28/2027
GBGPB202504160029,1963548-00-B,20250416001	返工主刮臂-B	4/30/2025	SHP2503-A55N798	5/28/2025	5/28/2027
GBGPB202504160030,1963548-00-B,20250416001	返工主刮臂-B	4/30/2025	SHP2503-A55N798	5/28/2025	5/28/2027
GBGPB202504160031,1963548-00-B,20250416001	返工主刮臂-B	4/30/2025	SHP2503-A55N798	5/28/2025	5/28/2027

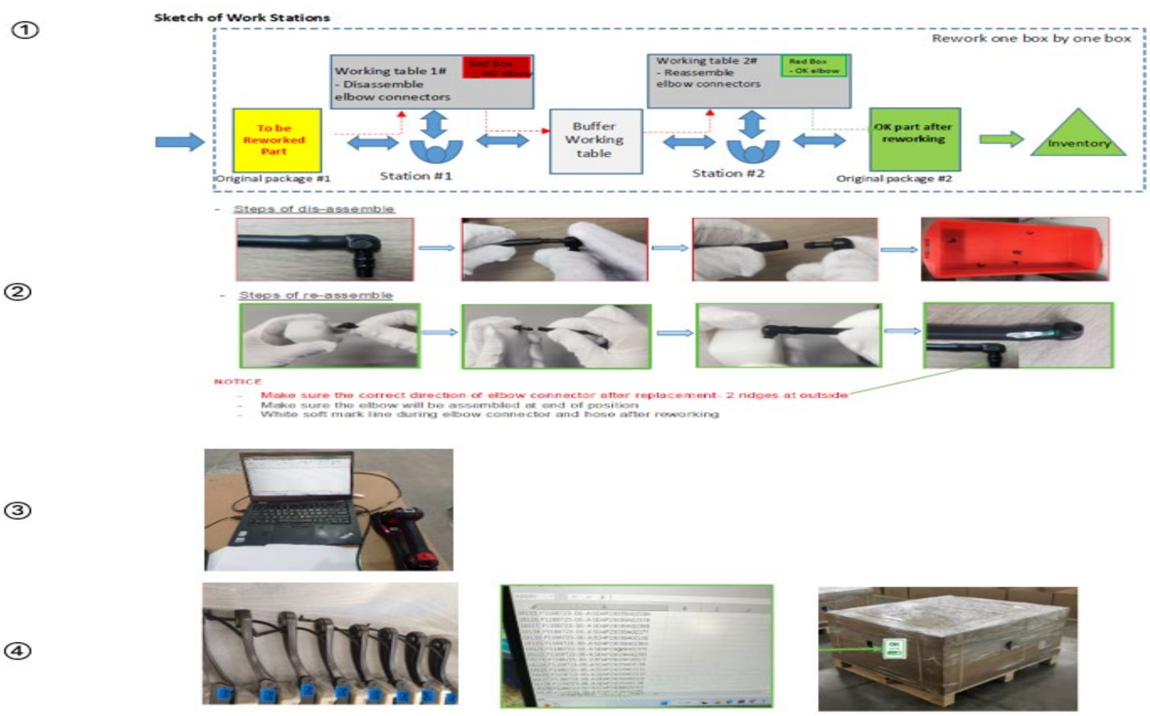


Figure 7. Modified Work Instruction for Quality Control Procedures.

Figure 7 presents a step-by-step explanation of the rework instruction, including preparation and initial checks to gather the required items:

1) Workflow Understanding
The QC staff must follow a defined workflow: receiving non-conforming (NG) parts, conducting an initial check, performing rework procedures, rechecking the parts, and finally returning the confirmed OK parts to the warehouse. This structured flow ensures consistency and traceability throughout the rework process.

2) Visual Inspection of Elbow Connection
During inspection, the elbow connector must be fully engaged with the lever to be considered acceptable. Correct setups are marked with a green check, while incorrect or misaligned connectors are identified with a red “X.” Any NG (Not Good) connectors must be reworked to ensure proper alignment and engagement before proceeding.

3) System Debugging
The QC staff connects a laptop to the diagnostic device to verify communication between hardware and software. Debugging protocols are executed to detect any system errors or misconfigurations. It is critical to confirm that the reworked connector is recognized by the system to validate the repair.

4) System Setup and Scanning
Using the designated software interface, the QC staff scans the reworked parts to ensure they are correctly logged into the system. The system must accept these parts as OK. Once confirmed, the scan results are saved and submitted, and the approved parts are returned to the warehouse for reintegration into inventory.

This newly created Work Instruction is designed with a sequential layout and supporting visuals to enhance employee comprehension of the elbow(example case) joint inspection procedure.

