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End-to-End Automation and Optimization of Assembly Line for Climate Control Units in Automotive Industry †

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Abstract

This paper explores the role of automation in the production of climate control units for the automotive industry, emphasizing the latest technological advancements and optimization strategies. Automation has become a key factor in enhancing production efficiency, reducing costs, and ensuring high-quality output. The article also delves into the principles of automated assembly lines, which leverage robots and smart technologies for faster, more precise operations. Additionally, robotic manipulators have revolutionized the handling of delicate components, ensuring high accuracy and minimizing human error.

Keywords: automation; climate control units; automotive industry; robotic arms; production optimization

1. Introduction

The automotive industry has been undergoing a transformation with the rapid integration of automation technologies, aimed at improving efficiency, precision, and productivity in manufacturing processes. One critical area where automation is having a significant impact is in the production of climate control units, which are essential for ensuring passenger comfort in modern vehicles.

This article focuses on the design, optimization, and automation of an assembly line dedicated to climate control units within the automotive sector. It explores how advanced automation systems can streamline the entire production process, reduce human error, and enhance overall production efficiency. By providing a detailed process flowchart of both the traditional and fully automated assembly lines, this paper will demonstrate the improvements that automation brings to the production of climate control units. The optimization of the assembly line through automation will be thoroughly examined, highlighting innovative methods for achieving faster production times while maintaining product quality.

2. Product Overview and Assembly Line Process Flowchart

This section explores the climate control unit, detailing its key elements and technical specifications. The automatic air conditioning panel control unit is a vital component in modern vehicles, significantly contributing to both passenger comfort and energy efficiency. Designed for a wide range of vehicle models, including the VW Golf 7, Seat Leon, Skoda Kodiak, and many others, this unit integrates advanced features that ensure optimal performance and sustainability.

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Additionally, this article presents a comprehensive process flowchart of the current assembly line, outlining the various stages involved in the production of the climate control units. It identifies critical areas within this process where automation can be integrated to drive substantial improvements in efficiency, consistency, and overall production quality. Through a detailed analysis of these stages, this article emphasizes the potential benefits of automation, such as reducing human error, optimizing resource utilization, and increasing production throughput.

2.1. Device Components and Technical Specifications

Featuring advanced technologies such as two-zone Climatronic systems, energy-efficient climate control, and compatibility with the automatic start–stop feature, the climate control unit not only provides superior comfort but also supports the vehicle's overall fuel efficiency and sustainability efforts. These sophisticated systems ensure a balance between performance, comfort, and environmental impact, meeting the growing demands of both automotive manufacturers and consumers. Figure 1 illustrates the climate control device [1].



Figure 1. Climate control unit.

2.2. BOM (Bill of Materials) for Climate Control Unit Assembly Line

Table 1 presents an overview of the primary components involved in the assembly of a vehicle climate control device. The unit, designed for both precision and durability, integrates electronic, mechanical, and structural elements to ensure optimal performance in a vehicle's HVAC system.

Table 1. BOM for climate control unit.

Component	Material	Function	Quantity/Unit
Housing	ABS Plastic/Polycarbonate	Outer casing that holds all internal components and provides structure to the unit.	1
Cover	Polycarbonate/ABS	Protective outer cover for the control panel, providing a durable, sleek surface for user interaction.	1
PCB (Printed Circuit Board)	FR4	Serves as the platform for all electronic components and wiring, enabling the functionality of the climate control unit.	1
Climate Sensor (ITOS)	Semiconductor, Plastic Casing	Measures the interior temperature of the vehicle cabin to provide feedback for the HVAC system.	1
Expanding Rivets	Plastic	Used to secure various components within the housing, ensuring a tight and reliable assembly.	Varies by design
Screws	Stainless Steel or Zinc-Plated	Fasten and secure different parts of the assembly, including the housing, cover, and PCB to maintain structural integrity.	Varies by design

2.3. Process Flowchart of the Assembly Line

The FMS (Flexible Manufacturing System) lines are designed to streamline and enhance the production process, incorporating advanced technologies to ensure high-quality output. One critical component of this system is the SMT (Surface–Mount Technology)

reflow process, which is used to mount components onto the PCB (Printed Circuit Board). This information is provided for a clearer understanding of the entire manufacturing process, helping to illustrate how each stage contributes to the final product. Following the SMT reflow process, a series of carefully coordinated stages in the assembly line ensures that each product is built with precision and efficiency. A process flowchart illustrating the various stages of the assembly line is presented below (Figure 2). This visual representation helps to clearly understand each step involved, from initial testing to final product validation.

