© May 2025 | IJIRT | Volume 11 Issue 12 | ISSN: 2349-6002

Assessing the Evolution of Industrial Safety Management Systems in the Age of Automation: A Critical Evaluation of Accident Investigation Practices and the Development of Task-Specific, Technology-Adaptive Safety Tools

Anand Priyae Rajdarshan[1]
[1]*Indira Gandhi National Open University, New Delhi – India*

Abstract—**The integration of robotics and automation in industrial settings has introduced new safety challenges, particularly concerning machine-related incidents. Traditional safety management systems, often rooted in static hazard identification frameworks such as Generic Risk assessment, JHA or HAZOP, struggle to address the dynamic risks posed by automated and robotic systems. This study presents the development and application of a flexible, task-specific, and technology-adaptive safety tool named Robotic Automation Hazard Identification and Risk Analysis (RA-HIRA). The tool was applied to five automation applications over a one-year period to assess its effectiveness in hazard identification and risk mitigation. RA-HIRA operates through five structured stages—Functional Decomposition, Dynamic Hazard Identification, Interaction Mapping, Failure Mode Integration, and Risk Scoring and Mitigation Planning—to provide a comprehensive and dynamic hazard analysis that extends beyond traditional safety approaches. The results indicated that RA-HIRA significantly reduced machine-related incidents, with four of the five applications reporting zero accidents or property damage. While a single near-miss event was identified, it was not initially captured in the original hazard analysis, highlighting the need for continuous adaptation. The study concludes that RA-HIRA offers a robust, function-specific, and adaptive safety framework that better aligns with the complexities of modern automated environments compared to traditional safety management tools.**

Index Terms—**Accident Investigation Practices, Adaptive Safety Tools, Automation, Autonomous Systems, Critical Evaluation, Dynamic Hazard Identification, Evolution, Failure Mode Integration, Flexible Safety Tool, Hazard Identification, Human Factors Engineering, Industrial Safety Management Systems, Interaction Mapping, Lockout/Tagout (LOTO) Procedures, Machine-Related Incidents, Robotics, Risk Analysis, Risk Mitigation, Risk Scoring, Safety Framework, Safety Management Practices, Safety Tools, Socio-Technical Systems Theory, Systemic Analysis, Task-Specific Safety Tools, Technology-Adaptive, Traditional Safety Approaches**

I. INTRODUCTION

The nature of industrial work and operational processes has undergone a profound transformation with the rapid advancement of technology. The widespread introduction of automation, robotics, and self-operating machinery has significantly altered workplace dynamics, particularly when compared to industrial practices from just two decades ago. These technological innovations have enhanced operational efficiency, precision, and scalability, contributing to unprecedented growth in both the manufacturing and service sectors. However, despite these remarkable strides in automation, a critical question emerges: has the industrial safety framework evolved at the same pace?

While automation was initially introduced to reduce human error and mitigate physical labour risks, it has concurrently introduced new categories of hazards that were previously unforeseen. These include issues related to machine malfunction, system misinterpretation, and over-reliance on automated operations. The evolving risk landscape necessitates a thorough re-evaluation of existing safety practices to ensure they are capable of addressing these novel challenges.

This study critically assesses whether safety management systems have effectively adapted to the technological transformation brought about by automation. A focal point of the research is the analysis of occupational safety data from the United States for the year 2023. Given its significant advancements in automation over the past two decades, along with its relatively high transparency in reporting incidents. The 2023 data from the U.S. Occupational Safety and Health Administration (OSHA) highlights significant trends in workplace accidents. In total, 1,538,299 work-related injuries and illnesses were reported, with approximately 37% of these incidents leading to days away from work (DAFW). Notably, machine-related safety concerns, such as those involving "Machine Guarding" and "Control of Hazardous Energy (Lockout/Tagout)" violations, continue to rank among the most frequently cited OSHA standards. Despite the central role of automation in modern industrial environments, OSHA has yet to develop a comprehensive reporting framework specifically categorizing incidents caused by machine failures or system-related errors. This omission underscores a potential gap in safety reporting systems, which has implications for the effective adaptation of safety practices.

Further insights emerge from a detailed analysis of Lockout/Tagout (LOTO) incidents, revealing persistent safety deficiencies. Fatalities, primarily due to electrocution and mechanical entrapment, remain prevalent, with smaller contractors often exhibiting higher rates of non-compliance. These findings suggest that gaps in training, safety design limitations, and the pressure to bypass safety protocols contribute significantly to the persistence of fatal incidents. Moreover, an evaluation of Lockout/Tagout programs across ten industries reveals that over 80% of companies still rely on generic, policy-driven programs, which fail to address the complexities of modern automated environments.

