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ENHANCING QUALITY ASSURANCE THROUGH AUTONOMOUS POKA-YOKE SYSTEMS IN INDUSTRY 5.0 ENVIRONMENTS

Abstract: *This study analyzes the integration of poka-yoke systems within the concept of Industry 5.0, where human-machine collaboration and intelligent autonomous systems play a key role. Poka-yoke, traditionally used to prevent errors at the source, is evolving into advanced, adaptive mechanisms supported by artificial intelligence (AI) and machine learning. This integration enables real-time process monitoring and predictive failure prevention, allowing poka-yoke to dynamically adapt to changing production conditions and demanding manufacturing environments. The analysis includes case studies that illustrate poka-yoke applications in smart factories, emphasizing proactive quality control, flexibility, and sustainability. Challenges related to implementing poka-yoke in Industry 5.0, such as technology interoperability, data security, and employee training needs, are also addressed. Findings indicate that poka-yoke in Industry 5.0 contributes to defect reduction, enhances product reliability, and supports the development of sustainable production systems aligned with modern standards of quality and efficiency.*

Keywords: *poka-yoke, industry 5.0, quality management, artificial intelligence, machine learning, automation*

1. Introduction

The evolution from Industry 4.0 to Industry 5.0 marks a transformative shift, focusing not only on advanced automation and digital integration but also on the harmonization between human creativity and machine intelligence (Alrabadi et al., 2023; Colim et al., 2021). Within this context, the poka-yoke principle—long recognized as a cornerstone for error prevention and quality assurance—adapts to new paradigms by integrating autonomous, intelligent systems. Unlike the automation focus of Industry 4.0, which emphasizes IoT devices, real-time analytics, and predictive AI-driven models, Industry 5.0 introduces collaborative systems where human insight and adaptive technology work in tandem to ensure optimal quality outcomes (El Makrini et al., 2019; Grabowska et al., 2022).

In Industry 5.0 environments, poka-yoke systems advance by the use of autonomous, AI-empowered mechanisms that not only detect and correct errors but also dynamically learn and adapt based on evolving production scenarios. This autonomy, combined with AI and machine learning, allows for predictive, preemptive quality management, enabling systems to anticipate deviations and mitigate risks proactively (Jokovic et al., 2023). Furthermore, human-machine collaboration

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in this context enhances poka-yoke by embedding real-time insights and data-driven adjustments that align quality management with flexibility and resilience—key attributes of modern, intelligent production ecosystems (Khan et al., 2024).

This study explores how autonomous poka-yoke systems are applied within the framework of Industry 5.0, examining how they contribute to a proactive and adaptive quality assurance model that leverages the latest advancements in AI, machine learning, and human-centric design principles (Mattsson et al., 2023; Żywiołek, 2024). Through this approach, we aim to showcase how industry stakeholders can benefit from integrating poka-yoke mechanisms in ways that enhance product reliability, minimize errors, and align with the sustainable and human-centered values of Industry 5.0.

2. The basics of Poka-Yoka approach

Poka-yoke, originating from Japanese, translates to "mistake-proofing" or "error prevention." It is an approach employed in various industries to eliminate or minimize errors in processes. It is possible by designing systems that prevent mistakes or make them immediately detectable. The concept of poka-yoke is based on the premise that human errors are inevitable, but their impact can be effectively minimized through intelligent design. By incorporating safeguards and intuitive mechanisms into production processes, companies can reduce the occurrence and impact of errors, which enhances quality, efficiency, and customer satisfaction (Cimini et al., 2020; Iftikhar et al., 2024).

Poka-yoke techniques encompass a wide range of solutions—from simple visual cues to advanced technological safety systems. Basic poka-yoke forms may rely on color coding, shape differentiation, or labeling, enabling operators to quickly identify the correct components or steps in a process, reducing the risk of errors (Gualtieri et al., 2021; Hinrichsen & Bendzioch, 2018). In more advanced applications, physical constraints or specialized mechanisms are implemented to prevent improper actions, ensuring that processes unfold as required.

