

Safety Optimization through Machine Guard Upgrades and Comprehensive Risk Assessment

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Abstract

In modern industrial settings, optimizing worker safety without compromising productivity is a critical objective. This project focuses on enhancing workplace safety through systematic evaluation and improvement of machine guarding systems. The initiative begins with a detailed audit of existing guards to identify outdated, non-compliant, or ineffective protections posing potential hazards. Using ISO 12100 and OSHA standards as reference frameworks, the study assesses mechanical, electrical, and human factors contributing to risk exposure. Machines involving frequent operator interaction, sharp tools, or exposed moving parts are prioritized for intervention. Upgraded guarding solutions include interlocked barriers, fixed enclosures, adjustable guards, and presence-sensing devices designed to minimize accidental contact with hazardous components. A comprehensive risk assessment matrix categorizes hazards by severity and likelihood, enabling a data-driven approach to safety planning. Concurrently, operator training modules and updated operational guidelines reinforce the adoption of new safety protocols and strengthen safety culture. Feedback from operators and maintenance personnel ensures that implemented solutions remain practical, efficient, and sustainable. Performance indicators such as incident frequency rates and near-miss occurrences are analyzed before and after upgrades to measure effectiveness. Preliminary outcomes demonstrate a notable reduction in operational hazards and improved compliance with safety standards. The project validates that integrating targeted engineering controls with systematic risk assessment significantly enhances workplace safety and operational reliability.

Keywords: Machine Guarding Systems, Risk Assessment Matrix, Industrial Safety Management, Engineering Controls, ISO 12100 and OSHA Standards.

1. Introduction

Safety optimization in industrial environments is essential to protect workers while maintaining efficient and reliable operations. Machinery with exposed moving parts, cutting tools, and high operator interaction poses significant risks if not adequately safeguarded. Traditional safety measures often focus on compliance rather than proactive risk reduction, leading to persistent hazards and unsafe practices. This study emphasizes a systematic approach to safety optimization through upgraded machine guarding combined with comprehensive risk assessment. By aligning engineering controls with recognized standards such as ISO 12100 and OSHA

guidelines, hazards are identified, evaluated, and controlled at the source. The integration of modern guarding solutions, operator training, and continuous monitoring enhances both physical protection and safety behavior. This holistic approach demonstrates that effective machine guard upgrades, supported by structured risk assessment, significantly reduce risk exposure while strengthening safety culture and operational reliability.

2. Literature Review

Recent research highlights significant advancements in machine guarding technologies, materials, and monitoring systems aimed at improving industrial

safety. Vele et al. (2025) developed nanofiber-reinforced GFRP guard rails, demonstrating superior tensile strength, reduced delamination, and improved durability compared to conventional metal guards, particularly when fabricated using VARTM techniques. These findings emphasize the role of advanced composite materials in enhancing guard performance while reducing weight and maintenance requirements. Several studies focus on intelligent and simulation-based guard design. King and Miller (2014) and Reyes et al. (2012) demonstrated the effectiveness of wireless machine guard monitoring systems in detecting removed or compromised guards, significantly improving hazard visibility. Similarly, Kim and Choi (2013), Meister and Uhlmann (2014), and Landi et al. (2018) validated finite element and impact simulations as reliable tools for evaluating guard strength, reducing dependency on costly physical testing. Behavioral and organizational challenges are addressed by Haghghi and Chinniah (2019), who identified incentives for guard bypassing and proposed integrated technical and organizational solutions. Rasnic and Capps (2004) reinforced the critical role of interlocked guards in preventing severe injuries. Recent trends reviewed by Ora et al. (2018) and Singh (2025) highlight the integration of advanced safeguarding devices and AI-based safety management systems. Collectively, the literature underscores the importance of combining robust guard design, intelligent monitoring, ergonomic considerations, and comprehensive risk assessment for effective and sustainable safety optimization.

