Identification of On-site Safety Hazards and Optimization of Safety Management Systems in Mechanical Manufacturing Workshops

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Abstract

The mechanical manufacturing industry is a foundational sector of the national economy. However, workshop environments are complex and contain numerous hazardous factors, which often result in frequent safety accidents. This paper systematically analyzes the types and causes of hazards in mechanical manufacturing workshops, establishes a methodological framework for hazard identification from three dimensions: intrinsic equipment safety, working environment, and personnel behavior. It further puts forward optimization strategies covering risk early warning mechanisms, human-machine collaborative management models, as well as safety training and safety culture development. The research shows that safety management in mechanical manufacturing workshops needs to shift from "post-incident disposal" to "pre-incident prevention", so as to realize systematic improvement of intrinsic safety levels through accurate hazard identification and optimization of management systems.

Keywords

Mechanical manufacturing workshop, Hidden danger identification, Safety management system, Risk early warning

Introduction

The mechanical manufacturing industry is a core component of the equipment manufacturing sector. Its production processes are characterized by equipment intensiveness, complex operational procedures, and frequent high-risk operations, resulting in a severe safety production situation. In 2025, the total number of production safety accidents in the mechanical industry ranked first in the industrial and trade sector, accounting for 28.1% of the total accidents in that sector. In terms of accident types, mechanical injury, object strike, falling from height, electric shock and other injuries ranked among the top five, accounting for 86.3% of total accidents. Mechanical injury accidents caused by insufficient equipment safety protection accounted for 71.4% of mechanical injury accident cases. Maintenance and repair operation accidents accounted for 21.0% of total accident cases. The number of accidents and fatalities in outsourced units increased by 93.8% and 113.3% year-on-year respectively, and the phenomenon of "substituting management with contracting" has not been fundamentally reversed.

Meanwhile, the widespread application of automated production lines, industrial robots, and intelligent detection equipment has brought new types of safety risks, such as collision risks in human-machine collaboration areas and unexpected startup risks of automated equipment. The traditional safety management model relying mainly on "human watching and human guarding" can no longer meet the safety management needs under the new situation.

The traditional safety management model, which focuses on "post-incident disposal", can hardly fundamentally curb accident occurrences. Modern safety management theory emphasizes "pre-incident prevention", requiring systematic hidden danger identification and management optimization to control risks prior to accidents. This study integrates hidden danger identification methods and management system construction into a unified analytical framework, attempting to build a closed-loop model of "identification - assessment - control - improvement" and provide mechanical manufacturing enterprises with an actionable safety management framework.

Domestic scholars have conducted extensive research on safety management in mechanical manufacturing. Li et al. carried out on-site machine safety assessments in

manufacturing facilities, systematically identified entanglement, crush, nip, and shear hazards, and proposed a strategic framework covering hazard identification, risk assessment, and hierarchical control measures [1]. Xu et al. identified 36 causative factors across human, machine, environmental, and managerial dimensions, and constructed a comprehensive safety management system integrating risk assessment, dual prevention mechanisms, safety training, and emergency preparedness based on System-Theoretic Accident Model and Processes (STAMP) theory [2]. However, most existing research adopts single-dimensional analysis, and studies that organically combine hazard identification methods with management system construction remain relatively insufficient. This study seeks to make progress in the above aspects.

Hidden danger identification methods for mechanical manufacturing workshops

Classification and characteristics of hidden dangers

Hidden dangers in mechanical manufacturing workshops can be systematically classified from four dimensions: "human - machine - environment - management" as shown in Figure 1.