In the automotive industry, where poka-yoke is widely applied, assembly lines are equipped with sensors and devices that detect deviations from standard procedures. This enables operators to be promptly alerted to rectify any errors. Such an approach not only improves product quality but also enhances operational efficiency by minimizing the need for rework (Singh et al., 2023), towards sustainability.

Poka-yoke aligns closely with the philosophy of lean manufacturing, which emphasizes waste elimination and process optimization. Unlike traditional quality control methods that focus on detecting errors at the end of production, poka-yoke promotes error prevention at the source. This approach allows organizations to reduce the likelihood of defects and foster a culture of responsibility and attention to detail among employees. In this way, its commitment to continuous improvement and reduction of defects is reinforced (Antony et al., 2023; El Zaatari et al., 2019) where Customer Satisfaction is important.

With the development of automation and Industry 4.0 technologies, poka-yoke has evolved to leverage advanced tools such as the Internet of Things (IoT), sensors, and real-time data analytics. Automation systems designed with built-in error-proofing mechanisms allow tasks to be executed with high precision and consistency, minimizing the risk of human error. Robots equipped with sensors can navigate complex production processes with great accuracy, ensuring smooth workflow. Additionally, the interconnected data networks of Industry 4.0 enable better communication and coordination across the entire production ecosystem, allowing for a comprehensive poka-yoke strategy that spans the entire value chain (Hussain et al., 2024).

As industry moves toward Industry 5.0, which emphasizes human-machine collaboration, poka-yoke takes the form of autonomous systems that not only detect and correct errors but also adapt to changing production scenarios. Integrating artificial intelligence and machine learning enables poka-yoke systems to predict potential issues and eliminate them before they impact product quality (Kartali et al., 2019; Khan et al., 2023). This shift from preventive to predictive quality management creates new opportunities for companies to adjust their poka-yoke strategies to dynamic production conditions, while highlighting the role of technological innovation in creating reliable, flexible, and highly efficient production systems. Poka-yoke in Industry 4.0 and 5.0 conditions is not just a tool for eliminating errors but also a quality management strategy that evolves alongside technological advancements. The integration of error-proofing mechanisms with advanced technologies allows companies to create production systems that are resilient, adaptive, and highly efficient. By applying poka-yoke, organizations can enhance product reliability, increase customer satisfaction, and strengthen their competitive position in the dynamic industrial market (Kim et al., 2019). Table 1 lists the main critical factors that link poka-yoke to Industry 5.0.

Table 1. Critical factors link poka-yoke to Industry 5.0

Key principle	Description
Elimination of Defects at Source	In Industry 5.0, poka-yoke aims to prevent errors at their origin, fostering a proactive approach that aligns with human-centered manufacturing by reducing the need for error detection later in the process.
Simplicity and Usability	Poka-yoke systems in Industry 5.0 should remain user-friendly, especially as collaborative roles between humans and intelligent machines expand. Simplicity ensures that both human operators and AI-driven systems can operate poka-yoke tools effectively.
Autonomous Error Correction	With the integration of autonomous systems, poka-yoke in Industry 5.0 can rely on fail-safe mechanisms where machines automatically correct errors. This minimizes human intervention and aligns with the autonomy goal of Industry 5.0.
Immediate Feedback and Alerts	In the collaborative environments of Industry 5.0, providing real-time feedback through alarms or visual indicators supports the human role in quality assurance, allowing operators to quickly address errors alongside machine-led corrections.
Predictive, Preventive Design	Leveraging AI and machine learning, Industry 5.0 enhances poka-yoke by embedding anticipatory designs that use data to predict potential issues and prevent errors, leading to smarter, adaptive error-proofing systems.
Source Inspection and Real-Time Monitoring	Industry 5.0 emphasizes real-time quality control at the source, using IoT and sensors for constant monitoring, which aligns with poka-yoke's principle of early-stage error detection.
100% Inspection and Verification	Complete inspection in Industry 5.0 is possible with advanced AI algorithms and robotics that verify each step of production, ensuring that defective products are identified instantly.
Jidoka (Autonomation)	Industry 5.0's vision for autonomous systems extends the jidoka concept by allowing machines to detect and halt processes when a defect occurs, supporting immediate quality control
Continuous Improvement through Learning Systems	Continuous improvement in Industry 5.0 is supported by poka-yoke systems that adapt based on data feedback, aligning with self-optimizing processes.
Enhanced Operator Training and Support	With Industry 5.0, human-centric poka-yoke emphasizes operator training in tandem with advanced technology use, ensuring human operators can effectively manage and interact with automated poka-yoke systems