3. Problem Identification

Despite advancements in automation and safety regulations, machinery-related accidents remain a significant concern in industrial environments. A primary contributor is the continued use of outdated, non-compliant, or poorly designed machine guarding systems that fail to adequately prevent operator exposure to hazardous moving parts. Over time, equipment modifications, wear, and evolving production requirements often render existing guards ineffective and misaligned with standards such as ISO 12100 and OSHA regulations. Inconsistent and unsystematic risk assessment practices further result

in overlooked hazards and uneven implementation of safety controls. Another critical issue is the lack of integration between engineering controls and human factors. Guards that interfere with workflow or visibility are frequently bypassed or disabled by operators, undermining their protective function. This issue is exacerbated by insufficient training and limited safety awareness. The absence of a structured risk evaluation framework based on hazard severity and likelihood makes it difficult for organizations to prioritize interventions and allocate resources efficiently. These challenges increase the risk of injuries, near-misses, downtime, regulatory non-compliance, and reputational damage. Consequently, a systematic, data-driven approach combining comprehensive risk assessment, ergonomic guard design, and active workforce involvement is essential to achieve sustainable safety improvements.

4. Methodology

The study follows a systematic and sequential methodology to ensure effective safety optimization through machine guard upgrades and comprehensive risk assessment. The process begins with a preliminary audit to identify existing machine hazards, guarding deficiencies, and unsafe operating conditions. This is followed by a compliance evaluation against ISO 12100 and OSHA standards to determine gaps in regulatory adherence. A detailed risk assessment and analysis are then conducted to evaluate hazard severity and likelihood, enabling prioritization of control measures. Based on the assessment outcomes, appropriate guarding upgrades are designed and implemented to eliminate or reduce operator exposure to hazardous zones. Operator training and safety awareness programs are subsequently carried out to reinforce safe practices and ensure proper use of upgraded safeguards. All activities are systematically documented, and continuous monitoring mechanisms are established to track performance and maintain compliance. The methodology concludes with results and discussion, identification of challenges and corresponding solutions, performance evaluation, and a final conclusion summarizing key findings and recommendations.

