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Risk Management Strategy of Automobile Manufacturing Engineering and Its Application in Welding Production

Qu Liang*

Guangqi Honda Automobile Co., Ltd., Guangzhou 510000, Guangdong, China

**Author to whom correspondence should be addressed.*

Abstract: Based on the PDCA cycle model of risk management and ISO31000 standard, this paper constructs the risk management system of automobile manufacturing engineering, expounds the risk characteristics of the automobile manufacturing industry, takes welding production as an example, details the risk management measures from the aspects of innovative identification and evaluation methods, optimization of control strategies, construction of fault early warning system, and points out the limitations of current research, and looks forward to the development direction of real-time risk early warning system based on edge computing.

Keywords: Automotive manufacturing engineering; Welding production; Risk management

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1. Introduction

With the deepening implementation of national strategies such as "Made in China 2025" (2015) and the "14th Five-Year Plan for Intelligent Manufacturing Development" (2021), the automotive manufacturing industry is accelerating its transformation towards intelligence and green development. Its production processes face multiple risks, including high equipment complexity, strict process precision, and long supply chains. As a critical link in automotive manufacturing, welding and assembly exhibit typical risk characteristics such as process sensitivity and strong equipment dependence, necessitating the establishment of a systematic and forward-looking risk management system. Based on the PDCA cycle and ISO31000 standards, this paper constructs a risk management framework applicable to automotive manufacturing engineering, focusing on in-depth research into risk identification, assessment, and control strategies for welding and assembly production. The aim is to enhance the stability of production processes and product quality, thereby promoting the industry's achievement of safe, efficient, and sustainable intelligent manufacturing goals.

2. Theoretical framework of risk management in automobile manufacturing engineering

2.1. Construction of engineering risk management system

The development of a risk management system for automotive manufacturing engineering adopts a systematic and forward-looking approach, adhering to the PDCA cycle model and aligning with the principles and framework established by the ISO 31000 international standard. The system begins with comprehensive risk identification, covering multi-dimensional risk sources such as equipment, processes, and supply chains. It then employs quantitative tools like FMEA for scientific risk assessment and classification. Based on this, targeted control measures are formulated and implemented, including risk mitigation or transfer. Ultimately, continuous monitoring forms a closed-loop management system [1]. This structured process ensures that risk management activities span the entire lifecycle of engineering projects. Its establishment and operation also actively respond to the strategic requirements outlined in the "14th Five-Year Plan for Intelligent Manufacturing Development" (2021) to enhance manufacturing process reliability and safety. It provides a standardized and iterative management foundation for automotive manufacturing engineering, particularly for high-risk processes such as welding and assembly production.

2.2. Analysis of risk characteristics of automobile manufacturing industry

The automotive manufacturing industry exhibits unique risk characteristics. In terms of supply chain management, its complexity is exceptionally high, involving numerous component suppliers. Any disruption in supply, quality issues, or logistical bottlenecks at any stage may impact production schedules and product quality [2]. Process parameter sensitivity also warrants attention. During manufacturing, parameters such as current, voltage, and welding pressure in welding processes can lead to quality defects like insufficient weld strength or poor welds with minor deviations. Additionally, the industry heavily relies on equipment. A malfunction in advanced automated production systems not only halts production but may also trigger chain reactions, causing disruptions in subsequent processes. Particularly in welding operations, equipment failures can easily result in process deviations, leading to quality defects and forming a complex risk transmission chain that severely impacts both quality and efficiency in automotive manufacturing.

3. Risk management strategy construction for welding production

3.1. Innovation in risk identification and assessment methods

In welding production risk management, developing innovative risk identification and assessment methods is crucial. By establishing a welding process risk matrix based on FMEA (Failure Mode and Effects Analysis), potential failure modes, causes, and consequences during welding can be comprehensively analyzed, with risk domains clearly defined [3]. Simultaneously, integrating fuzzy comprehensive evaluation (FCE) with Monte Carlo simulation technology enables quantitative assessment of multi-variable coupled risks. FCE effectively addresses ambiguity and uncertainty in risk evaluation by quantifying qualitative indicators, while Monte Carlo simulation simulates numerous random variables to accurately quantify risk levels by considering complex interdependencies among variables. This approach enhances the scientific rigor and reliability of risk assessment results, providing robust evidence for formulating welding production risk management strategies.

3.2. Optimization design of risk control strategies

To optimize risk control strategies, a multi-faceted approach is required. Establishing a preventive maintenance system involves conducting regular comprehensive inspections and maintenance of welding equipment. By analyzing operational status and historical failure data, key equipment metrics can be visualized and statistically analyzed. Implementing predictive maintenance for equipment vibrations enables early replacement of vulnerable components, thereby reducing the probability of sudden equipment failures [4]. Implementing process parameter tolerance control requires precise setting of parameter ranges. Advanced sensors and monitoring systems collect real-time data, triggering immediate alerts and automatic adjustments when parameters exceed tolerances to ensure stable welding processes. Enhancing emergency response mechanisms involves developing detailed contingency plans for sudden risks like fires and gas leaks, clearly defining emergency procedures and personnel responsibilities. Regular emergency drills should be organized to improve emergency response capabilities. Moreover, combining error prevention devices with human-machine collaboration technology helps prevent operational errors. Through real-time industrial camera monitoring and AI-powered analysis, critical components can be intelligently identified, missing or incorrect installations detected, and defects classified. This approach limits erroneous behaviors while improving operational accuracy and efficiency through human-machine synergy, achieving effective risk control.

