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IMPLEMENTATION OF INDUSTRY 4.0 IN THE AUTOMOTIVE INDUSTRY ACCORDING TO ISO 16949

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Abstract: This paper examines the implementation of Industry 4.0 elements in enhancing the quality of cables and connectors in the automotive industry, with a focus on meeting ISO 16949 requirements. Modern quality control solutions are presented, including smart sensors, digital twins, and predictive analytics. Special emphasis is placed on multi-stage testing methods and process digitalization for quality monitoring. Through a case study from the company Leoni, the impact of QRQC, Q4.0, and Q-Loop systems on defect reduction in the production of BMW components is analyzed. The paper demonstrates how the integration of Industry 4.0 technologies enhances reliability, efficiency, and compliance with automotive industry standards.

Keywords: automotive industry, Industry 4.0, quality control, predictive analytics, SPC, ISO 16949, connectors, cables.

1. INTRODUCTION

Electrical and electronic systems are increasingly attracting the attention of customers in the highly demanding automotive market. A modern car represents a complex technological system, where the transfer of energy and information is considered one of the most reliable subsystems and assemblies. Essential electrical cables and connectors form the foundation of such advanced electronic systems in next-generation vehicles, industrial

machines, and devices, ensuring stable transmission of energy and data between various components. Their technical design and reliability directly affect the safety and functionality of the entire system, making quality control in this segment crucial.

With the growing implementation of electric drive systems and the development of autonomous technologies, wiring systems are becoming increasingly complex, which further complicates fault detection and raises the risk of serious consequences, from reduced

performance to complete system failure. Traditional approaches, which primarily rely on technical trials, electrical and electronic tests, manual inspections, and statistical process control, are no longer sufficient to detect all deviations in the finished product that occur during production. In this context, Industry 4.0 elements bring new possibilities through automated inspection, digitalized control, artificial intelligence, and predictive analytics, enabling timely error detection and a more stable production process.

This paper analyzes the application of Industry 4.0 technologies in the company Leoni and the ways in which they contribute to improving the quality of cables and connectors for the automotive industry.

2. SHORT ANALYSIS OF THE CABLE INDUSTRY

Recent research and industrial practice indicate the increasing application of multi-stage testing methods for wiring harnesses to ensure their reliability under real operating conditions. These methods include visual inspection, continuity testing, insulation resistance measurement, dielectric strength testing, and mechanical testing under simulated extreme conditions such as high temperatures, vibrations, and humidity. Critical tests such as the High Voltage Test, Insulation Resistance Test, and Functional Testing [1] enable the detection of hidden defects that manual inspections often cannot identify.



Figure 1. Multifunctional wiring harness with circular and rectangular connectors

Although traditional testing methods are still present, they rely heavily on human

involvement and are therefore prone to errors. On the other hand, modern automated systems increase the accuracy and repeatability of measurements, contributing to a higher level of quality and reduced production losses.

Parallel to the development of testing methods, modern industry is increasingly integrating the principles of Industry 4.0 into its quality control processes. By using technologies such as the Internet of Things (IoT), Artificial Intelligence (AI), Big Data, and Digital Twins, it becomes possible to monitor and analyze key production parameters in real time [2]. Smart sensors record data and automatically send alerts in case of deviations, while predictive analytics enables error prevention before they even occur.

This approach is based on the concept of Cyber-Physical Systems (CPS), which represents the foundation of smart manufacturing within Industry 4.0. According to Lee, Bagheri, and Kao (2015), CPS enables the integration of the physical and digital worlds through continuous data collection, processing, and real-time analysis, ensuring full process control and improved product quality [7].

Modern testing systems also employ specialized software tools, such as LabVIEW for managing testing stations, Q-DAS for statistical process control, and ANSYS for simulating cable and connector load conditions. These tools allow for integrated data analysis and efficient process optimization.

Among the most commonly used tools in practice are:

- **SPC (Statistical Process Control)** – for real-time variation monitoring,
- **6S methodology** – for workplace organization and waste elimination,
- **7-Point Measurement Method** – ensuring quality control across all critical stages of production [1][5],
- Additionally, systems such as **ASP (Automated Smart Processing)** enable early detection of irregularities and significantly improve quality in cable and connector production [2].