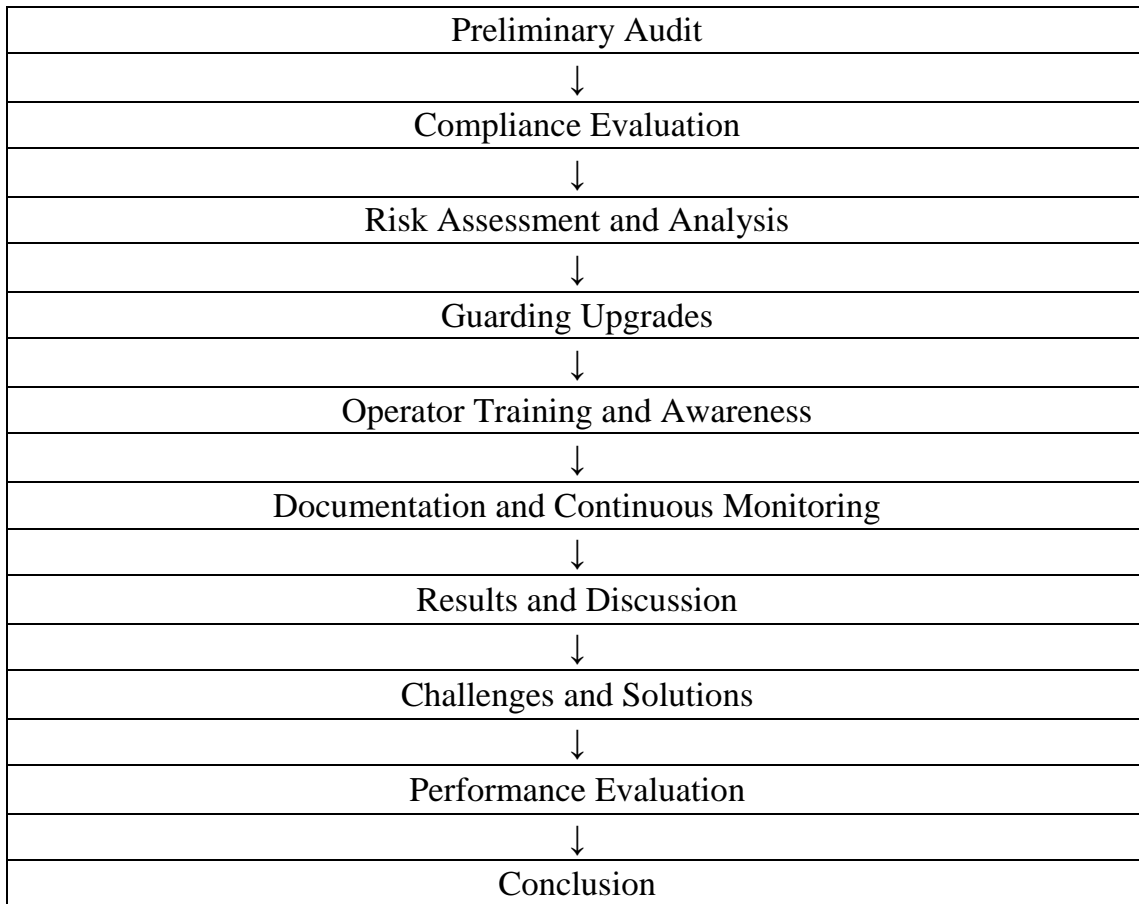


Figure 1 Methodology

4.1. Preliminary Audit

The preliminary audit represents the foundational phase of the project and establishes the baseline for all subsequent safety interventions. Its primary purpose is to identify existing deficiencies in machine guarding, understand operational practices, and evaluate compliance with recognized safety standards such as ISO 12100 and OSHA 29 CFR 1910 Subpart O. Rather than functioning as a routine inspection, the audit adopts a diagnostic approach to uncover visible and latent hazards related to mechanical, electrical, and human factors. The audit covers all machinery within the selected manufacturing area, including cutting machines, conveyors, presses, lathes, milling machines, and automated systems with moving or rotating components.

Each machine is assessed for the physical condition and integrity of guards, functionality of interlocks and emergency stops, ergonomic suitability, accessibility, and maintenance practices. Operator interactions are also observed to identify behaviors that may encourage guard bypassing or unsafe workarounds. Historical data such as incident records, near-miss reports, maintenance logs, and previous audit findings are reviewed to assess existing safety performance. Audit findings are systematically recorded, and machines are classified based on risk severity and frequency of human interaction. This structured evaluation establishes a factual benchmark, supports prioritization of corrective actions, and provides a reliable foundation for risk assessment, guarding upgrades, and continuous safety improvement. The preliminary audit of 50

machines highlights moderate overall compliance with significant safety gaps. Only 54% of machines were fully compliant, while 46% showed partial or non-compliance, indicating widespread deficiencies in guarding systems. Mechanical hazards were the most prevalent, accounting for 64% of identified risks, and 36% of machines were classified as high-risk. Interlock failures, ergonomic issues, and inconsistent maintenance practices further increased exposure. These findings emphasize the urgent need for prioritized machine guard upgrades, systematic risk control, and ergonomic improvements.

4.2. Compliance Evaluation

Compliance evaluation is a crucial phase of this project, aimed at assessing the extent to which machine guarding systems and associated safety measures conform to recognized standards such as ISO 12100 and OSHA 1910. Building on the findings of the preliminary audit, each machine was systematically evaluated using a structured checklist covering mechanical guarding integrity, functionality of interlocks and emergency stop devices, ergonomic accessibility, maintenance and inspection practices, and overall regulatory compliance. Machines were classified as compliant, partially compliant, or non-compliant based on their ability to meet both functional and regulatory requirements. Higher priority was assigned to equipment involving

frequent operator interaction, exposed moving parts, or high-energy operations, as these present a greater risk of injury. The evaluation identified common compliance gaps, including missing or damaged guards, malfunctioning or misaligned interlocks, poorly accessible control interfaces, and inadequate maintenance documentation. The compliance data were quantified to generate statistical insights, enabling identification of trends and high-risk areas. Results indicated that mechanical guarding and regulatory compliance exhibited the highest levels of non-compliance, requiring immediate corrective action. Interlocks, emergency stop systems, ergonomics, and maintenance practices generally showed partial compliance, indicating the need for targeted improvements rather than complete redesign. The outcomes of this phase directly informed the selection and prioritization of machine guard upgrades, ergonomic modifications, preventive maintenance planning, and operator training programs. By establishing a clear compliance baseline, this evaluation provides a measurable reference for post-implementation performance assessment and ensures that safety interventions are data-driven, practical, and aligned with statutory safety requirements.