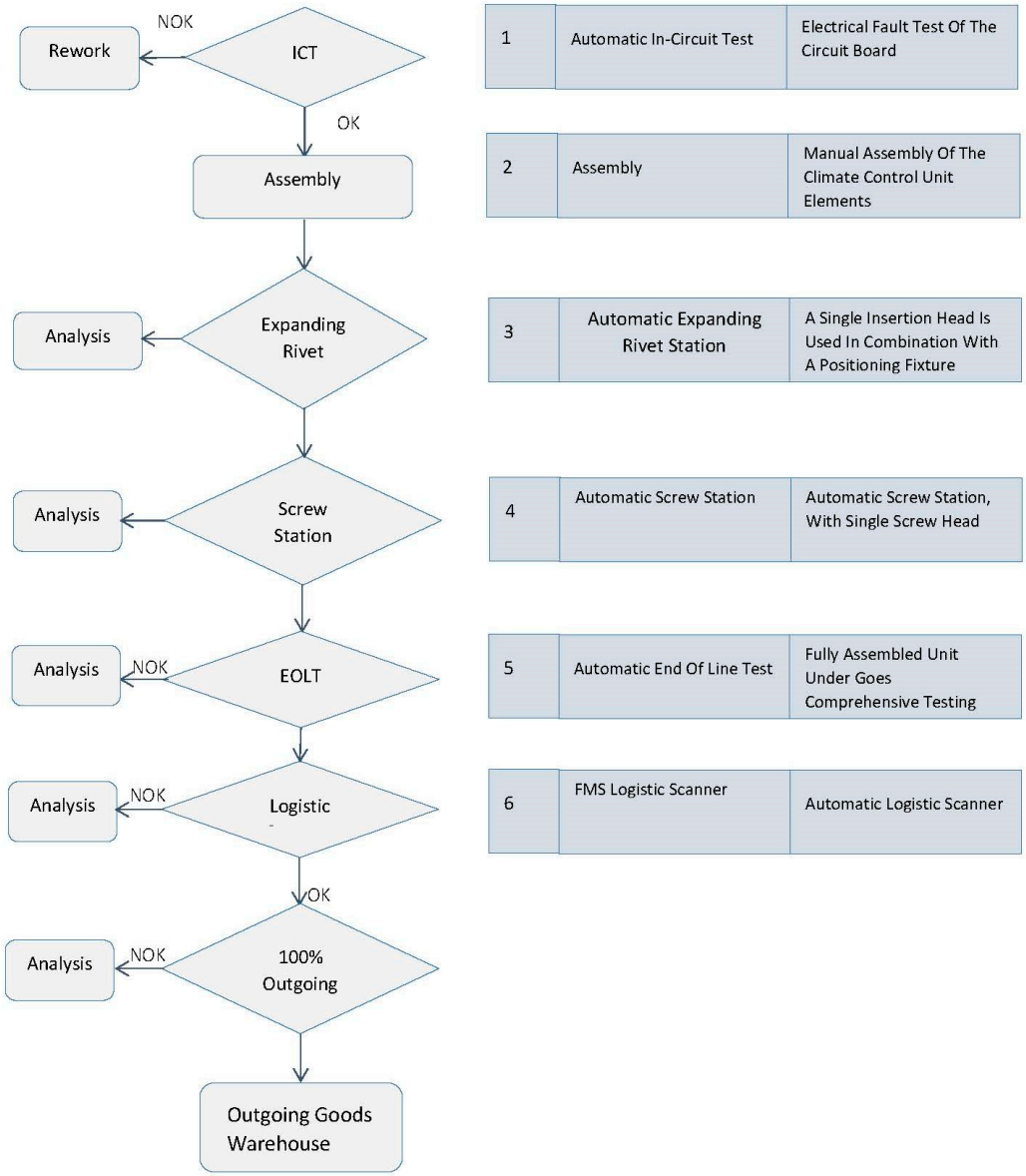


Figure 2. Process flowchart of the assembly line.

The assembly line begins with the ICT (In-Circuit Test) for the PCB. This stage ensures that the PCB is free from electrical faults before moving forward in the process. Once the PCB passes the ICT test, the assembly of the PCB, cover, housing, and sensor is carried out. Skilled operators, ensuring careful handling and precise fitting of components, perform this task manually.