5.2 Impact of RFID Implementation in Etras and Work Instructions on Defect Reduction

To analyze the distribution of inspection errors among quality control (QC) staff prior to the RFID intervention, a histogram was employed. This visualization technique allows for the grouping of defect counts into defined intervals (bins), providing a clear overview of how frequently certain error ranges occurred. In this study, the histogram was configured with 10 bins, offering a balanced level of granularity that reveals subtle patterns in the data while maintaining readability. By examining the shape, spread, and central tendency of the histogram, we can assess whether the defect rates were concentrated, symmetrical, or skewed, and identify any outliers or trends. This insight supports the statistical findings and helps illustrate the baseline performance before digital transformation.

Step 1: Enter individual defect count data from all 80-quality control (QC) staff into the histogram tool, with the aim of comparing pre-training and post-training scores to assess statistical significance (Figure 8).

Raw Data: Defects Before RFID
20,18,22,19,21,17,16,23,19,20,18,21,22,20,19,17,18,20,21,19,20,18,22,19,21,17,16,23,19,20,18,21,22,20,19,17,18,20,21,19,20,18,22,19,21,17,16,23,19,20,18,21,22,20,19,17,18,20,21,19,20,18,22,19,21,17,16,23,19,20,18,21,22,20,19,17,18,20,21,19

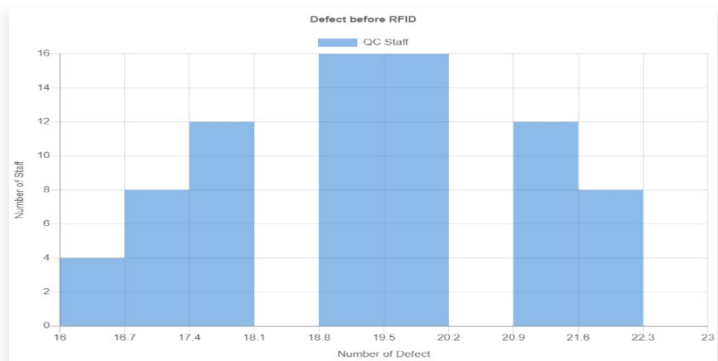


Figure 8. Histogram of defect counts before RFID implementation.

Key Observations:
The defect distribution among QC staff peaks at 19.5 defects (16 staff), with adjacent ranges of 18.1 and 20.2 defects including 10 staff each. The lowest and highest ranges (16 and 22.3 defects) have 5 staff each. The overall bell-shaped, symmetrical distribution aligns with the statistics: Mean = 19.5, Median = 19.5, Skewness = 0.0.

Implication:
Most staff had defect counts close to the mean, showing consistent baseline performance before RFID implementation. The narrow variation makes it easier to detect and measure improvements after intervention.

Raw Data: Defects After RFID
3,2,4,3,2,2,1,5,2,3,2,2,4,3,2,2,2,3,2,2,3,2,4,3,2,2,1,5,2,3,2,2,4,3,2,2,2,3,2,2,3,2,4,3,2,2,1,5,2,3,2,2,4,3,2,2,2,3,2,2,3,2,4,3,2,2,1,5,2,3,2,2,4,3,2,2,2,3,2,2

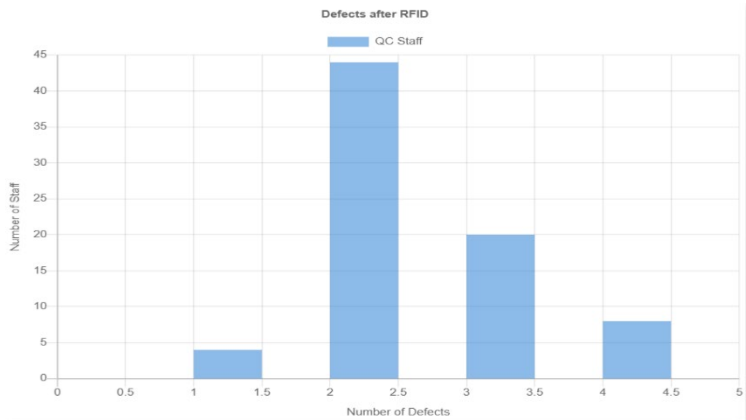


Figure 9. Histogram of defect counts after RFID implementation.

After the training and RFID system were introduced, the number of defective parts reported by QC staff dropped significantly. The majority of employees—around 45 out of 80—recorded only 2.5 defects, compared to the previous average of 19.5 defects. This sharp decline indicates a substantial improvement in inspection accuracy and adherence to work instructions (Figure 9).