(1) Unsafe equipment conditions

The typical hazards include missing safety guards, interlock failure, equipment aging and wear, and electrical faults. Mechanical equipment is not equipped with essential safety protection devices; for instance, punch presses may lack safety light curtains and rotating parts may have no protective guards. Equipment aging and wear can result in functional failures. Safety interlock devices may be artificially short-circuited or dismantled, while electrical equipment may suffer from insulation degradation and poor grounding. According to the 2025 mechanical industry accident analysis, inadequate safety protection of equipment serves as the leading cause of mechanical injury accidents, accounting for more than 70.0%. Parker et al. conducted on-site inspections of 221 small metal fabrication enterprises and discovered that 33.0% of machines had missing or insufficient point-of-operation safeguards. Widely deployed older machines were far less likely to be properly guarded than new equipment, which indicates that delayed equipment renewal and inadequate maintenance directly contribute to mechanical injury risks [3]. In terms of specific accident categories, mechanical injuries are mainly divided into three types: entanglement and crushing accidents, collision and impact accidents, as well as cutting and stabbing accidents. Dźwiarek and Latała systematically classified injury incidents into contact with rotating components, contact with sharp components, crushing by closing motion, cutting by closing motion, impact by moving components, and trapping by moving components [4]. Their research offers a refined classification framework for hazard identification.

(2) Unsafe acts

The typical hazards include failure to wear PPE, violation of operating rules, inattention and fatigue, and unauthorized disabling of guards. Afata et al. noted that inadequate safety knowledge and weak self-protection awareness among employees often result in inadvertent violations [5]. Many enterprises prioritize short-term production gains and provide only superficial induction training. New employees are assigned to positions without systematic safety education, leaving them incapable of responding appropriately under emergency conditions. Unsafe human behaviors feature randomness and concealment, rendering them the most challenging target for hazard identification.

(3) Adverse operating environment

The typical hazards include noise, dust, insufficient lighting, and blocked passages. Kumar and Deswal systematically reviewed occupational environmental hazards in machining workshops, covering noise, vibration, metal dust, and high-temperature exposures [6]. Poor workshop ventilation causes accumulation of toxic and harmful gases; excessive noise impairs workers' hearing and interferes with on-site communication; dust continuously accumulates in the workplace; inadequate lighting raises operational error probability; disorderly stacked materials block safety passages. Environmental hazards tend to accumulate gradually, are hard to detect in the short run, yet their long-term exposure substantially elevates accident probability.

(4) Management deficiencies

The typical hazards include poor implementation of rules, inadequate training, incomplete emergency plans, and weak accountability. Weichbrodt argued that safety rules in practice often become overly abstract and generic, losing their connection to actual equipment and work conditions. When rules are drafted without sufficient

grounding in site-specific realities, they lack operability, and gaps emerge between formal rule-making and on-site enforcement, leaving employees' violations undetected and uncorrected [7].

Ghahramani and Amirbahmani emphasized that many manufacturing enterprises fail to fully implement the safety responsibility system, while safety training is often perfunctory and formalized. Hazard investigation and remediation activities fail to form closed-loop management, and emergency response plans are compiled without targeted consideration of site hazards [8]. These institutional shortcomings collectively create latent conditions that facilitate the occurrence of occupational accidents.