Next comes the Expanding Rivet Station, where rivets are inserted to secure components or parts together, providing added strength and stability to the assembly. The Screw Station follows, where screws are applied to tighten the assembly and ensure a secure fit for

the components. Finally, the line reaches the EOLT (End-of-Line Test), where the finished product undergoes rigorous testing to verify functionality, quality, and safety before it is approved for shipment. If the unit successfully completes EOLT, an identification label is printed and affixed automatically.

3. Advanced Automation Systems in Assembly Line

The traditional manual assembly line has limitations in terms of consistency, speed, and labour costs. This paper explores the potential of integrating advanced robotic arms to overcome these challenges. By leveraging robotics, it is possible to streamline the production process, reduce human error, and enhance the ability to produce climate control units that meet the highest standards of quality.

This part aims to identify the types of robotic arms that are most suited for optimizing the assembly line in the production of climate control units.

Based on research and the specific requirements of the assembly line, we have identified several categories of robotic arms that align with the needs for the quality of the product [2,3]. These types were selected for their capabilities in improving efficiency, precision, and flexibility in the production of climate control units. Above are the robotic arm types considered for our optimized assembly process, presented in Table 2.

Table 2. Selection of robotic arm types.

Robotic Arm Type	Description	Key Advantages	Optimal Applications
6-Axis Robotic Arms	Highly versatile with precise movements in multiple directions.	Provides flexibility to rotate, adjust, and position components with high accuracy.	Complex tasks like assembling components such as covers, PCBs, and housings.
Delta Robots (Parallel Robots)	Designed for high-speed, high-precision tasks, ideal for lightweight components.	High-speed picking and placing with minimal compromise on accuracy.	Lightweight parts such as PCBs and small electronic components.
SCARA Robots (Selective Compliance Assembly Robot Arm)	Ideal for high-speed, high-precision pick-and-place operations, especially for repetitive tasks.	Fast, accurate, and reliable for tasks requiring consistent alignment in straight or circular motions.	Component placement, screw driving, and tasks requiring precision in linear or circular motion.
Automated Guided Vehicles (AGV) with Robotic Arms	Integrates mobility with robotic arms, transporting components while performing assembly tasks.	Increased flexibility and mobility, reduces manual handling, enhances productivity.	Transporting components and performing assembly tasks between stations on the assembly line.

After thoroughly evaluating various robotic arm types, two specific categories were identified as the most suitable for automating the assembly line of the climate control units. The selection was made based on critical factors such as precision, flexibility, and speed, which are essential for meeting the high standards of the climate control unit assembly process.

3.1. 6-Axis Robotic Arms: A Versatile Solution for Complex Assembly Tasks

The 6-axis robotic arm is known for its exceptional versatility and precision, making it an ideal choice for tasks requiring intricate movements. These robotic arms offer a combination of horizontal and vertical flexibility, allowing them to navigate complex assembly operations with ease. Their ability to move in multiple axes provides the necessary freedom for precise component placement, which is crucial when handling components such as PCBs, covers, and housings. The integration of a 6-axis arm into the assembly line enables seamless movements, from placing and aligning components to performing insertions and adjustments in various orientations.

One of the primary advantages of 6-axis robotic arms (Figure 3) lies in their adaptability to different component sizes, shapes, and orientations [4].

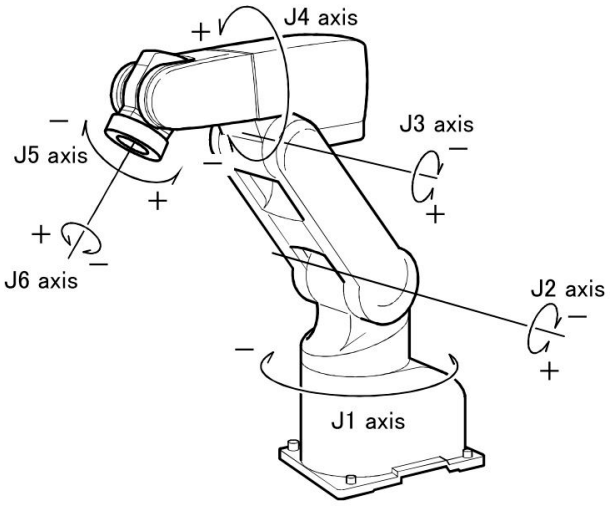


Figure 3. 6-axis robotic arm.

Whether handling delicate electronics like PCBs or larger components such as covers and housings, these robots are equipped to perform high-precision tasks while ensuring minimal risk of error or damage to sensitive parts. The flexibility provided by the multi-axis design allows for handling a wide range of assembly needs, making the 6-axis arm an ideal option for complex and high-precision assembly tasks within the climate control unit production process.