Table 1 Compliance Evaluation Of Machine Guards And Safety Systems

S.No.	Machine / Equipment	Guarding Compliance	Interlocks / Safety Devices Compliance	Ergonomics & Accessibility Compliance	Maintenance & Inspection Compliance	Regulatory Compliance (ISO / OSHA)	Overall Compliance Score (0-100)	Remarks / Action Required
1	Hydraulic Press 1	Partial (enclosure incomplete)	Compliant (E-stop functional, interlock)	Non-compliant (controls hard to reach)	Partial (maintenance irregular)	Partial (ISO 12100 partially met)	72	Upgrade guards, improve

			operation al)					ergono mics, schedul e mainten ance
2	CNC Lathe 2	Complia nt (full guardin g)	Partial (sensor misalign ment)	Complian t	Compliant	Complian t	88	Adjust sensors to ensure correct interloc k activati on
3	Millin g Machi ne 3	Non-complia nt (guard missing on moving spindle)	Non-complian t (no interlock present)	Partial	Non-compliant (maintenan ce logs missing)	Non-compliant	45	Immedi ate replac ement of guard and installat ion of interloc ks; retraini ng require d
4	Conve yor System 4	Complia nt	Complian t	Complian t	Partial (inspecti on not documente d)	Complian t	85	Implem ent regular inspecti on log updates
5	Autom ated Press 5	Partial	Partial	Complian t	Compliant	Partial	70	Upgrad e interloc k system and re-evaluat

								Guard adequacy
6	Drilling Machine 6	Compliant	Compliant	Partial (controls hard to operate in confined space)	Compliant	Compliant	82	Modify control panel layout for better operator access
7	Shearing Machine 7	Non-compliant (exposed blades)	Non-compliant	Non-compliant	Non-compliant	Non-compliant	38	Immediate guard installation and interlock integration required; operator training essential
8	Grinding Machine 8	Partial	Compliant	Compliant	Compliant	Partial	76	Adjust guard height and verify ISO compliance
9	Lathe 9	Compliant	Compliant	Compliant	Compliant	Compliant	95	No immediate action required
10	Press	Partial	Partial	Partial	Partial	Partial	65	Compre

	Brake 10							ensive upgrade and mainten ance plan recomm ended
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Table 2. Compliance Evaluation

Compliance Category	Compliant (%)	Partial (%)	Non-Compliant (%)
Guarding	40	30	30
Interlocks / Safety Devices	50	30	20
Ergonomics & Accessibility	60	25	15
Maintenance & Inspection	55	30	15
Regulatory Compliance	45	35	20
Overall Compliance (Weighted Avg)	50	30	20

Table 3 Compliance Evaluation – Machine Guarding

Compliance Category	Compliant (%)	Partial (%)	Non-Compliant (%)
Guarding	40	30	30
Interlocks / Safety Devices	50	30	20
Ergonomics & Accessibility	60	25	15
Maintenance & Inspection	55	30	15
Regulatory Compliance	45	35	20
Overall Compliance (Weighted Avg)	50	30	20

Table 3. Compliance Evaluation – Machine Guarding

Compliance Parameter	Total Machines Audited	Compliant (Fully)	Partial Compliance	Non-Compliant	% Compliant	% Partial	% Non-Compliant	Action Priority
Guarding (Mechanical)	50	20	15	15	40%	30%	30%	High – Immediate upgrade required for non-compliant machines
Interlock	50	25	15	10	50%	30%	20%	Medium –

s / Safety Devices								Adjust and test devices in partial/non-compliant machines
Emergency Stop / E-stop	50	30	10	10	60%	20%	20%	High – Immediate repair of non-functional E-stops
Ergonomics & Accessibility	50	28	12	10	56%	24%	20%	Medium – Redesign operator access and controls
Maintenance & Inspection Practices	50	27	13	10	54%	26%	20%	Medium – Implement routine inspection schedules
Regulatory Compliance (ISO/OSHA)	50	22	18	10	44%	36%	20%	High – Correct non-compliant machines and review documentation
Overall Compliance Score (Weighted Avg)	50	–	–	–	50%	28%	22%	High – Target non-compliant and partial machines for priority upgrades