- For example, the company **Leoni**, a supplier for **BMW**, uses automated testing stations for wiring harnesses that transmit real-time data to a central system. These data are analyzed using AI algorithms to predict potential issues and optimize the process, ensuring high precision and reduced waste.

2.1 Types of Connectors in the Automotive Industry

Connectors in the automotive industry are classified according to various criteria, one of the most common being the housing shape – circular and rectangular – depending on technical requirements and specific areas of application.



Figure 2. Circular Connectors

Circular Connectors

Circular connectors, such as M12, M23, and D38999 (MIL-standard), are used for power and signal transmission in demanding conditions due to their resistance to moisture, vibrations, and mechanical stress. For example, the M12 connector with a metal housing and rubber seal is commonly used in industrial machinery and vehicles where high reliability and resistance to external factors are required.

Rectangular connectors, such as D-sub, Fakra, and Amphenol AT06, are widely used in electronics and the automotive industry. Due to easier integration, modularity, and reliability, they are often employed for communication modules, infotainment systems, power connections, and safety components.

Besides the basic classification by shape, connectors also differ by function and performance:

- **High-speed connectors** – designed for fast data transmission,
- **High-voltage connectors** – used in high-voltage systems,

- **Waterproof connectors** – for components exposed to external influences (moisture, dust).

Modern trends include miniaturization, modular design, and the use of environmentally friendly materials, in compliance with REACH and RoHS directives.



Figure 3. Rectangular Connector



Figure 4. Rectangular Automotive Fakra Connector

The selection of connectors directly affects product design, connection reliability, assembly quality, and the applied control methods. Connectors must comply with the requirements of vehicle manufacturers (OEMs) and international standards, particularly ISO 16949 [3], which defines the quality management system requirements in the automotive industry.

3. BRIEF PROBLEM DESCRIPTION

One of the key challenges in modern cable and connector manufacturing is the timely detection of defects before the product reaches the final assembly stage. In high-volume production environments, such as in the case of the company Leoni, traditional control methods, which rely on manual inspection, are often insufficient to detect deviations such as incorrect lengths, weak connections, or improperly formed contacts. The lack of real-time automated monitoring further complicates the maintenance of stable quality and increases the risk of customer complaints and additional costs [4].

The development of electric and smart vehicles adds further complexity, as the increased intricacy of electrical circuits demands greater precision and reliability of cable systems. In this context, the traditional

“wire-to-wire” connection system is being replaced by the concept of “one wire – multiple functions” [5], which saves space, reduces the number of components, and increases the overall efficiency of the system.



Figure 5 Example of a Standard Wire Harness with Multiple Connectors (RCCN)

Figure 5 shows a wire harness with multiple types of connectors, commonly used in automotive and industrial production. These harnesses enable the connection of various functional systems, including power supply, signaling, and communication. Their reliability largely depends on the quality of the connections as well as adequate protection from external influences such as moisture, dust, and mechanical wear.

Modern technological advancements in the automotive industry are placing increasing demands on the manufacturing process of wire harnesses and connectors. To ensure system reliability, it is essential to carefully select input materials by strict internal and international standards, such as ISO 16949, as well as specific performance requirements for automotive applications. Special attention is given to the properties of the materials used – their resistance to heat, moisture, chemicals, and mechanical stress – both in standard and extreme operating conditions.

In addition to proper material selection, every stage of the production process must be subjected to strict and multilayered control, both process-based and physical, in compliance with ISO 16949 requirements. Without a systematic and digitalized approach to quality management, it is difficult to meet the challenges posed by intelligent vehicle systems and the high expectations of end users.

4. PROPOSED SOLUTIONS

In response to the challenges of modern manufacturing, companies are implementing integrated quality control strategies that combine multi-level testing, digitalization, and automation. The process begins with CAD simulation, the selection of high-quality materials, and precise production by the ISO 16949 standard. Quality is ensured through multiple stages of electrical, mechanical, and environmental testing, as well as final visual inspection. Software tools for automatic data collection enable real-time process monitoring, deviation detection, and fast decision-making. Systems such as digital twins and SPC (Statistical Process Control) tools allow for the simulation of production conditions and defect prevention.

In the production of connectors for BMW, Statistical Process Control (SPC) plays a key role, enabling continuous monitoring of the stability of dimensional and functional characteristics of the product. By using control charts and Cp/Cpk analysis, processes can be timely adjusted to ensure compliance with ISO 16949 requirements.