3.2. SCARA Robots: Speed and Precision for High-Volume Assembly

On the other hand, SCARA robots are particularly well suited for high-speed, repetitive tasks that demand precise placement and consistent performance. These robots excel at tasks such as component insertion, screw driving, and assembly of lightweight parts like the cover and PCB. SCARA arms are designed with a configuration that prioritizes fast lateral movements, making them ideal for pick-and-place operations, where speed and accuracy are paramount. The arm's ability to move in a controlled and precise manner allows it to perform repetitive operations with minimal variance, ensuring high throughput and consistent product quality.

The SCARA robotic arm is a perfect fit for high-volume production lines, where the need for speed without compromising quality is crucial. Its design enables quick component placements with a high degree of precision, ensuring that parts like PCBs and housings are assembled correctly and securely. SCARA robots also have the advantage of being easy to program and integrate into the assembly line, making them an effective solution for repetitive tasks that require consistent accuracy and rapid execution.

3.3. Model Selection for SCARA and 6-Axis Robotic Arms

After identifying SCARA and 6-axis robotic arms as the most suitable types for automating the climate control unit assembly process, the next step involves selecting specific models within each category. The models (Tables 3 and 4) under consideration were chosen based on key performance metrics, including reach, repeatability, speed, and special features [5].

Table 3. SCARA robots—model comparison.

Model	Reach	Repeatability	Speed	Manufacturer	City	Country
FANUC SR-3iA	400 mm	±0.01 mm	Up to 7000 mm/s	FANUC Corporation	Oshino-mura	Japan
Yaskawa SG650	650 mm	±0.01 mm	Very fast (cycle-optimized)	Yaskawa Electric Corporation	Kitakyushu	Japan
Omron i4L SCARA	450 mm	±0.01 mm	Up to 8500 mm/s	Omron Corporation	Kyoto	Japan

Table 4. 6-axis robotic arms—model comparison.

Model	Reach	Repeatability	Speed	Manufacturer	City	Country
Universal Robots UR5e	850 mm	±0.03 mm	Up to 1 m/s (collaborative safe speed)	Universal Robots A/S	Odense	Denmark
FANUC M-10iD/12	1441 mm	±0.02 mm	High-speed industrial	FANUC Corporation	Oshino-mura	Japan
KUKA KR 6 R700 Agilus	706 mm	±0.03 mm	Extremely fast (short cycle time)	KUKA Robotics	Augsburg	Germany

The different models were presented in Figures 4 and 5 [6–8].

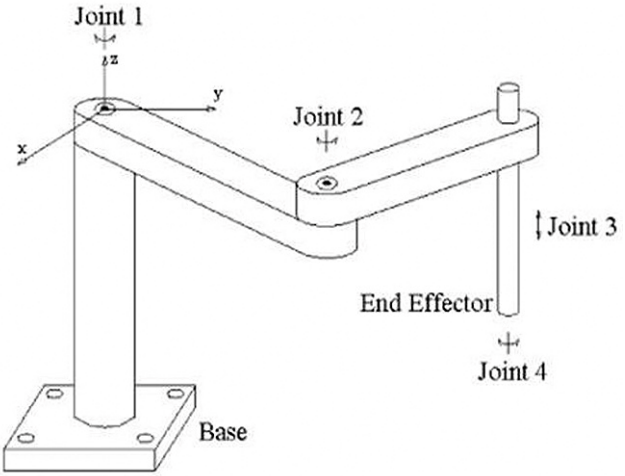


Figure 4. SCARA robot.