4. Implementation path of risk management in welding workshop

4.1. Risk management of process equipment

4.1.1. Welding robot fault early warning system

In the risk management of process equipment in welding workshops, the welding robot fault early warning system plays a vital role. By developing equipment health prediction models based on vibration spectrum analysis and temperature monitoring, predictive maintenance for spot welder electrode wear can be achieved. Vibration spectrum analysis captures subtle vibration changes during robot operation, where different vibration patterns often correlate with potential fault. For instance, abnormal vibrations may indicate mechanical component loosening. Temperature monitoring provides real-time tracking of electrode temperature during operation, as excessive electrode wear can cause abnormal temperature increases. The predictive model built with these two technologies conducts an in-depth analysis of collected data to detect wear trends in spot welder electrodes early. This enables predictive maintenance by replacing electrodes before failure occurs, reducing welding quality issues and robot downtime caused by electrode wear, thereby ensuring continuous and stable production in welding workshops [5].

4.1.2. Application exploration of AI visual inspection in quality control of automotive welding workshop

Quality inspection of components in manufacturing workshops is critical. The welding workshop, in particular, involves numerous specification checks such as part derivation and component specification verification. Historically, these tasks relied heavily on manual identification and traditional automated line inspection, both of which posed significant risks, where manual inspection was inefficient, error-prone, and costly; automated solutions required high customization costs with poor versatility and portability. The high-precision image detection system leveraging visual AI and deep learning technology addresses these challenges. By capturing real-time images through industrial cameras and automatically analyzing them with AI models, the system enables intelligent recognition of critical components, detects missing or incorrect installations, and classifies defects. Upon identifying any errors or omissions, the system instantly triggers alarm alerts on on-site displays and across multiple platforms, ensuring timely resolution. This provides an efficient, low-cost, and intelligent solution for quality inspection, effectively reducing production risks [6].

4.2. Risk control in the production process

4.2.1. Real-time monitoring of process parameters

In the real-time monitoring of process parameters for risk control in welding assembly workshop production, establishing a three-dimensional process control chart integrating welding current, pressure, and time proves crucial. By precisely tracking and recording these key parameters, the data is visually presented through 3D graphics, enabling operators to swiftly identify dynamic changes and interrelationships [7]. Additionally, an online welding quality diagnosis system based on Statistical Process Control (SPC) has been developed. Utilizing IoT platforms to analyze collected welding parameters and fully implementing AI-powered welding models, the system provides real-time quality alerts. When parameters exceed predefined thresholds, the system immediately triggers warnings, alerting operators to potential welding quality risks. This allows timely process adjustments to effectively prevent welding defects caused by parameter anomalies, ensuring production stability and product quality in welding assembly operations.

4.2.2. Intelligent foreign body management system

The risk of foreign objects in the production process of welding workshops can severely impact product quality, making intelligent foreign object control systems crucial. A machine vision-based welding body surface inspection and foreign object removal device has been developed. This device utilizes advanced image recognition technology to accurately capture foreign objects on the body surface. The machine vision system features high resolution and rapid processing capabilities, enabling real-time detection and localization of foreign objects' positions and shapes. On top of that, an integrated pneumatic cleaning mechanism responds swiftly upon detecting foreign objects, automatically removing them through robotic operations to achieve automated defect handling. This intelligent system not only significantly improves the accuracy and efficiency of foreign object detection but also ensures timely processing, preventing subsequent production impacts and effectively reducing product quality risks caused by foreign objects [8].

5. Evolution of risk management in the context of intelligent manufacturing

5.1. Application of digital twin technology

5.1.1. Virtual debugging risk simulation

In automotive manufacturing's welding assembly production, digital twin technology has revolutionized risk management through virtual debugging. By establishing digital twin models of welding assembly lines, manufacturers can accurately simulate real production scenarios and workflows in virtual environments. This enables comprehensive simulation of various process configurations, allowing for effective validation of technical feasibility, including evaluating welding path rationality and assessing whether sequence variations impact product quality. The system also identifies potential interference risks, such as equipment collisions or fixture-workpiece conflicts. Through this virtual risk rehearsal, manufacturers can preemptively address issues, significantly reducing production delays and cost overruns caused by operational risks. This approach has become a critical risk management tool in smart manufacturing environments for welding assembly production [9].