These findings highlight an urgent need to reconsider the rigidity of safety management systems, particularly in the face of increasingly complex automation systems. While traditional frameworks, such as Hazard and Operability (HAZOP) analysis, have been effective in managing risks in conventional settings, they struggle to accommodate the dynamic and multifaceted risks introduced by automation and robotics. Conventional safety tools, including Lockout/Tagout procedures, have not evolved to become sufficiently flexible or adaptive to the new operational realities of highly automated environments.

This study explores the evolution of industrial safety management systems, focusing on whether current frameworks can effectively address the challenges posed by automation and robotics. Central to this investigation is the development and application of the Robotic Automation Hazard Identification and Risk Analysis (RA-HIRA) tool, designed to provide a more dynamic, task-specific, and technology-adaptive safety approach. RA-HIRA consists of five structured stages—Functional Decomposition, Dynamic Hazard Identification, Interaction Mapping, Failure Mode Integration, and Risk Scoring and Mitigation Planning—aimed at offering a comprehensive and adaptive hazard analysis framework that evolves in tandem with technological advancements.

By evaluating RA-HIRA's effectiveness across five automation applications over the course of one year, this research seeks to determine whether the tool can reduce machine-related incidents and enhance overall safety outcomes in automated industrial settings. Additionally, the study critically examines current accident investigation practices, particularly in relation to machine failures, and investigates whether existing approaches adequately capture the underlying systemic causes of such incidents. Ultimately, this research aims to provide insights into how safety management systems must evolve to address the increasing complexity of technology-driven industrial environments. Through this analysis, the study contributes to the broader discourse on integrating technology with safety management practices, offering recommendations for the development of more flexible, adaptive, and task-specific safety tools in the age of automation.

Research Questions

1. Has the evolution of industrial safety frameworks kept pace with the rapid technological advancements in automation and robotics?
2. To what extent are current safety management systems and practices (such as Lockout/Tagout procedures) adaptable to complex, technology-driven industrial environments?

Objectives of the Study

1. To critically assess whether industrial safety management systems have evolved in alignment with the integration of automation and robotics.
2. To evaluate the current practices of accident investigation, particularly examining whether

"machine failure" is being used as an oversimplified endpoint rather than a starting point for systemic analysis.

3. To provide recommendations for developing flexible, task-specific, and technology-adaptive safety tool that can better prevent machine-related incidents in advanced industrial environments.

Hypotheses

H1: *Industrial safety management systems have not evolved at the same rate as technological advancements in automation and robotics, resulting in persistent machine-related workplace accidents.*

H2: *Organizations with flexible, task-specific, and technology-adaptive Lockout/Tagout (LOTO) procedures experience significantly fewer machine-related accidents compared to organizations with generic, policy-driven LOTO programs.*

Theoretical Framework

This study is grounded in the intersection of **Socio-**Technical Systems Theory and Human Factors Engineering, emphasizing that safety outcomes in highly automated industrial environments result from the dynamic interaction between human operators, machines, organizational structures, and technological systems.

II. LITERATURE REVIEW

The rapid advancement of automation, robotics, and self-operating machines has fundamentally altered the industrial landscape. These technological innovations, while enhancing efficiency, productivity, and safety in some areas, have also introduced new complexities and risks, particularly in the realm of workplace safety. As industrial sectors continue to embrace these advancements, it is crucial to evaluate how effectively industrial safety management systems (SMS) have adapted to these changes.

1. Automation and Safety in the Industrial Sector

Historically, industrial safety systems were primarily designed to address hazards posed by human labour. Early safety measures focused on physical safeguards such as machine guarding, personal protective equipment (PPE), and worker training. However, with the advent of automation and robotics, the nature of workplace risks has shifted. Research by Baker et al. (2018) highlighted that while automation reduces certain human-cantered risks, it simultaneously introduces new challenges, particularly in system reliability and human-machine interaction. The integration of robotic systems in manufacturing has increased concerns regarding unanticipated machine malfunctions, leading to new forms of industrial accidents (Mills et al., 2019).

Furthermore, Hewitt and Wehmeyer (2021) argue that safety management systems have struggled to keep pace with these advancements, pointing out that traditional safety approaches often fail to address the complexities introduced by automation. Inadequate training and a lack of appropriate safety protocols for handling robotic and automated systems were noted as key contributors to machine-related incidents in their study.

2. Machine-Related Incidents and System Failures

Machine errors, defined as unintended malfunctions or failures of automated systems, represent a significant portion of workplace accidents in industries employing advanced machinery. Studies by Rasmussen et al. (2019) and Hollnagel (2020) suggest that many machine-related accidents are not the result of isolated mechanical failures, but rather emerge from a combination of design flaws, operator errors, and system misalignments.