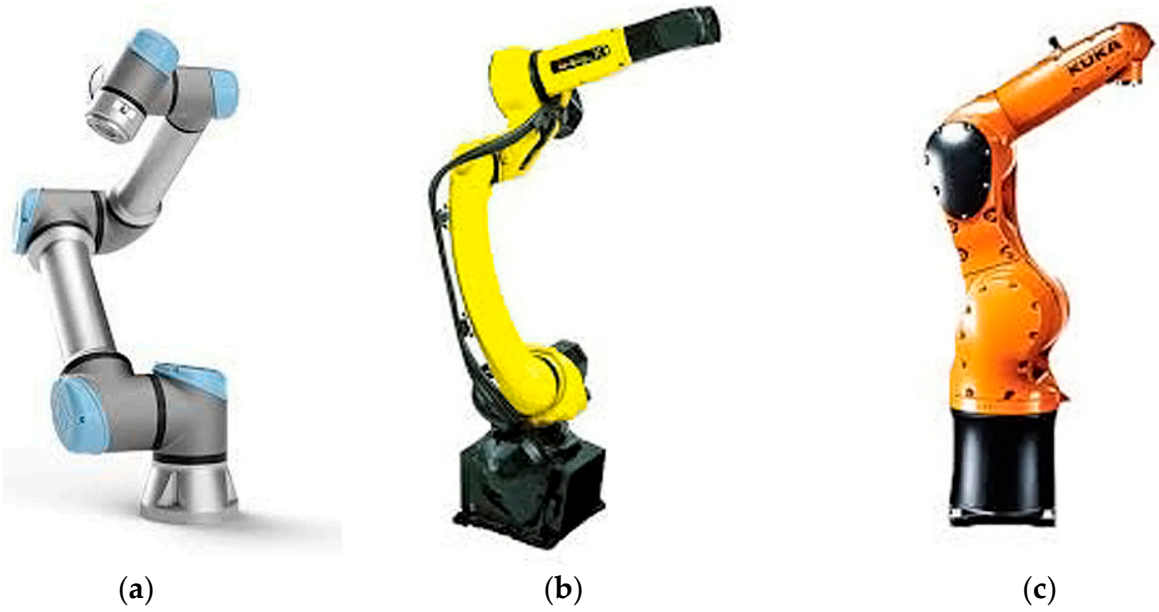
(**a**) (**b**) (**c**)

Figure 5. SCARA robot models: (**a**) FANUC SR-3iA; (**b**) Yaskawa SG650; (**c**) Omron i4L SCARA.

Following a comprehensive evaluation of robotic arm models suitable for automating the assembly of climate control units, two remarkable solutions have been identified. These models not only demonstrate exceptional performance in high-throughput environments

but also offer the adaptability needed to handle varying product configurations and assembly tasks. Their compact design and efficient range of motion make them well suited for integration into existing production lines without significant reconfiguration [6,9,10].

The Omron i4L SCARA has been identified as the optimal solution for the specified tasks. Designed for space-constrained environments, the i4L features a compact footprint, making it highly suitable for integration into existing work cells. Additionally, it comes equipped with EtherCAT connectivity and built-in diagnostic tools, facilitating seamless integration with automation systems and simplifying maintenance and monitoring tasks. These features collectively make the Omron i4L SCARA an ideal choice for improving speed and consistency on the assembly line while maintaining a high level of quality control (Figure 6).



(**a**) (**b**) (**c**)

Figure 6. 6-axis robotic arm models: (**a**) Universal Robots UR5e; (**b**) FANUC M-10iD/12; (**c**) KUKA KR 6 R700 Agilus.

As a flexible and collaborative alternative, the Universal Robots UR5e presents a strong solution for the assembly process. Its six degrees of freedom allow it to operate in scenarios where more than basic lateral or vertical motion is required. Moreover, one of the UR5e's key strengths is its user-friendly interface and low-code programming environment, allowing for fast deployment and easy reprogramming. This makes it especially useful in dynamic production settings where the process may evolve over time or require frequent adjustments.

After conducting research on various robotic arms, two models were selected as the most suitable solutions for optimizing and automating the presented Flexible Manufacturing System line. In the second stage of the process, robotic arm was implemented for the assembly of the PCB, cover, and housing components. This assembly is carried out automatically using the Universal Robots UR5e or the Omron i4L SCARA robots, ensuring precise alignment and gentle handling of each part.

Figure 7 illustrates the fully automated end-to-end assembly line used in the manufacturing process of climate control units.