4.3. Risk Assessment and Analysis

Risk assessment and analysis form the core of this project by providing a systematic approach to identify, evaluate, and control hazards associated with industrial machinery. Conducted after the preliminary audit and compliance evaluation, this phase establishes a comprehensive understanding of risk sources, their causes, and potential consequences to workers, equipment, and productivity. The primary objective is to prioritize safety interventions using a data-driven framework while ensuring uninterrupted

operational performance. Hazard identification was carried out through detailed inspections, operator observations, and review of incident and maintenance records. Hazards were categorized into mechanical, electrical, and human factors. Mechanical hazards included exposed moving parts, rotating tools, pinch points, and sharp edges commonly observed in presses, lathes, conveyors, and CNC machines. Electrical hazards such as damaged insulation, improper grounding, and exposed wiring were assessed, particularly in automated and aging

equipment. Human factors, including unsafe work practices, inadequate training, fatigue, and ergonomic issues, were evaluated through interviews and task observations. Each identified hazard was analyzed using a risk assessment matrix combining severity and likelihood to determine overall risk levels. Risks were classified as high, medium, or low to support effective prioritization. High-risk machines—such as presses, shearing equipment, and lathes with exposed components—were targeted for immediate guarding upgrades and engineering controls. Medium-risk machines were scheduled for corrective actions and monitoring, while low-risk equipment required routine inspections. The analysis integrated quantitative data from incident history and near-miss reports with qualitative input from operators and maintenance personnel, ensuring that both technical and behavioral causes of accidents were addressed. Failure Mode and Effects Analysis (FMEA) further supported risk prioritization by identifying critical failure points in machine guarding systems. Overall, this structured risk assessment ensures efficient allocation of resources, effective hazard mitigation, and continuous improvement in machine safety, supporting regulatory compliance and fostering a proactive safety culture.

4.4. Guarding Upgrades

Machine guarding plays a vital role in controlling hazards and preventing injuries in industrial environments. The Guarding Upgrades phase of this project focuses on replacing outdated, non-compliant, or ineffective guarding arrangements with engineered safety solutions that minimize risk exposure while preserving operational efficiency. Based on the outcomes of the preliminary audit, compliance evaluation, and risk assessment, high-risk machines such as presses, lathes, milling machines, conveyors, CNC equipment, and shearing tools were prioritized for immediate intervention.

A range of guarding solutions was implemented to address machine-specific hazards. Interlocked barriers were installed on presses and CNC machines to prevent operation unless guards were correctly positioned, eliminating access to hazardous zones during operation. Fixed enclosures with transparent panels were introduced on lathes, grinders, and high-

speed equipment to prevent contact with rotating or cutting components while maintaining visibility. Adjustable guards were applied to machines requiring periodic access for material handling or adjustments, ensuring flexibility without compromising protection. In high-risk automated areas, presence-sensing devices such as light curtains and pressure-sensitive mats were deployed to instantly stop machine motion when operator intrusion was detected. Guarding upgrades were executed using a risk-based implementation approach, prioritizing machines with high severity and likelihood ratings. Ergonomic considerations, workflow compatibility, and maintenance requirements were carefully evaluated to prevent guard bypassing and ensure long-term effectiveness. Installation was carried out in coordination with operators and maintenance personnel to enhance usability and acceptance. The upgraded guarding systems resulted in significant reductions in mechanical hazard exposure, improved compliance with ISO 12100 and OSHA standards, and enhanced operator confidence. This phase demonstrates that well-designed, risk-driven guarding upgrades form a critical foundation for sustainable safety improvement and operational reliability in industrial settings.