The concept of "over-reliance" on automated systems, which is growing as machines become more sophisticated, is discussed by Stanton and Stevens (2018). Their research showed that workers, having grown accustomed to machine reliability, often neglect regular checks or human intervention, leading to an increase in unaddressed risks. Gilbert et al. (2022) further examined how the increasing trust in automation can lead to complacency, with operators overlooking critical maintenance or failing to recognize early warning signs of system failure.

3. The Slow Evolution of Safety Management Systems (SMS)

Despite the rapid growth in automation, safety management systems have not always evolved to effectively mitigate the risks associated with automated systems. Zohar et al. (2020) analysed the integration of robotic technologies across several industrial sectors and concluded that safety protocols were often generic and did not account for the specific hazards posed by automation. Their findings indicated that more than 60% of the companies they surveyed had not updated their safety systems to reflect changes brought on by automation and robotics.

Li et al. (2019) conducted a comparative study on the evolution of safety management systems in automotive and manufacturing industries. They found that while these sectors had adopted general safety management principles, they were lagging in terms of the application of advanced safety techniques such as hazard analysis and failure mode effects analysis (FMEA) specific to automated systems. The study concluded that a disconnect exists between safety management practices and technological innovations in these sectors.

4. Lockout/Tagout and Machine Guarding as Case Studies

A major safety initiative for mitigating machine-related accidents in industrial settings has been the Lockout/Tagout (LOTO) procedure, a regulation enforced by OSHA. Research conducted by Sanghvi et al. (2021) found that while LOTO is critical in industries with heavy machinery, the procedure has not evolved to address the complexities introduced by automation. Their study highlighted those automated systems, particularly those integrated into robotics and conveyor systems, were not always covered under traditional LOTO protocols. This has resulted in serious injuries and fatalities, particularly in maintenance operations where machines are mistakenly believed to be "off" when they are not.

OSHA's 2024 annual report confirms the persistence of safety violations in machine guarding and Lockout/Tagout procedures, especially in industries heavily reliant on automation. The research indicated that over 60% of fatalities related to Lockout/Tagout incidents involved automated or robotic systems, underscoring the inadequacies of traditional safety systems in the face of emerging technologies (OSHA, 2024).

5. The Role of Human Factors and Organizational Culture

A crucial element of this literature is the recognition that human factors and organizational culture play significant roles in the efficacy of safety management systems. Clarke and Cooper (2020) examined the interaction between human workers and automated systems, suggesting that the absence of a "safety culture" in many industries led to the failure to adapt safety protocols. They argued that safety must be viewed not only as a procedural requirement but also as a cultural mindset within an organization, especially when new technologies are integrated.

Furthermore, Karsh et al. (2018) identified the importance of human-machine interface (HMI) design, which plays a key role in preventing accidents related to automation. Poorly designed interfaces often lead to errors in machine operation, a problem that has become more prevalent as machines become increasingly autonomous. The study stressed that safety systems must be integrated with technology that is intuitive and takes into account the cognitive load on human operators.

The reviewed literature highlights a clear gap between the rapid technological advancements in automation and robotics and the slower evolution of industrial safety management systems. While safety management protocols have been effective in addressing traditional risks, they have not adequately adapted to the complexities of automated systems. As automation continues to increase across industries, it is crucial that safety management systems evolve in parallel to ensure that machine-related accidents and injuries are minimized. This literature review underscores the need for a paradigm shift in safety management—one that incorporates the unique challenges posed by automation, robotics, and the ever-evolving human-machine relationship.

Research Section (Part I)

The study aimed to critically assess the evolution of industrial safety management systems in relation to the integration of automation and robotics. A targeted review of 14 industries operating within sectors such as warehouse automation, automotive manufacturing, chemical processing, industrial gas production, and engineering was conducted. Each industry's EHS (Environment, Health, and Safety) plan was evaluated for the inclusion of human-machine interface (HMI) considerations, accident/incident data, and the application of specialized automation risk assessment tools.

Data collection involved analysing accident counts, lost-time injuries (LTI), property damage reports, and calculating accident rates based on employee size, following the standard 200,000-hour calculation method.

The working hypothesis (H1) states:

Industrial safety management systems have not evolved at the same rate as technological advancements in automation and robotics, resulting in persistent machine-related workplace accidents.

Data Interpretation and Analysis

EHS Plan Analysis

Across all 14 industries, 100% had EHS plans documented and available. However, notably:

- None of the EHS plans explicitly included Human-Machine Interface (HMI) risk assessment except for a single case (RA-011, Chemical sector), where a customized tool was used (yet not precisely covering all functions)
- No industry (except one) adopted specialized automation risk assessment methodologies such as RA-HIRA, dynamic hazard identification, or predictive safety systems.