Source: (Antony et al., 2023; Botti et al., 2022; Bousdekis et al., 2023; Brun & Wioland, 2021; Gajdzik & Wolniak, 2022; Jonek-Kowalska & Wolniak, 2021; Khourshed & Gohar, 2023)

2. How the Poka-Yoke Method Can Be Integrated with Industry 4.0 and Quality 5.0 Concepts - results

The transition to Industry 5.0 brings a new dimension to manufacturing, where technology and human-centered values merge to create intelligent, adaptive, and collaborative production systems. Industry 5.0 emphasizes not only advanced automation but also a close synergy between human creativity and machine precision, promoting sustainable, resilient, and highly customized production environments (Burggräf et al., 2019; Hopko et al., 2021; Pervaz et al., 2024). This is also the way to improve the economy of countries, namely with better industry.

This human-centric approach aligns naturally with poka-yoke principles, which focus on preventing errors at their source through simple, intuitive design, further enhanced by intelligent, self-correcting mechanisms.

In Industry 5.0, poka-yoke systems benefit from integration with AI, robotics, and real-time data, allowing for dynamic collaboration between human operators and machines. Advanced sensors, Internet of Things (IoT) devices, and data analytics enable poka-yoke mechanisms to instantly detect deviations and alert operators or initiate automated corrective actions. By learning from past errors, AI and machine learning algorithms embedded in poka-yoke systems allow continuous adaptation to changing production conditions, leading to smarter, anticipatory quality management systems (Iftikhar et al., 2024; Liau & Ryu, 2020; Sureshchandar, 2023).

The concept of Quality 5.0 complements this integration by broadening poka-yoke's impact beyond the manufacturing floor to encompass the entire value chain, including supply chain, logistics, and customer interaction. This comprehensive approach fosters a holistic view of quality that leverages poka-yoke for mistake-proofing across diverse touchpoints, ensuring consistent quality and minimizing error at every step (Savković et al., 2022). Additionally, the data generated from these interconnected systems provide a valuable feedback loop, enabling poka-yoke strategies to be continuously refined based on real-time insights, fostering a culture of continuous improvement and resilience within organizations.

By integrating poka-yoke with the frameworks of Industry 5.0 and Quality 5.0, manufacturers can achieve proactive, adaptive error prevention that enhances both product quality and system agility, positioning them to thrive in an era where the boundaries between human expertise and machine intelligence become increasingly seamless (Antony et al., 2023; Bousdekis et al., 2023). Table 2 presents examples of integrating the poka-yoke method with Industry 5.0. These aspects collectively contribute to the evolution of poka-yoke within Industry 5.0, fostering a human-centered and intelligent approach to error prevention and quality management, enhanced by collaborative technologies and adaptive systems.

Table 3 shows the main problems of Poka-Yoke integration with industry 5.0

Table 2. Poka-Yoka integration with industry 5.0

Aspect	Description
Synergy between Humans and Machines	Industry 5.0 focuses on harmonious collaboration between humans and machines, incorporating values like creativity, personalization, and sustainability. Through poka-yoke, intuitive support systems for operators can be designed to minimize operational errors. Examples include smart user interfaces and augmented reality (AR), which provide operators with guidance on the next steps in processes, enabling more effective interaction with automation systems and reducing the risk of errors (Grabowska et al., 2022).