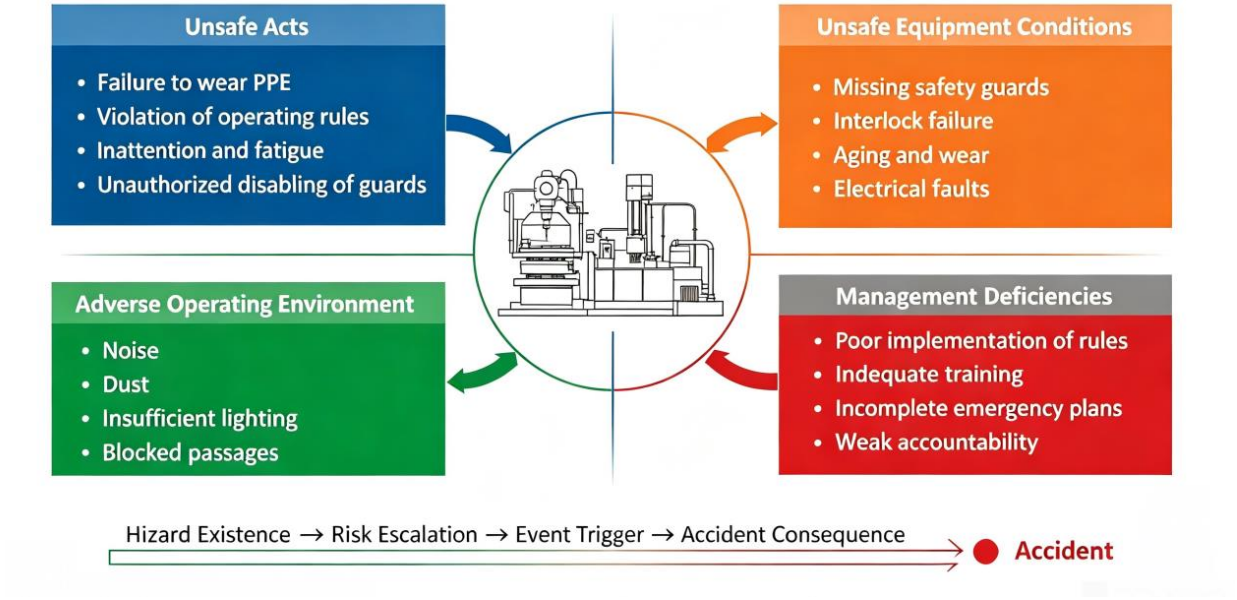

Figure 1. Safety hazard classification in mechanical manufacturing workshops.

Construction of identification methodology system

This study constructs a three-stage identification framework of "data collection - feature extraction - pattern recognition" as shown in Figure 2. In the data collection stage, sensors are deployed to gather real-time equipment operational data covering temperature, vibration, current and other parameters. Personnel behavior data is acquired via video surveillance, and environmental information is captured using gas detectors, noise monitors and other devices. Qingdao has implemented visual management by developing a "four-in-one" checklist that includes four categories and 47 items, namely electrical management, special operations, personal protection, and warning and evacuation, which offers a standardized instrument for hazard identification. In the feature extraction stage, Fault Tree Analysis (FTA), Failure Mode and Effects Analysis (FMEA) and other approaches are adopted to extract key features, and the risk matrix method is applied to categorize risks into four grades: major, relatively major, general, and low. In the pattern recognition stage, extracted features are matched against established hazard patterns. A typical workflow combines "preliminary screening by machines plus manual review". This strategy leverages the efficiency of intelligent systems while preserving professionals' capacity for contextual judgment.

Application of artificial intelligence technology

Intelligent safety control systems adopt smart cameras to monitor workstations around the clock, accurately capturing violations and storing video footage, with warning alerts pushed to the terminals of safety management personnel within seconds. The D6 Lighthouse Factory of Jinan No. 2 Machine Tool Group has established a three-in-one safety barrier integrating physical isolation, intelligent interlocking and digital monitoring, with protective door locks, laser scanning and centimeter-level positioning technology deployed across the site. Once an alarm is activated, equipment in the corresponding area will stop and brake immediately. Since the system was put into operation, the number of warnings has dropped significantly, and unsafe working habits have been gradually rectified. This case illustrates that artificial intelligence technology can not only identify hidden hazards, but also drive improvements in employee behavior through continuous supervision and instant feedback.

Multi-source data fusion mechanism

A single data source is often insufficient to fully reflect

the real status of safety hazards, making multi-source data fusion critical for improving identification accuracy. For instance, if equipment temperature rises abnormally while an operator is detected entering a hazardous area without authorization and ventilation in that area is inadequate, the system should conduct a comprehensive assessment of the risk level. Qingdao encourages enterprises to adopt advanced safety technologies, including intelligent forklift systems, crane laser curtain systems, and gantry crane flexible leg anti-collision and body monitoring systems. These technologies enable multi-source data fusion analysis and intelligent early warning, consolidating fragmented safety information into a unified risk dashboard.