4.5. Operator Training and Awareness

In industrial environments, operator behavior and awareness are as critical to workplace safety as engineering controls and machine guarding systems. Even the most advanced safety devices can fail to prevent accidents if operators lack adequate knowledge, skills, or motivation to follow established procedures. Therefore, operator training and awareness form a fundamental pillar of this safety optimization project, ensuring that personnel understand hazards, use upgraded guards correctly, and respond effectively to abnormal or emergency situations. The primary objective of operator training is to reduce risk through knowledge and competency. Operators are educated on mechanical, electrical, and human-factor hazards associated with presses, lathes, conveyors, milling machines, and CNC equipment. Special emphasis is placed on the correct use of upgraded guarding systems, including interlocked

barriers, adjustable guards, fixed enclosures, and presence-sensing devices, ensuring operators understand how these controls function in preventing injuries. Emergency preparedness is another key focus area, covering safe shutdown procedures, response to equipment malfunction, near-miss handling, and basic first aid. Additionally, training aims to promote a proactive safety culture by encouraging hazard reporting, safe work practices, and shared responsibility for workplace safety. Regulatory awareness of ISO 12100 and OSHA requirements is integrated to reinforce compliance and accountability. The training program is delivered through a blended methodology combining classroom instruction, hands-on machine demonstrations, simulation-based emergency drills, and practical assessments. Ergonomic and behavioral safety modules address fatigue management, posture

correction, repetitive strain prevention, and stress reduction to minimize human error. Continuous awareness is reinforced through visual signage, toolbox talks, and recognition of safe behaviors. The effectiveness of the training program is evaluated using pre- and post-training assessments, incident statistics, compliance audits, and operator feedback. Results demonstrate significant improvements in safety knowledge, correct use of machine guards, emergency response capability, and overall compliance. By integrating operator training closely with guarding upgrades, the project ensures that technical improvements are fully supported by competent, safety-conscious personnel, leading to sustainable reductions in workplace risk and enhanced operational reliability

Table 4 Overview of Operator Training and Awareness Program

Parameter	Pre-Training Data	Post-Training Data	% Improvement / Change	Notes / Observations
Number of Workplace Incidents	15 incidents per month	5 incidents per month	66.7% reduction	Includes minor injuries and near-misses
Number of Near-Misses Reported	22 per month	12 per month	45.5% reduction	Improvement indicates better hazard avoidance
Operator Compliance Rate (Safety Protocols)	70%	95%	+25%	Measured via audit and observation
Correct Use of Machine Guards	68%	97%	+29%	Assessed during practical evaluations
Operator Knowledge Scores (Written Test)	Avg. 62%	Avg. 92%	+30%	Reflects understanding of hazards and procedures
Practical Skills Assessment	Avg. 65%	Avg. 93%	+28%	Hands-on proficiency with upgraded guards

Feedback Survey: Safety Awareness	Avg. 3.2 / 5	Avg. 4.7 / 5	+1.5 points	Measures perceived confidence in operating safely
Emergency Response Competency	60% of operators competent	90% of operators competent	+30%	Includes shutdown and first aid response
Frequency of Safety Reporting	2 reports per operator per month	5 reports per operator per month	+150%	Indicates proactive engagement in safety culture
Ergonomic Risk Compliance	55%	85%	+30%	Includes proper posture, lifting, and workstation adjustment
Training Attendance Rate	80%	100%	+20%	Achieved after mandatory refresher sessions
Operator Satisfaction with Training	3.5 / 5	4.8 / 5	+1.3 points	Evaluates perceived usefulness and practicality of training