The distribution is now skewed toward lower defect counts, with very few staff reporting more than 4 defects. This shift reflects the effectiveness of the training program and the RFID system in enhancing quality control processes, reducing human error, and standardizing inspection procedures.

Step 2: Collect the total scores for each topic to evaluate the outcomes after the training (Table 5 - Table 7).

Table 5. Summary of Employee Satisfaction Levels After Training.

Level	Number of Employees	Total Score
5	36	180
4	28	112
3	10	30
2	6	12
1	0	0

Table 6. Survey Results on Training Effectiveness.

No.	Survey Question Topic	Total Score (∑x)	Respondents Rated Level 5
1	Work Instruction documents are easy to understand	324	36
2	WI can be practically applied to the job	328	38
3	Training increased confidence in performing tasks	332	40
4	Teamwork became more systematic after training	316	32
5	Able to follow all steps completely	308	30

Step 3: Calculate the average score and percentage using the following formulas (Figure 10):

- Average score = ∑x ÷ Number of respondents
- Percentage of Level 5 responses = (Number of respondents who selected level 5 ÷ 80) × 100

Table 7. Average Scores and Level 5 Satisfaction Percentages.

No.	Average	Percentage of Level 5 responses (%)
1	324 ÷ 80 = 4.05	(36 ÷ 80) × 100 = 45.0%
2	328 ÷ 80 = 4.10	(38 ÷ 80) × 100 = 47.5%
3	332 ÷ 80 = 4.15	(40 ÷ 80) × 100 = 50.0%
4	316 ÷ 80 = 3.95	(32 ÷ 80) × 100 = 40.0%
5	308 ÷ 80 = 3.85	(30 ÷ 80) × 100 = 37.5%

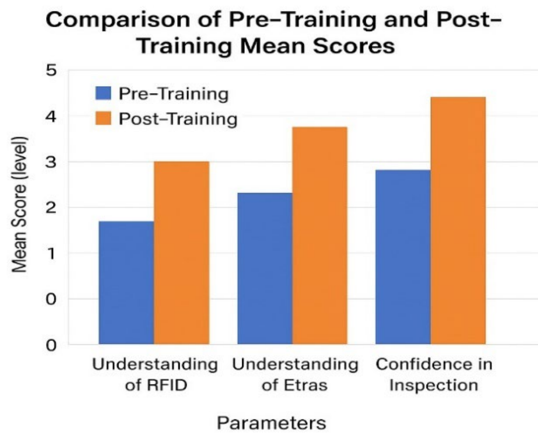


Figure 10. A comparison graph of scores before and after training.

5.3 Control

Training results were recorded in the system to support technical evaluation of the Paperless Data Entry Solution. The summary includes the actual devices used by employees, such as tablets and RFID scanners. An analysis of employee training status revealed that 41% are currently undergoing training, 11% have not yet been trained, and 33% are confidently using the system. Training sessions are scheduled every six months to enhance skills and reduce data entry errors (Figure 11).

Figure 11. Training Status Overview of QC Staff: Completed vs. Pending

5.4 Limitations

While the study offers strong evidence of improvement, it is limited to a single EV manufacturing site with a sample of 80 QC staff. The findings may not fully represent broader industry conditions, and external factors such as supplier variability and system compatibility were not explored in depth.

6. Conclusion

This study set out to answer two key research questions: RQ1: How does the implementation of the RFID–Etras system affect inspection efficiency and defect reduction in electric vehicle (EV) manufacturing? RQ2: What is the impact of Work Instruction (WI)-based training on QC staff performance, accuracy, and satisfaction?
The findings clearly demonstrate that integrating RFID technology with the Etras ERP system significantly improves inspection efficiency and traceability. The average defect count per employee dropped from 19.5 to 2.5, which represents a reduction of approximately 87.18% in inspection errors. This percentage was calculated using the formula:

$$\frac{19.5 - 2.5}{19.5} \times 100 = 87.18\%$$

This sharp decline confirms that the digitalized system effectively minimizes human error and streamlines the quality control process.

In response to RQ2, the structured WI-based training leads to measurable improvements in employee performance and satisfaction. Post-training survey results show high average scores across all topics, with 50% of respondents rating their confidence in inspection at Level 5. The training also enhances teamwork, practical application of WI, and adherence to procedures, as reflected in average scores ranging from 3.85 to 4.15.
Together, these results validate the proposed smart QC framework as a scalable and effective solution for digitalized quality assurance in EV manufacturing. The integration of RFID–Etras with structured training not only reduces defects and inspection time but also empowers the workforce with greater accuracy and confidence.

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