Table 1. Key Parameters of SPC Quality Control for Connectors

Parameter	Measuring Device	Control Chart	Response to Deviations
Housing dimension	Modern optical CMM	$\bar{X}$ -R chart	Tool calibration, line stoppage
Insertion force	Force tester	$\bar{X}$ -R chart	Die replacement, press inspection
Electrical resistance	4-point ohmmeter	P chart	Contact cleaning, batch recall
Cp/Cpk process value	SPC software	Cp/Cpk monitoring	Process analysis, corrective actions

In addition to SPC, the 7 Point Method also plays an important role, covering all key stages – from incoming material inspection to final process analysis. This combination of methods

provides a comprehensive approach to quality and reduces the risk of defective products.

Qin, Liu, and Grosvenor (2016) emphasize that such an approach enables more flexible and intelligent production flows that can quickly adapt to changes in market demands and quality standards [8].

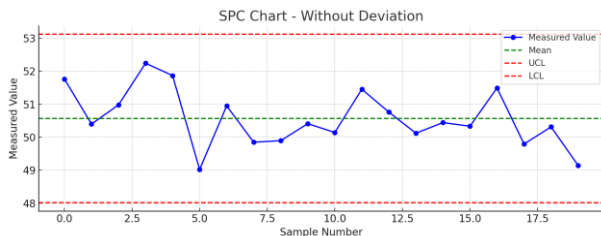


Figure 6. Change in Force Outside Control Limits

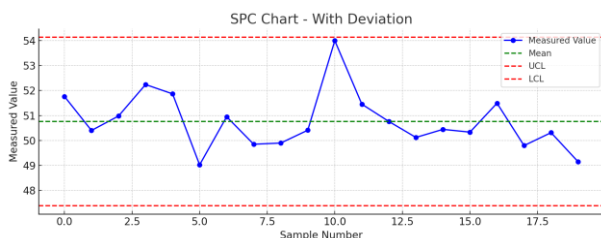


Figure 7. Force Within Control Limits

In the presented SPC charts (Figures 6 and 7), the monitored parameter is the connector insertion force, which is one of the most critical indicators of connection reliability. The insertion force is measured using specialized force testers under real production conditions, and the results are displayed on $\bar{X}$ -R control charts. When values remain within the control limits (LCL and UCL), the process is considered stable, whereas any deviation—as shown in Figure 6—requires immediate analysis and corrective action.

Additional methods for improving quality control include:

- Automatic scanning and digitalization of components using systems such as InspecVision Planar 2D and RPS Measuring Arms.
- Software support through High QA Inspection Manager for complete traceability and rapid response.
- Surface and contour analysis using Waveline and Formline systems.
- Intelligent crimping systems with real-time automatic correction.

- Use of digital twins and predictive analytics for process optimization and defect prevention.

This approach ensures a high level of quality and reliability, meeting the strict requirements of the automotive industry and ensuring compliance with international standards, including ISO 16949.

Table 2. Seven Critical Quality Control Points

Control Point	What Is Checked	Response to Deviations
1. Incoming material inspection	Quality of plastic and metal	Supplier replacement, material rejection
2. Dimensional control	Length, width, tolerances	Tool correction, process stoppage
3. Insertion force control	Minimum and maximum insertion force	Connector rejection
4. Electrical testing	Continuity, resistance	Batch blocking, additional analysis
5. Visual and surface inspection	Damage, roughness, contamination	Cleaning, tool replacement
6. Functional fit test	Connection with matching components	Batch recall, corrective actions
7. Final SPC analysis	Cp, Cpk, process stability	Parameter adjustment, process optimization

4.1. Case study: LEONI – implementation of industry 4.0 in quality control

Leoni Wiring Systems represents a successful example of Industry 4.0 implementation in the field of quality control for cables and connectors used in BMW vehicles. Through its *Zero Defect Mindset* strategy, the company has introduced automated and digitalized systems that enable early defect detection and rapid response, thereby increasing production stability and reliability.