5.1.2. Big data analysis platform development

In automotive welding production within smart manufacturing environments, the development of big data analytics platforms proves essential. By establishing a comprehensive data hub that covers equipment operation, quality inspection, and energy consumption, enterprises can dynamically monitor risk indicators. This platform collects massive datasets from all production stages, employing advanced algorithms to conduct in-depth analysis and accurately identify potential risks. For instance, equipment operation data enables early prediction of failure risks, quality inspection data facilitates timely detection of product defects, while energy consumption data assists in assessing energy risks and optimizing resource utilization. Through big data analytics platforms, companies can perform real-time monitoring and dynamic updates of risk metrics, providing robust support for risk management decisions. This approach enhances the scientific rigor and efficiency of risk management, thereby improving the overall stability and safety of automotive welding production [10].

5.2. Human-machine collaborative risk management

5.2.1. Collaborative work safety protection

In human-machine collaborative operations within automotive welding production, safety protection is paramount. Through safety logic verification and the deployment of protective measures, including safety grilles, zone scanners, and human-shaped camera detection systems. The system can promptly issue warnings and halt automated line operations when personnel approach hazardous areas. Zone scanners utilize light curtain sensors installed in work zones, which immediately cease operation upon detecting any obstruction to prevent injuries. The development of human-shaped camera detection technology enables flexible adjustment of safety zones based on actual production conditions. For instance, during welding operations for different vehicle models, the camera coverage can automatically adapt to changes in workflow and equipment layout. This approach ensures personnel safety without compromising production efficiency, achieving more efficient and safer human-machine collaboration. By effectively reducing safety risks in collaborative operations, it enhances overall safety and stability in automotive welding production.

5.2.2. Optimization of abnormal operating condition management

In the intelligent manufacturing environment of automotive welding production, optimizing abnormal condition handling is critical. Developing an augmented reality-assisted decision-making system serves as a key initiative. This system can analyze fault codes in real-time, leveraging big data analysis and intelligent algorithms to rapidly and accurately match the most suitable handling plan, which is then intelligently pushed to on-site operators. This not only avoids errors and delays caused by manual judgment, improving handling efficiency, but also breaks the spatiotemporal limitations of information transmission. Through paperless electronic smart devices, operators can intuitively access detailed handling procedures and guidance information, as if experts were present on-site. With this system, even complex abnormal conditions can be handled efficiently and accurately, reducing risks such as production delays and quality defects caused by abnormal conditions. It elevates human-machine collaborative risk management to new heights, ensuring stable and efficient automotive welding production.

5.3. Sustainable risk management

5.3.1. Carbon footprint tracking system

In automotive welding production, the carbon footprint tracking system serves as a critical component of sustainability risk management. By establishing a monitoring model for energy consumption and carbon emissions in welding workshops, it enables precise tracking of carbon emissions at each production stage. This model utilizes real-time energy consumption data from various equipment, combined with process parameters, to comprehensively evaluate carbon emissions throughout the entire welding process. Based on the data collected through this monitoring model, green optimization plans for process parameters are developed. For instance, adjusting parameters such as current, voltage, and welding speed of welding equipment can ensure welding quality while reducing energy consumption and thereby minimizing carbon footprints. Such optimization solutions not only help enterprises reduce production costs but also effectively meet environmental requirements, enhancing their competitiveness in sustainable development. This approach provides robust support for achieving sustainability risk management in automotive manufacturing engineering within smart manufacturing environments.

5.3.2. Enhanced supply chain resilience

In the intelligent manufacturing environment of automotive welding production, enhancing supply chain resilience is critical. The multi-level supplier risk assessment model developed using complex network theory can comprehensively and accurately identify and quantify various risks faced by suppliers, including supply disruptions and quality fluctuations. The dynamic adjustment mechanism for resilient supply chains designed based on this model enables rapid and flexible adjustments to supply chain strategies according to real-time risk assessment results. When a supplier encounters supply risks, the mechanism can promptly identify alternative suppliers and optimize logistics routes to ensure stable supply of components required for welding production. Meanwhile, through dynamic monitoring and adjustment of the supply chain, it effectively responds to market demand fluctuations, maintains the continuity and stability of welding production, thereby enhancing supply chain resilience while ensuring the overall efficiency and sustainable development of automotive manufacturing engineering.

6. Conclusion

This study has developed a risk management methodology tailored for automotive manufacturing engineering, with practical case studies from welding workshops demonstrating its effectiveness in enhancing both economic efficiency and product quality. The implemented risk management strategies have significantly optimized production processes and reduced potential losses in welding operations. However, current research still faces limitations, particularly in the depth of intelligent algorithm application, which has not fully unlocked the full potential of AI in risk management. A promising future direction lies in developing real-time risk early-warning systems based on edge computing. By leveraging edge computing technology, it is expected to enable real-time monitoring and early warning of risks during welding processes, thereby improving the timeliness and precision of risk management in automotive manufacturing. This advancement will drive the industry’s transition toward smarter and more efficient production practices.

Disclosure statement

The author declares no conflict of interest.

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