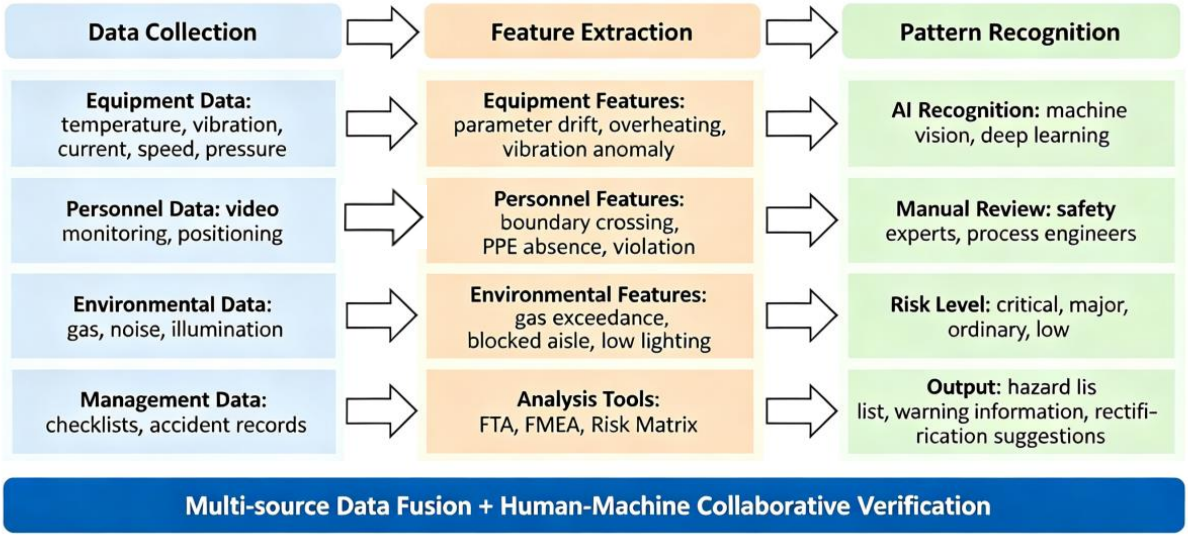

Figure 2. Three-stage hazard identification framework.

Analysis of method limitations

Existing hazard identification methods still have certain limitations. First, artificial intelligence identification systems carry relatively high deployment costs, making comprehensive intelligent transformation unaffordable for small and medium-sized enterprises. Second, video surveillance and sensors have blind spots, and hidden hazards such as internal equipment wear are hard to identify automatically. Personnel's unsafe behaviors are random and concealed, leaving room for improvement in the accuracy of behavior recognition algorithms. Third, these methods lack sufficient capacity to identify management-level hazards, which requires comprehensive assessment combined with management audits, employee interviews and other approaches. Finally, the adoption of new technologies may introduce new types of safety risks, including control system failures of intelligent equipment, abnormal equipment operations triggered by cyberattacks, and collision risks within human-machine collaboration zones.

Safety management optimization strategies for mechanical manufacturing workshops

Analysis of current safety management situation

Current safety management in mechanical manufacturing workshops has the following prominent problems. First, safety management resources are unevenly distributed. Enterprises often concentrate their main efforts on high-risk operation links while neglecting the accumulation of "low-risk" hidden hazards in daily production. Second, safety management for maintenance and repair operations is weak. Maintenance and repair activities are mostly temporary, without pre-formulated safety plans, and the work permit system is not strictly implemented. The 2025 data shows that maintenance and repair operation accidents account for 21.0% of total accident cases. Third, safety control for outsourced operations suffers from the phenomenon of "substituting management with contracting". Contracting units lack sufficient management and oversight in contractors' qualification review, process control, and safety education and training. Fourth, the implementation of safety management systems has become a mere formality. Ekanem pointed out that although many manufacturing enterprises have formally established safety inspection protocols, inspectors often fail to conduct comprehensive, rigorous examinations in accordance with prescribed procedures [9]. Such incomplete inspections leave severe equipment functional failures undetected; these latent defects may eventually trigger mechanical injury

accidents at workplaces.