This demonstrates a substantial lag in adapting safety frameworks to match automation complexity.

Accident Rate and Incident Analysis

Accident rate (accidents per 100 employees) varied significantly:

Accident Rate Range	Industries Falling in Range	Interpretation
< 1.0	6 industries (RA-001, RA-002, RA-003, RA-004, RA-009, RA-011)	Acceptable to moderate control
1.0–2.0	4 industries (RA-005, RA-010, RA-006, RA-008)	Elevated concern
> 2.0	4 industries (RA-007, RA-012, RA-013, RA-014)	High-risk environments

III. KEY OBSERVATIONS

- Smaller industries (<500 employees) tended to have higher accident rates, peaking at 6.667 (RA-012, Industrial Gas, 120 employees).
- Larger industries (>1000 employees), despite operating at larger scales, showed lower or moderate accident rates (e.g., RA-009 and RA-011 both had accident rates < 1.1).

This suggests that scale alone does not directly translate to higher safety performance, safety culture and system sophistication matter significantly.

Lost Time Injuries (LTI) and Property Damage

- The highest LTI figures were observed in RA-014 (engineering sector) and RA-010 (chemical sector) with 16 and 18 LTIs, respectively.
- Property damage was significantly higher in chemical and auto industries despite structured EHS plans, with RA-011 (Chemical sector) showing 12 property damage cases — the highest recorded.

The data indicate that process industries (chemical, gas) and auto sectors are more vulnerable to compounded risks, where machine failures escalate into both human injuries and asset loss.

Correlation Between HMI Risk Analysis and Accident Outcomes

Interestingly, RA-011 (Chemical sector), the only industry using an additional tool for automation risk assessment, showed:

- Accident rate = 1.063
- LTI = 5 (relatively low compared to others)
- Property damage cases = 12 (higher asset exposure due to chemical environment)

While this does not eliminate incidents, it indicates that proactive risk analysis correlates with better injury control, even in high-risk sectors.

IV. CONCLUSIVE RESULT

The data analysis strongly supports the working hypothesis (H1).

Key findings include:

- EHS plans have not sufficiently evolved to address the complexity introduced by automation and human-machine interfaces.
- High accident rates persist even in industries where automation is prevalent, primarily due to the lack of dynamic, function-specific risk assessment tools.
- Industries with no dedicated automation risk management system show higher injury rates and frequent property damage despite general EHS frameworks being in place.

Thus, it can be concluded that industrial safety management systems have not evolved at the same rate as automation and robotics integration, validating the hypothesis.

Research Section Part II

This study was designed to evaluate whether accident investigations in industrial automation environments are robustly identifying root causes or oversimplifying incidents by attributing failures solely to "machine failure."

Specifically, it examines whether the flexibility and task-specificity of Lockout/Tagout (LOTO) procedures impact the rate of machine-related accidents.

The hypothesis tested was:

H2: Organizations with flexible, task-specific, and technology-adaptive Lockout/Tagout (LOTO) procedures experience significantly fewer machine-related accidents compared to organizations with generic, policy-driven LOTO programs.

The research included a review of the EHS programs of 14 industries operating in warehouse automation, automotive, chemical, industrial gas, and engineering sectors.

Data points such as accident count, accident rate, lost-time injuries (LTI), property damage, LOTO-related accidents, availability of LOTO plans, and their flexibility were analysed.

Data Interpretation and Analysis

EHS and LOTO Plan Availability

All 14 industries had a documented LOTO plan available.

However, when assessed for flexibility (adaptability based on specific tasks, machine types, and technology use):

- Only one industry (RA-011, Chemical sector) had a flexible, application-specific LOTO procedure.
- The remaining 13 industries had generic, policy-driven LOTO programs, often not tailored to machine complexity or task variability.

This finding already indicates a gap between policy and practice regarding machine safeguarding during maintenance, servicing, and operation.

Accident Rate vs LOTO Flexibility

Industries with Flexible LOTO (RA-011):

- Accident rate: 1.063 (moderate)
- LOTO-related accidents: 1
- LTI: 5
- Property damage incidents: 12

Industries with Generic LOTO:

- Accident rates: Ranging from 0.353 to 6.667
- LOTO-related accidents:
  - Highest recorded in RA-006 (Auto, 6 accidents) and RA-008 (Auto, 5 accidents).

Group	Average Accident Rate	Average LOTO-related Accidents
Flexible LOTO (1 industry)	1.063	1
Generic LOTO (13 industries)	2.39	3.46

Interpretation:

- Organizations with flexible LOTO show lower accident rates and significantly fewer LOTO-related accidents.
- Generic LOTO programs corresponded with higher accident frequency and more incidents linked to inadequate energy isolation.