Customization of Error Prevention Systems	Industry 5.0 emphasizes tailoring technology to the individual needs of users. Using machine learning, poka-yoke can adjust operational functions to the skill level of the operator, supporting task personalization and increasing efficiency. This approach makes poka-yoke in Industry 5.0 more flexible, adapting to changing requirements and user experience levels (Botti et al., 2014; Bousdekis et al., 2023).
Predictive Error Prevention	Industry 5.0 leverages artificial intelligence (AI) algorithms to predict potential problems in processes. The poka-yoke method can utilize predictive analytics to prevent errors before they occur. By analyzing real-time data, poka-yoke systems can identify anomalies and proactively adjust their operation, which is key to preventive quality management (Bousdekis et al., 2023; Gualtieri et al., 2020).
Automated Process Stopping (Jidoka)	In the context of Industry 5.0, jidoka—automation with human oversight—plays a critical role. Integrating poka-yoke with jidoka allows for automatic stopping of the production process in case of an error, enabling immediate human intervention. This approach minimizes losses resulting from defective production and makes quality control more reliable (Jonek-Kowalska & Wolniak, 2021).
Extending Poka-Yoke across the Supply Chain	In Industry 5.0, poka-yoke extends beyond production to encompass the entire supply chain. With IoT technology, poka-yoke can monitor stages of production, logistics, and distribution, preventing errors at every stage. Integrated poka-yoke ensures consistency and quality along the entire product journey from supplier to customer (Romero et al., 2022).
Using Data Analytics for Continuous Improvement	By applying data analytics and big data in Industry 5.0, poka-yoke can dynamically adapt based on historical operational data. Machine learning systems enable the identification of root causes of errors and optimization of preventive measures, creating a culture of continuous improvement (Antony et al., 2023; Escobar et al., 2024).
Predictive Maintenance	Predictive maintenance, supported by IoT and data analysis, plays an important role in Industry 5.0, where poka-yoke helps in predicting and preventing machine failures before they impact production. This prevents downtime, increasing efficiency and reliability of production processes (Luttmer et al., 2024; Psarommatis et al., 2022).
Employee Training and Competence Development	Industry 5.0 emphasizes the importance of employee skill development in collaborating with intelligent systems. Poka-yoke can be integrated with training programs that help employees understand the importance of error prevention systems and effectively use advanced technology. Education is a foundation for the successful adaptation of poka-yoke in environments based on human-machine collaboration (Narkhede et al., 2023).

Table 3. The problems of Poka-Yoka integration with industry 5.0

Problem	Description
Complexity of Implementation and Costs	Integrating advanced technologies such as artificial intelligence (AI), the Internet of Things (IoT), and cyber-physical systems can be costly and complex. Implementing poka-yoke with automation and predictive elements requires significant financial investments and collaboration between technological and operational departments. Companies often need to modernize infrastructure and provide additional training for employees, leading to high initial costs (Antony et al., 2023; Gajdzik & Wolniak, 2022).
Interoperability Issues	Many companies still rely on legacy systems that can be challenging to integrate with modern Industry 5.0 technologies. Achieving interoperability between poka-yoke systems and other production systems, such as ERP (Enterprise Resource Planning) and SCM (Supply Chain Management), can be problematic. The lack of unified standards and communication protocols may lead to errors, data incompatibility, and issues with information flow (Bousdekis et al., 2023; Escobar et al., 2024).
Data Security and Privacy	Industry 5.0, based on continuous data exchange, generates large volumes of sensitive information that may be vulnerable to cyber-attacks. Integrating poka-yoke with IoT and AI increases the risk of data breaches, requiring additional safeguards like encryption, access authorization, and regular security audits. Maintaining a high level of security is crucial to prevent data leaks and ensure trust among employees and customers (Jonek-Kowalska & Wolniak, 2021; Leng et al., 2023).

Skills Gaps and the Need for Employee Training	Introducing advanced poka-yoke technologies in Industry 5.0 requires skilled employees capable of operating and maintaining these systems. Skills gaps can slow down the implementation process and increase the risk of errors when handling new technologies. Companies need to invest in training and skill development to ensure that employees can effectively use poka-yoke in an Industry 5.0 context (Antony et al., 2023; Martini et al., 2024; Mentzas et al., 2024).
Balancing Automation with the Human Factor	Industry 5.0 emphasizes close human-machine collaboration, which can be challenging in the context of poka-yoke. Excessive automation may limit the role of human operators, potentially reducing their engagement and sense of responsibility for quality. Achieving the right balance between machine autonomy and human oversight is essential to maintain human values and creativity while benefiting from automation (Colim et al., 2021; Grabowska et al., 2022).
Change Management and Organizational Adaptation	Implementing poka-yoke in Industry 5.0 requires organizational change, which may be met with resistance from employees and management. Companies need to effectively manage the change process, educate teams on the benefits of new technologies, and motivate employees to actively participate in the implementation (Cherubini et al., 2016; Gualtieri et al., 2021).