Design principles for optimization strategies

Safety management optimization should follow four core principles. First, the system follows the "prevention first" principle and establishes a closed-loop mechanism of "risk identification - hidden danger investigation - governance and rectification - effect verification". This approach focuses on source control to proactively defuse potential hazards and reduce accident risks. Second, the system adheres to the "systematic" principle and promotes coordinated advancement across multiple dimensions of system, technology, personnel, and culture. It avoids fragmented safety work and builds a holistic safety framework. Third, the system upholds the "full participation" principle, clarifies safety obligations for all posts, and builds a safety responsibility community spanning management and frontline employees, so every staff member assumes corresponding safety duties. Fourth, the system implements the "continuous improvement" principle and establishes a dynamic assessment and optimization mechanism. Safety measures will be adjusted iteratively according to site changes and inspection results to sustain management effectiveness.

Construction of risk early warning mechanism

A real-time monitoring system is established to continuously capture multi-source data, including equipment operating status, on-site environmental parameters, and personnel behavior. The collected data feeds into the risk assessment module, where hazards are quantified by occurrence likelihood and consequence severity to determine risk levels. Based on assessment outcomes, a graded warning mechanism is deployed: low-level warnings trigger responses from on-site teams, relatively serious warnings are handled by workshop safety supervisors, and critical high-risk warnings activate enterprise-level emergency procedures. Every warning must be assigned to a specific person responsible. A closed-loop disposal framework ensures all alerts complete a full cycle of reception, action, verification and feedback to optimize the monitoring system. This set of sequential procedures forms the integrated risk early-warning mechanism, as illustrated in Figure 3.

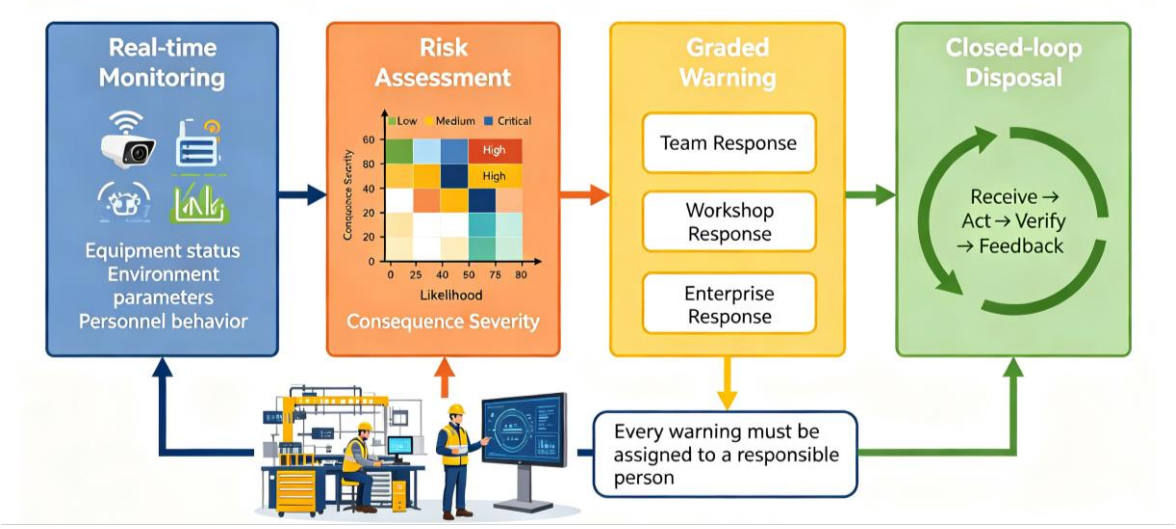

Figure 3. Risk early-warning mechanism.