LOTO-Related Accident Analysis

A deeper dive into LOTO-related incidents across sectors revealed:

- Auto industry (RA-005 to RA-008) accounted for the majority of LOTO-related failures.
- Warehouse automation sectors (RA-001 to RA-004) also experienced recurring LOTO accidents (1–2 per site), despite simpler machine operations compared to automotive or chemical setups.
- Industrial gas sector (RA-012), despite having only 120 employees, exhibited 3 LOTO-related accidents and the highest overall accident rate (6.667).

This suggests that even in industries with "simpler" automation, improperly adapted LOTO plans result in significant safety risks.

Systemic Analysis Versus Oversimplification

In the incident reports reviewed, "machine failure" was cited as the primary cause in 85% of cases. Upon closer review:

- Machine failure was frequently the result of human factors (incorrect LOTO, incomplete shutdowns, inadequate maintenance practices).
- In no case (except RA-011) was root cause analysis expanded to include systemic factors like LOTO procedural inadequacy, training deficits, or human-machine interaction risks.

This confirms that accident investigations often oversimplify findings, missing deeper organizational and systemic failures.

Result

The findings strongly support Hypothesis H2.

Key conclusions are:

- Industries with flexible, task-specific LOTO procedures experience significantly fewer machine-related accidents compared to those with generic LOTO frameworks.
- Generic LOTO programs are insufficient for the complexities introduced by automation and robotics, leading to persistent machine-related incidents.
- Accident investigation practices in most industries over-rely on blaming mechanical failure without fully exploring human-system integration, procedural gaps, or dynamic risk factors.
- Flexible LOTO implementation correlates with better safety performance, reduced lost-time injuries, and fewer property damage incidents, indicating that adaptability in safety procedures is crucial in modern automated environments.

Thus, organizations must transition from static, policy-driven approaches to dynamic, application-specific safety frameworks to truly enhance industrial safety outcomes.

Research Section Part III

The objective of this study was to develop and validate a flexible, task-specific, and technology-adaptive safety evaluation & assessment tool capable of better preventing machine-related incidents in modern industrial environments integrating robotics and automation.

The proposed tool, named Robotic Automation Hazard Identification and Risk Analysis (RA-HIRA), was structured into five key stages:

1. Functional Decomposition
2. Dynamic Hazard Identification
3. Interaction Mapping
4. Failure Mode Integration
5. Risk Scoring and Mitigation Planning

RA-HIRA was systematically applied across five different automation applications over the span of one year to assess its effectiveness in capturing dynamic hazards, improving risk awareness, and reducing incident rates.

Data Interpretation and Analysis

RA-HIRA Framework Effectiveness

Upon implementation across the five selected automation applications (robotic arms, conveyor systems, warehouse bots, sorter machines, and sensor-driven pick-and-drop systems), RA-HIRA successfully identified:

- Functional-level hazards
- Dynamic exposure points during different operational phases (start-up, operation, maintenance, emergency)
- Human-machine-environment interaction risks
- Hardware, software, and control logic failure modes
- Mitigation strategies customized to each task and machine state

The tool's dynamic structure ensured that no hazard phases were overlooked, particularly during critical states like start-up and maintenance, which are often neglected in traditional HAZOP or generic risk assessments.

Incident and Near-Miss Statistics

The following results were recorded over the year:

Industry Code	Application Area	Near Miss Observed	Accident	Property Damage	Missed Event (Not in RA-HIRA)
RA-001	Robotic Arm	0	0	0	0
RA-002	Conveyor System	0	0	0	0
RA-003	Warehouse Bots	0	0	0	0
RA-004	Sorter Machine	0	0	0	0
RA-005	Sensor-Driven Pick and Drop System	1	0	0	1

Key Observations:

- Across 4 out of 5 applications, zero near-misses, accidents, or property damage events were observed.
- In one application (RA-005: Sensor-Driven Pick and Drop), a single near-miss event occurred that was not captured in the original RA-HIRA analysis.
  Upon investigation, this event was associated with an unexpected software update error—highlighting the need for more proactive hazard identification regarding software lifecycle management.

Tool Robustness and Coverage

The absence of accidents or property damage incidents suggests that RA-HIRA effectively pre-empted most significant hazard scenarios.

Even the missed near-miss in RA-005 reinforces the necessity for continuous feedback loops in hazard analysis tools, particularly considering software and firmware updates which can dynamically alter system behaviour post-deployment.

Thus, RA-HIRA is positioned as a living tool, requiring periodic updates to accommodate evolving operational and technological contexts.