Table 3 outlines the challenges of implementing the poka-yoke approach in Industry 5.0 and strategies to address them. Effectively overcoming these issues requires a holistic approach that integrates advanced technologies, organizational adaptability, and strong change management. By proactively addressing these challenges, organizations can fully leverage the benefits of integrating poka-yoke with Industry 5.0's human-centered and intelligent manufacturing systems.

3. Poka-yoka and indutry 5.0 – study case

1) Toyota – Human-Centric Error Prevention in Assembly Lines

Toyota, long known for its commitment to quality and lean manufacturing principles, has adopted poka-yoke in innovative ways that align with Industry 5.0's emphasis on human-machine collaboration. In their assembly lines, Toyota integrates poka-yoke principles through collaborative robots (cobots) that assist human workers in precision tasks, such as assembling complex components. These cobots are equipped with sensors and AI algorithms that monitor real-time data and identify potential deviations from standard processes.

For example, if a component is misaligned or placed incorrectly, the cobot stops and alerts the human operator, allowing them to correct the error before the assembly moves to the next stage. This human-centric poka-yoke approach enables Toyota to maintain high-quality standards while supporting workers through automation, minimizing fatigue and reducing the risk of repetitive stress injuries. By enabling cobots to "learn" from past errors, Toyota's poka-yoke system continually improves its accuracy in error detection, enhancing the safety and efficiency of the production line.

2) Bosch – Predictive Maintenance with AI-Driven Poka-Yoke

Bosch leverages poka-yoke in Industry 5.0 by integrating it with predictive maintenance systems across their manufacturing plants, focusing on avoiding machinery-related errors before they occur. In traditional settings, poka-yoke would be applied to prevent operator errors; however, Bosch extends this concept to machinery, utilizing IoT sensors and AI algorithms to monitor equipment conditions such as vibration, temperature, and pressure.

When these sensors detect readings outside the normal range, the poka-yoke system sends alerts to maintenance teams, allowing them to take preemptive action before a failure disrupts production. For example, if abnormal vibrations indicate a potential bearing failure, the poka-yoke system will either slow down or stop the machine, preventing further damage and minimizing downtime. This predictive poka-yoke application not only ensures higher equipment reliability and product consistency but also supports Bosch's commitment to sustainability by reducing waste from unexpected breakdowns. This system exemplifies Industry 5.0's proactive approach to quality and maintenance, where machines work "intelligently" to prevent issues in collaboration with human oversight.

3) Siemens – Augmented Reality for Quality Assurance and Error Prevention

Siemens integrates poka-yoke with augmented reality (AR) to enhance quality assurance in complex assembly tasks, making it easier for operators to avoid errors and ensure precision. In Siemens' manufacturing lines for products such as industrial turbines and medical devices, AR systems display real-time, step-by-step instructions to guide operators through each stage of assembly. These instructions are visualized through AR headsets or screens, providing an immersive experience that enhances worker focus and accuracy.

The AR system can detect when an operator deviates from the prescribed sequence or selects an incorrect part, immediately issuing an alert or providing corrective feedback. This poka-yoke solution not only reduces the risk of assembly errors but also accelerates the training process for new employees by offering on-the-job guidance, even for complex tasks. Siemens' AR-enabled poka-yoke aligns with Industry 5.0's focus on empowering human workers with advanced technology, ensuring a high standard of quality while supporting workers' skills and efficiency.