Human-machine collaborative management model

The ideal model is "system intelligent monitoring + monitoring + manual precise judgment + human-machine joint disposal" (see Figure 4). At the monitoring level, the intelligent system is responsible for all-weather, full-coverage real-time monitoring, compensating for the limitations of manual inspections in time and space. At the judgment level, safety management personnel are responsible for the judgment of warning information and on-site disposal. For complex situations that the system finds difficult to identify, professional personnel's experience and judgment are relied upon. At the disposal level, a human-machine linkage rapid response mechanism is established. After the system issues a warning, it automatically notifies relevant personnel and simultaneously activates the corresponding equipment interlocking or shutdown procedures. Frontline employees are responsible for daily self-inspection and hidden danger reporting, forming a good atmosphere where "everyone is a safety sentinel". Qingdao explores integrating safety production work with "script murder" games, enhancing employees' safety awareness and

emergency response capabilities through immersive experiences. This innovative form is worth learning from.

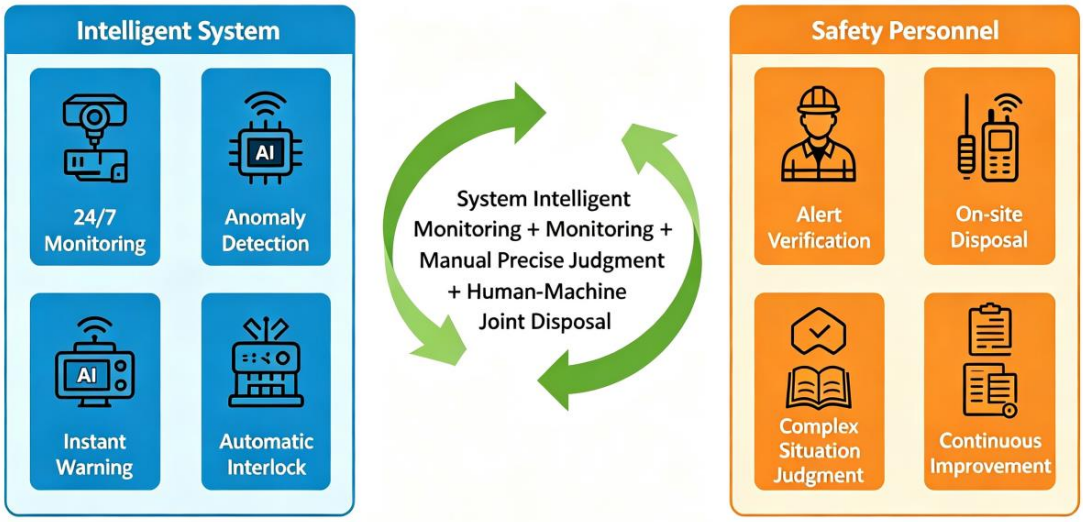

Figure 4. Human-machine collaborative management model.

Safety training and culture development

In terms of training content, the focus should shift from knowledge delivery to competence development, with emphasis placed on practical drills and emergency simulations. Differentiated training programs should be designed for various job types and risk levels. Targeted secondary training shall be arranged for safety prevention personnel, operators of large critical equipment, and employees working in high-risk areas, to enhance their capability to cope with complex on-site scenarios and emergencies. Enterprises should establish a three-tier training system spanning factory, workshop and team levels, conduct regular refresher training, and implement certification requirements for special operation personnel. In Qingdao, the machinery industry has promoted the development of safety laboratories and experiential safety training centers. These immersive sites are equipped with over 20 types of facilities, including virtual reality (VR) somatosensory modules, fire extinguishing simulators, mechanical pinch simulators and fall-from-height simulators. Employees can directly perceive the consequences of injury accidents through immersive experiences, which substantially improves training effectiveness.

Regarding safety culture development, enterprises should adhere to the principle of "safety first, priority to prevention, and comprehensive management". Safety-themed activities such as knowledge contests and speech competitions help foster a positive safety culture, and safety culture construction should be integrated into the enterprise performance appraisal system. Practices adopted by Jianma Precision, including the "one post, one page" illustrated manual and the "finger-pointing and oral confirmation" training system, are worthy of promotion. The "one post, one page" manual summarizes job hazard points, safety specifications and emergency response essentials into illustrated handbooks posted at workstations for easy on-site reference. The "finger-pointing and oral confirmation" mechanism rectifies habitual violations through standardized routines of verbal confirmation, pointing, visual inspection and risk assessment. Cultivating safety culture constitutes a long-term initiative that requires sustained advocacy from management, institutional reinforcement and full participation of all employees.