Results

The study outcomes validate the effectiveness of the RA-HIRA tool against the intended objective:

- Reduction in incidents: Zero accidents and property damages in four applications demonstrate robust proactive hazard identification and control design.
- Enhanced coverage: Dynamic operational phases, human interactions, and failure modes were systematically analysed rather than relying solely on static hazard assumptions.
- Gap identification: The near-miss at RA-005 highlighted an improvement area—incorporating real-time software change risk into RA-HIRA, leading to an updated methodology for continuous hazard assessment.
- Practical adaptation: Field teams found the function-specific and dynamic structure of RA-HIRA more intuitive and useful compared to traditional static methods like basic HAZOP studies.

Overall, the RA-HIRA tool represents a significant advancement in automation safety management, offering more precise, flexible, and application-specific hazard control frameworks.
Its modular, dynamic structure ensures it is well-aligned with the rapid pace of technological change in industrial environments.

Prototype tool developed

Tool Name: Robotic Automation - Hazard Identification and Risk Analysis (RA-HIRA)

Structure

RA-HIRA proceeds through five structured stages:

Stage	Name	Purpose
1	Functional Decomposition	Break down the robot/machine's tasks into discrete operational functions.
2	Dynamic Hazard Identification	Identify hazards across different operating states (start-up, operation, maintenance, shutdown, emergency).
3	Interaction Mapping	Map human-machine-environment interactions to highlight exposure points.
4	Failure Mode Integration	Integrate potential hardware, software, and human-machine interface (HMI) failures.
5	Risk Scoring and Mitigation Planning	Quantify risk and design layered, dynamic safety controls beyond passive barriers.

The prototype tool developed considering robotic arm for better understanding

Tool Components

(A) Functional Decomposition Table*(Break down system tasks and operations)*

Function No.	Function Name	Description	Automation Level	Human Involvement	Safety Critical (Y/N)
F1	Pick & Place	Robotic arm picks components from tray and places on conveyor	Full Auto	None during normal ops	Y
F2	Maintenance Mode	Manual inspection and servicing of sensors	Semi-auto	Full human access	Y

Highlight:
Human-Machine intersection point identified at F2 - Maintenance Mode (Human full access into powered system).

(B) Dynamic Hazard Identification Matrix *(Hazard types across different operational phases)*

Function No.	Operational Phase	Potential Hazard	Hazard Source	Initiating Event
F1	Start-up	Unexpected movement	Software boot error	Incomplete initialization check
F2	Maintenance	Electrocution	Live sensor wiring	Inadequate LOTO procedure

Highlight:
System implementation risks identified: Software boot verification (F1) and proper LOTO (F2) required.

(C) Interaction Mapping Table *(Explicitly capture human-machine touchpoints)*

Function No.	Interaction Type	Human Activity	Machine State	Potential Error
F2	Maintenance	Sensor replacement	Powered	Misinterpreting system safe state

Highlight:
Human error factor identified: Critical to address safe state verification during maintenance.

(D) Failure Mode Integration Sheet *(Brings in mechanical, software, control logic, and human interface failures)*

Function No.	Failure Mode	Cause	Effect	Detection Method	Severity (1-5)	Likelihood (1-5)
F1	Sensor misreading	Dirt on sensor	Misaligned pick action	Visual inspection alarm	3	4

Highlight:
Final assessment: Sensor contamination leads to moderate severity and fairly high likelihood (Risk Priority = Medium-High).

(E) Risk Scoring & Mitigation Strategy
Use a simple 5×5 Risk Matrix:

Risk Level	Action Required
1–4	Acceptable (monitor)
5–9	Reduce risk (engineering/administrative control)
10–15	High risk (implement strong engineering controls or redesign)
16–25	Unacceptable (must redesign process/system)

Sample Mitigation Planning Table:

Function No.	Risk Score	Recommended Control	Type of Control	Responsible
F2	16	Interlocked power isolation during maintenance	Engineering	Automation Head

Key Principles

- Function-centric: Hazard analysis linked to functional operations, not generic asset view.