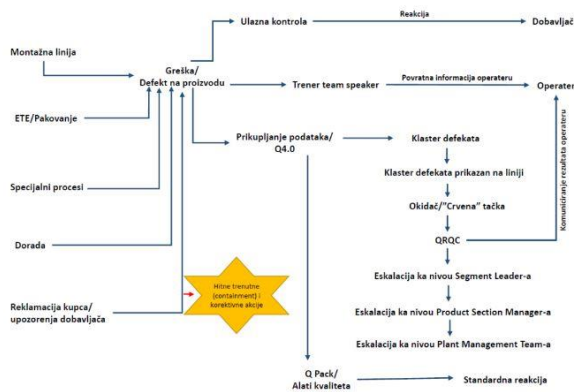


Figure 8. Flow of quality issue escalation and corrective actions in Leoni – Industry 4.0 application

Figure 8 illustrates the escalation flow of quality issues within Leoni's Industry 4.0 framework, starting from incoming inspection and supplier reaction, continuing through defect detection on the line and data collection via Q4.0, all the way to QRQC activation and corrective actions. Reischauer (2018) further points out that the concept of Industry 4.0 is increasingly used not only as a technological framework but also as a strategic tool for institutionalizing innovation systems within manufacturing organizations [9]. This role of Industry 4.0 as a strategic factor is reflected in how companies like Leoni manage quality by modern requirements.

Leoni employs three key methods for quality management:

- **QRQC (Quick Response Quality Control)** – enables rapid defect resolution directly on the production line, including root cause analysis (5Why), implementation of corrective actions, and full traceability;
- **Q-Loop** – a seven-phase cycle covering the entire process from planning to continuous improvement, incorporating SPC software, CMM measurements, and digital twins;
- **5Why & 2How analysis** – used to identify the root cause of problems and define preventive and verification measures.

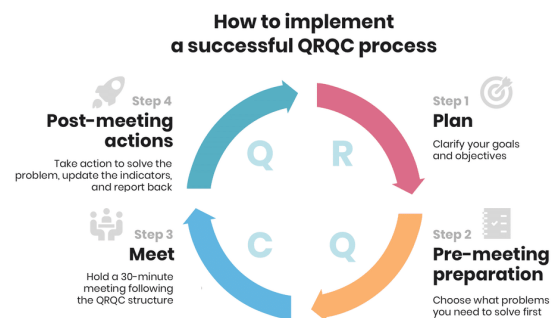


Figure 9. Four-step method for rapid quality problem resolution

As shown in Figure 9, the company applies a four-step method for rapid quality problem resolution, beginning with defect identification and escalating toward management-level intervention.

The quality system at Leoni includes central databases (QDE and SE Masterdata) that enable full traceability of connectors. The assembly process is digitally controlled, and each component undergoes electrical, mechanical, environmental, and visual testing. Regular QRQC meetings ensure continuous improvement, while deeper analyses utilize tools such as PDCA, FTA, 8D, and A3.

The implementation of Industry 4.0 has brought:

- a reduction in defect rates and increased product reliability,
- faster decision-making and automated quality analysis,
- Improved collaboration with BMW and a stronger market position.

To OEM specifications and offer nearly identical dimensions and functionality as original products from well-known brands (Molex, TE Connectivity, Delphi, Deutsch), but at lower cost and with significantly shorter lead times.

Alternative connectors provide greater flexibility in the supply chain and cost reduction without compromising quality, provided that they meet all technical and certification requirements (e.g., ISO 16949). Although there may be technical limitations in certain specialized cases, their use is increasingly common in the industry, especially when a

rapid response is needed in case of original component shortages. [3]

5. CONCLUSION

The implementation of Industry 4.0 in the automotive industry, specifically in the production of electrical cables and connectors for BMW, represents a significant advancement toward improving the quality, reliability, and efficiency of manufacturing processes. Through the integration of advanced technologies such as smart sensors, digital twins, predictive analytics, and Statistical Process Control (SPC), the company Leoni successfully applies digitalization principles to achieve a high level of automation and precision.

The QRQC and Q-Loop methodologies enable rapid response to defects and thorough analysis, minimizing the likelihood of recurring issues and reducing the number of defective products. By establishing the digitalized Q4.0 system, Leoni ensures complete traceability and control over every segment of production, contributing to compliance with the stringent requirements of ISO 16949 standards and the expectations of prestigious customers like BMW.

The results confirm that Industry 4.0 is not only a technological but also a strategic key to achieving zero defect tolerance and long-term competitiveness in the automotive industry. This work can serve as a foundation for applying similar approaches in other sectors with complex manufacturing processes.

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