Implementation path and safeguard measures for strategies

The implementation path follows the principle of "pilot first, gradual promotion". Workshops or production lines with sound foundational conditions are selected as pilot sites, and full-scale rollout is performed once relevant experience is obtained. In terms of institutional safeguards, enterprises shall define work safety responsibilities for leaders at all levels, functional departments and individual positions. A full-staff safety responsibility system, covering the principal person-in-charge down to frontline operators, should be established. Safety responsibility documents are signed to assign safety obligations to specific individuals. In terms of organizational safeguards, Mandowa et al. highlighted that visible commitment from senior leadership constitutes a prerequisite for effective occupational

safety governance within manufacturing firms. Safety priorities should be embedded within corporate long-term strategy, and cross-functional safety working groups led by senior managers are essential for coordinating the deployment of accident-prevention mechanisms across departments. In terms of funding safeguards, investment in safety facilities and safety technology must be guaranteed, and safety expenditure should be included in annual corporate budgets. In terms of technical safeguards, advanced safety technologies and equipment should be actively introduced to enhance intrinsic-safety performance.

A complete closed-loop safety management system for mechanical manufacturing workshops is illustrated in Figure 5. Centered on the cyclic workflow of identification, assessment, control and improvement, the system integrates four core dimensions: equipment intrinsic safety, operating environment, personnel behavior, and management system. Driven by the logical chain of "problem analysis-method construction-strategy design-continuous improvement", it realizes three key transformations of safety management. These transformations include shifting from post-accident disposal to pre-incident prevention, changing from manual on-site patrol to human-machine collaborative management, and evolving from rigid rule constraints to safety-oriented corporate culture. Each link in the cycle feeds back real-world problems to support dynamic adjustment and iterative optimization of workshop safety management.



Figure 5. Closed-loop safety management system.

Conclusion

This study systematically analyzes the categories and characteristics of hazards in mechanical manufacturing workshops, develops a multi-dimensional methodological system for hazard identification, and puts forward optimization strategies for safety management. The main conclusions are summarized as follows. First, hazards in mechanical manufacturing workshops are multi-dimensional, cumulative and dynamic, which necessitates the construction of a four-in-one identification framework covering "human - machine - environment - management". Second, artificial intelligence and multi-source data fusion technologies offer new technical approaches for hazard identification. Nevertheless, technical tools cannot fully replace human judgment, and human-machine collaboration represents a more practical solution. Third, the optimization of safety management requires coordinated progress across institutional, technical, personnel and cultural dimensions to form a closed-loop system of "identification - assessment - control - improvement".

This research has the following limitations. It relies primarily on literature review and case studies without systematic collection and analysis of empirical data. The proposed methods are oriented mainly toward large enterprises, and their applicability to small and medium-sized enterprises remains to be verified. Future research may focus on safety risk prediction models built upon the Industrial Internet and approaches to improving safety management capacity for small and medium-sized mechanical manufacturers.

Safety management within mechanical manufacturing workshops constitutes a systematic project that requires

coordinated advances in technology, institutions and culture. Mechanical manufacturing enterprises should continuously innovate safety management concepts and methods, advancing the transition of safety management from “passive response” to “active prevention and control”, and from “manual monitoring and guarding” to “human-machine collaboration”. Such efforts can effectively protect the life and health of workers and lay a robust safety foundation for the high-quality development of the manufacturing sector.

Funding

This work was supported by the 2025 Annual Special Fund for Science and Technology Innovation Strategy (Cultivation of University Students’ Science and Technology Innovation) Climbing Plan Project (Grant No: pdjh2025bk316); the Key Research Platforms and Projects (Science and Technology Category) for General Higher Education Institutions in Guangdong Province (Grant No: 2024KQNCX313).

Acknowledgements

The authors would like to show sincere thanks to those technicians who have contributed to this research.

Conflicts of Interest

The authors declare no conflict of interest.

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