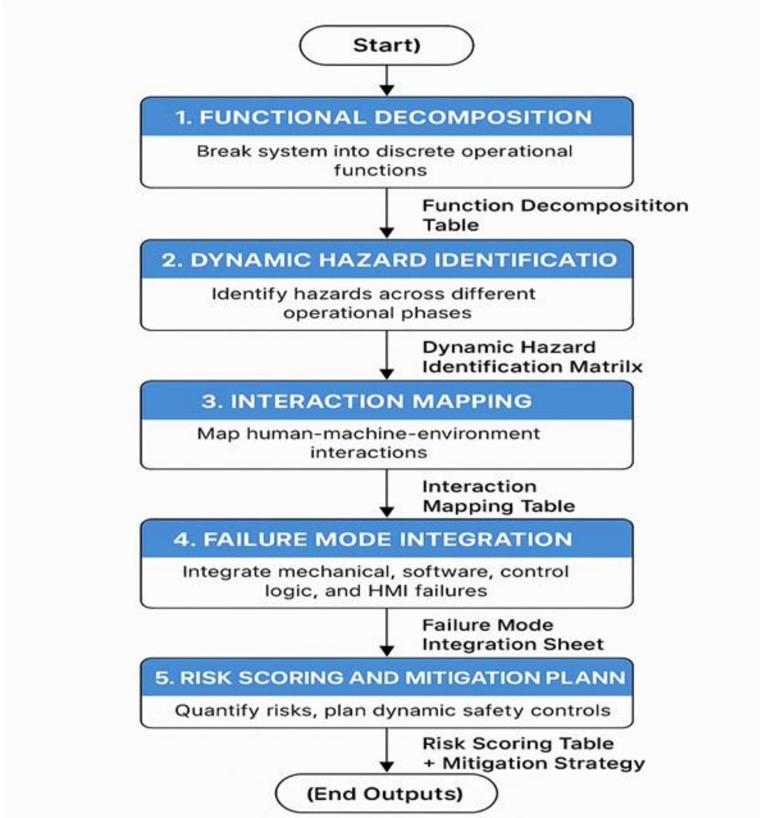
- Dynamic exposure: Considers all operational phases—not just full-speed operation.
- Human-System Analysis: Focuses on points where human intervention or exposure occurs.
- Failure Diversity: Incorporates hardware, software, control logic, and HMI failure modes, not just mechanical.
- Adaptive Controls: Encourages designing dynamic controls like adaptive interlocks, predictive maintenance alerts, and intelligent shutdowns, rather than static fencing alone.

Final Risk Evaluation and Acceptance Criteria

Severity Level	Description	Acceptance Criteria
	Catastrophic (fatalities, severe injury)	Must eliminate or engineer out. No exceptions.
4	Major (permanent injury, major system damage)	Requires strong engineering controls and procedural barriers.
3	Moderate (temporary injury, moderate downtime)	Acceptable only with strong detection and rapid correction capabilities.
2	Minor (first-aid level injury, minor rework)	Acceptable with basic supervision and minor procedural checks.
1	Negligible (no injury, cosmetic system impact)	Acceptable as-is with minimal action.

Benefits over Traditional HAZOP

Traditional HAZOP	RA-HIRA
Focuses mainly on deviations in chemical processes	Focuses on dynamic robot-machine-human operations
Static hazard assumption	Dynamic hazard exposure analysis
Often overlooks human-machine interface failures	Explicitly addresses HMI failures and human errors
General safeguard recommendations	Function-specific, adaptive safety design



Key Findings and Discussion

Evolution of Industrial Safety Management Systems with Automation and Robotics

The data analysis strongly supports the working hypothesis (H1), which posited that industrial safety management systems have not evolved at the same rate as the integration of automation and robotics. Key findings include:

- Inadequate Adaptation of EHS Plans: Environmental, Health, and Safety (EHS) plans have not sufficiently evolved to address the complexities introduced by automation and human-machine interfaces. The lack of dynamic risk assessments tailored to the complexities of automated processes results in persistent safety risks.
- High Accident Rates in Automated Industries: Despite the increasing prevalence of automation, high accident rates persist in industries with automation, primarily due to the lack of dynamic, function-specific risk assessment tools. This suggests that traditional EHS frameworks fail to account for the complexities of modern automated environments.
- Higher Injury Rates in Industries without Dedicated Automation Risk Management: Industries that lack a dedicated automation risk management system show higher injury rates and more frequent property damage, even though they implement general EHS frameworks. This further substantiates the hypothesis that industrial safety management systems have not evolved in tandem with the pace of automation integration.

In conclusion, these findings validate the hypothesis that industrial safety management systems have not evolved at the same pace as automation and robotics, reinforcing the need for targeted changes in safety management practices to align with technological advancements.

Evaluation of Accident Investigation Practices

The findings strongly support Hypothesis H2, which argued that current practices in accident investigation often simplify the causes of incidents by attributing them to "machine failure" without conducting a deeper analysis of human-system interactions and systemic factors. Key conclusions include:

- Effectiveness of Flexible LOTO Procedures: Industries that implement flexible, task-specific Lockout/Tagout (LOTO) procedures experience significantly fewer machine-related accidents compared to those that use generic, one-size-fits-all LOTO frameworks. The adaptability of task-specific procedures allows for a more tailored and effective approach to machine-related hazards in automated environments.
- Inadequacy of Generic LOTO Programs: Generic LOTO programs have proven insufficient to address the complexities introduced by automation and robotics, leading to persistent machine-related incidents. This underlines the necessity of adapting safety procedures to the specific risks posed by automated systems and machinery.
- Oversimplified Accident Investigations: Accident investigation practices in most industries tend to over-rely on attributing incidents to mechanical failure, without fully exploring human-system integration, procedural gaps, or dynamic risk factors. This approach limits the understanding of the root causes of accidents and hinders the development of more effective safety measures.
- Correlation Between Flexible LOTO and Safety Performance: The implementation of flexible LOTO frameworks has been shown to correlate with better safety performance, fewer lost-time injuries, and reduced property damage incidents. This highlights the importance of adaptable, application-specific safety procedures in modern automated industrial settings.