4) BMW – Customized Poka-Yoke for Individualized Production

BMW has adapted poka-yoke to support mass customization in its production lines, which is central to Industry 5.0's human-centric and flexible manufacturing approach. In BMW's production environment, poka-yoke mechanisms are integrated with AI and machine learning to handle varying product configurations and customer-specific customization. For each unique vehicle, poka-yoke settings are automatically adjusted in real time based on data from previous production processes.

For instance, if a vehicle model requires a unique combination of parts or specific assembly sequences, the poka-yoke system customizes its parameters to ensure the correct parts are used and assembled in the proper order. Should a deviation occur, the system immediately stops the process and alerts the operator, allowing them to make necessary adjustments. This intelligent poka-yoke application not only maintains BMW's commitment to quality but also allows the company to fulfill customized orders efficiently, aligning with the Industry 5.0 vision of personalized, high-quality manufacturing.

5) Procter & Gamble (P&G) – Smart Packaging Lines with Poka-Yoke and IoT

Procter & Gamble (P&G) utilizes poka-yoke in its smart packaging lines, leveraging IoT and AI to ensure high-quality packaging standards and prevent defects. In these smart lines, poka-yoke is integrated with IoT-enabled quality checks that monitor critical aspects of packaging, such as seal integrity, label accuracy, and fill levels. Sensors placed along the packaging line verify each step, and if discrepancies are detected—such as an incorrect label or insufficient fill—the system stops the process and alerts operators to correct the error.

For example, in cases where a product package is sealed improperly, the poka-yoke system identifies the defect, and the package is redirected for re-sealing or quality checks. This application not only minimizes waste but also ensures that each product meets P&G's strict quality standards, reducing the risk of recalls and enhancing customer satisfaction. Through this poka-yoke integration, P&G aligns with Industry 5.0's sustainability and quality objectives, where intelligent systems support both quality control and waste reduction.

These examples illustrate how poka-yoke has evolved to meet Industry 5.0’s demands, enhancing collaboration between human operators and intelligent systems, ensuring product customization, and using real-time data to maintain consistent quality across manufacturing processes.

4. Conclusion

The integration of poka-yoke with Industry 5.0 represents a transformative shift in error prevention and quality management, expanding upon the technological advancements of Industry 4.0 by incorporating a strong emphasis on human-centered design and collaboration. In Industry 5.0, poka-yoke not only leverages smart technologies—such as sensors, IoT, AI, and data analytics—but also focuses on enhancing the synergy between human operators and intelligent systems. This integration allows for real-time error detection, proactive prevention, and continuous improvement, fostering an environment where human insight and machine intelligence work in harmony.

Industry 5.0 builds on poka-yoke's foundational principles of eliminating errors at the source, with additional emphasis on customization, adaptability, and sustainability. Through predictive analytics and machine learning, poka-yoke systems in Industry 5.0 are capable of learning from historical data and adapting to dynamic production conditions, supporting a proactive approach to quality control that anticipates and addresses potential issues before they arise. Furthermore, the emphasis on human-machine collaboration enables workers to focus on tasks requiring creativity and problem-solving while relying on automated systems for routine, repetitive error-prevention functions.

Key benefits of integrating poka-yoke with Industry 5.0 include increased flexibility in production, enhanced safety and ergonomics, and improved training and support for workers. Real-time feedback, augmented reality (AR), and other assistive technologies create a supportive environment for employees, enabling them to engage more effectively with complex manufacturing processes and contributing to a culture of continuous learning and quality improvement.

However, implementing poka-yoke in Industry 5.0 is not without challenges. Organizations must address issues such as the high initial costs of advanced technologies, data security concerns, and the need for skilled employees capable of operating and maintaining these systems. Achieving interoperability between legacy systems and modern Industry 5.0 technologies also requires careful planning and investment in technological infrastructure and training.

The integration of poka-yoke with Industry 5.0 represents a strategic evolution in manufacturing, where error prevention and quality management become more adaptive, resilient, and human-centered. By combining advanced technology with human expertise, Industry 5.0 and poka-yoke create a foundation for sustainable, flexible, and highly efficient production systems that align with the values of modern industrial production. This integration positions poka-yoke as an essential component in building intelligent, responsive, and quality-focused manufacturing environments in the era of Industry 5.0.

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