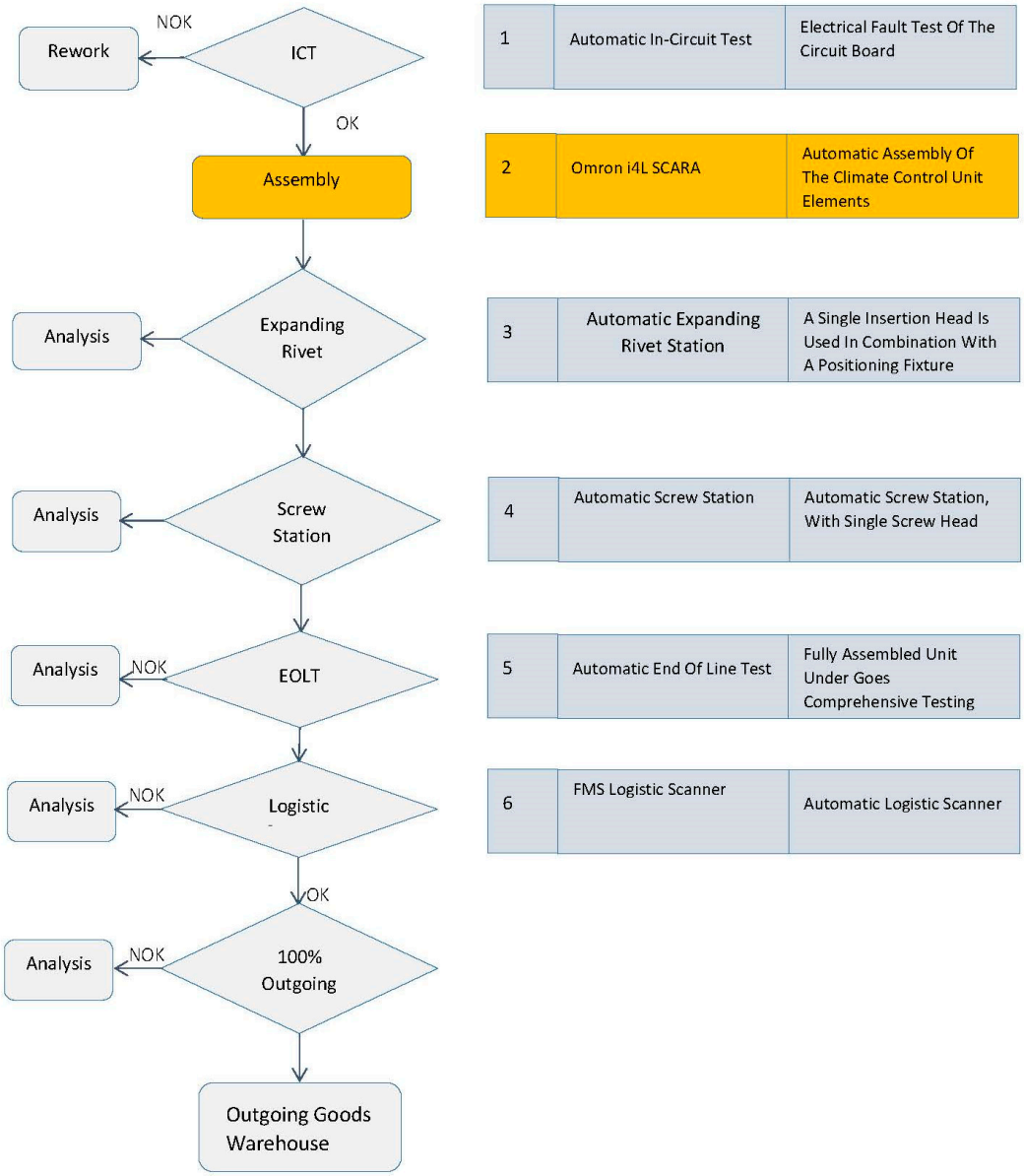


Figure 7. Process Flowchart of the fully automated assembly line.

4. Conclusions

In conclusion, after a comprehensive evaluation of potential robotic solutions for the climate control unit assembly line, the Omron i4L SCARA has been identified as the most suitable choice for assembling the PCB, cover, and housing components. While the Universal Robots UR5e offers impressive flexibility and collaborative capabilities, the i4L SCARA stands out for its compact design, high-speed performance, and ease of system integration.

Designed specifically for space-constrained environments, the i4L SCARA's small footprint enables seamless incorporation into existing work cells without requiring extensive reconfiguration. Its built-in EtherCAT connectivity and diagnostic tools simplify integration, monitoring, and maintenance—contributing to reduced downtime and enhanced system reliability. Moreover, its precision and repeatability make it exceptionally well suited for high-volume assembly tasks where speed and accuracy are paramount.

By selecting the Omron i4L SCARA, the assembly line benefits from a cost-effective, high-throughput automation solution that meets current operational demands while supporting long-term scalability. This strategic decision enhances production consistency and

efficiency, positioning the manufacturing system for sustainable, intelligent growth in an increasingly competitive landscape.

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Abbreviations

The following abbreviations are used in this manuscript:

FMS	Flexible Manufacturing System
ICT	In-Circuit Test
EOLT	End-of-Line Test
BOM	Bill of Materials
PCB	Printed Circuit Board
HVAC	Heating, Ventilation, and Air Conditioning

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