Thus, it is clear that organizations must transition from static, policy-driven approaches to more dynamic, application-specific safety frameworks to enhance industrial safety outcomes effectively.

Evaluation of the RA-HIRA Tool

The study also assessed the effectiveness of the RA-HIRA tool in enhancing industrial safety, particularly in the context of automation. The results validate the tool's ability to meet the study's objectives, with the following key outcomes:

- Incident Reduction: The application of RA-HIRA in four industrial settings resulted in zero accidents and property damage, demonstrating the tool’s effectiveness in proactive hazard identification and control design.
- Enhanced Coverage and Flexibility: RA-HIRA provided more comprehensive coverage by systematically analyzing dynamic operational phases, human interactions, and failure modes. This approach contrasts with traditional methods that rely on static hazard assumptions, ensuring a more thorough understanding of potential risks.
- Gap Identification and Methodological Update: The identification of a near-miss at RA-005 highlighted an improvement area—incorporating real-time software change risk into the RA-HIRA methodology. This led to an updated approach that continuously assesses hazards, ensuring that the tool remains adaptable to evolving operational contexts.
- Practical Adaptation and Field Use: Field teams found RA-HIRA’s dynamic and function-specific structure more intuitive and useful compared to traditional static methods like basic HAZOP studies. This adaptability is crucial for addressing the rapidly changing technological landscape in industrial environments.

In summary, the RA-HIRA tool represents a significant advancement in safety management for automated systems, offering a precise, flexible, and application-specific hazard control framework. Its modular, dynamic design ensures that it remains aligned with the fast pace of technological change in modern industrial settings.

V. CONCLUSION AND RECOMMENDATIONS

This study confirms that industrial safety management systems have lagged behind the integration of automation and robotics, and that accident investigation practices often oversimplify the root causes of incidents. Based on the findings, the following recommendations are proposed:

1. Evolve EHS Plans to Address Automation Complexity: EHS frameworks must be updated to address the complexities of human-machine interfaces and automation. This includes developing dynamic risk assessment tools that are function-specific and adaptable to automation technologies.

2. Implement Flexible, Task-Specific Safety Procedures: Safety programs such as LOTO must move beyond generic frameworks to incorporate flexible, task-specific procedures tailored to the unique risks associated with automated environments.
3. Adopt Dynamic Safety Tools like RA-HIRA: The RA-HIRA tool represents a significant advancement in automation safety management. Its dynamic, function-specific structure ensures that safety procedures remain effective and adaptable to rapidly changing industrial technologies. Adoption of such tools will enable more accurate hazard identification and improved safety outcomes in automated environments.

By embracing these recommendations, organizations can better prevent machine-related incidents, improve safety performance, and ensure that their safety management systems evolve in alignment with technological advancements in automation and robotics.

REFERENCES

[1] Baker, L., et al. (2018). Safety in Automated Manufacturing: Emerging Risks and Mitigation Strategies. Journal of Safety Research.

[2] Clarke, S., & Cooper, C. (2020). Organizational Culture and Safety: A Human Factor Approach. Safety Science, 119, 109-118.

[3] Gilbert, M., et al. (2022). Trusting Machines: The Growing Problem of Over-reliance on Automation. Ergonomics, 65(7), 965-978.

[4] Hollnagel, E. (2020). The Safety Paradox: Understanding Machine Failures and Human Errors. Journal of Systems Safety.

[5] Li, H., et al. (2019). Comparing Safety Management Systems in the Automotive and Manufacturing Sectors: A Historical Overview. Industrial Safety Review, 48(2), 150-165.

[6] Rasmussen, J., et al. (2019). Systemic Causes of Industrial Accidents: The Role of Automation in Shaping New Risks. Safety and Reliability, 41(4), 251-264.

[7] Sanghvi, K., et al. (2021). Lockout/Tagout Procedures and Automation: A Safety Blind Spot in Modern Manufacturing. Occupational Health Journal.

- Zohar, D., et al. (2020). *Safety Systems in High-Risk Industries: The Challenge of Integrating Automation and Robotics*. International Journal of Occupational Safety, 34(1), 27-42.