4.6. Documentation and Continuous Monitoring

Documentation and continuous monitoring are essential for sustaining safety optimization in industrial environments. While machine guard upgrades and risk assessments provide immediate hazard control, their long-term effectiveness depends on structured documentation, regular evaluation, and proactive monitoring. In the project “Safety Optimization Through Machine Guard Upgrades and Comprehensive Risk Assessment”, documentation ensures traceability, accountability, and regulatory compliance, while continuous monitoring verifies that implemented controls remain effective over time. This integrated approach aligns with ISO 12100, OSHA guidelines, and established Safety Management System (SMS) practices. A comprehensive documentation framework is maintained throughout the project lifecycle, covering planning, implementation, operation, monitoring,

and review stages. Key documents include machine safety audit checklists, compliance evaluation reports, hazard identification and risk assessment sheets, risk registers, guard upgrade design and approval records, installation logs, SOPs, training records, maintenance logs, incident and near-miss reports, CAPA reports, and management review records. Together, these documents provide a systematic record of safety decisions, engineering changes, and performance outcomes, supporting audits and continuous improvement. Continuous monitoring complements documentation by providing ongoing oversight of machine safety performance. Routine inspections by operators and supervisors, periodic safety audits, and maintenance checks ensure that guards remain intact, functional, and compliant. Where applicable, sensor-based and automated monitoring systems such as interlocks, emergency stop diagnostics, and presence-sensing devices provide real-time feedback and alerts. Incident and near-miss trend analysis further supports

proactive risk management by identifying recurring issues and emerging hazards. Performance indicators, including incident rates, near-miss reporting frequency, guard-related non-conformities, training compliance, and audit closure time, are used to evaluate monitoring effectiveness. Regular management reviews analyze these indicators and drive corrective actions and system improvements. Overall, robust documentation combined with continuous monitoring ensures sustainable hazard control, regulatory compliance, and long-term enhancement of workplace safety culture.

4.7. Results and Discussion

The implementation of machine guard upgrades integrated with a comprehensive risk assessment framework resulted in significant improvements in workplace safety and operational reliability. Safety performance was evaluated by comparing conditions before and after the intervention phases, which included preliminary audits, guard upgrades, operator training, and continuous monitoring. The results clearly demonstrate that combining engineering controls with structured risk management and behavioral interventions effectively reduces hazard exposure without adversely affecting productivity. Reduction in Identified Hazards and Risk Levels Initial safety audits and risk assessments identified numerous mechanical and operational hazards associated with exposed moving parts, rotating components, cutting tools, and frequent operator interaction zones. Prior to intervention, many of these hazards were categorized as high risk due to inadequate or damaged guarding and non-compliance with ISO 12100 and OSHA requirements. Following the installation of upgraded guarding solutions such as fixed and adjustable guards, interlocked barriers, and presence-sensing devices most high-risk hazards were reduced to medium or low risk levels. This improvement was achieved by physically isolating hazardous zones and incorporating fail-safe mechanisms that stopped machine operation when guards were opened or compromised, confirming the effectiveness of engineering controls in lowering both injury severity and likelihood. Impact on Incidents, Near-Misses, and Operator Behavior

A notable reduction in machine-related incidents and near-miss occurrences was observed after implementation. Pre-upgrade records showed recurring minor injuries and unsafe practices, often linked to guard bypassing and limited hazard awareness. Post-intervention data indicated a decline in such events, supported by improved guarding, effective interlocks, and targeted training. An initial increase in near-miss reporting following training reflected heightened safety awareness and proactive reporting, which later stabilized as actual hazard exposure decreased. Compliance audits and observations further showed reduced unsafe behaviors and improved adherence to SOPs, highlighting positive behavioral change. Productivity, Monitoring, and Overall Effectiveness Concerns regarding increased downtime due to enhanced guarding were not substantiated. While minor stoppages occurred during initial adjustment phases, overall downtime related to accidents and unplanned maintenance decreased. Machines equipped with upgraded guards demonstrated more stable and reliable operation. Continuous monitoring through inspections, maintenance logs, and performance indicators played a crucial role in sustaining improvements by enabling early detection of deviations and equipment issues. Although the study period limited long-term statistical validation, the findings confirm that systematic risk assessment combined with appropriate machine guard upgrades and training leads to reduced high-risk hazards, lower incident rates, improved operator compliance, and better alignment with ISO and OSHA standards. Overall, the results demonstrate that a holistic approach to machine safety enhances both worker protection and operational performance, providing a strong foundation for continuous improvement and future adoption of predictive safety systems.

4.8. Challenges and Solutions

The implementation of safety optimization through machine guard upgrades and systematic risk assessment presented several technical, operational, and behavioral challenges. One major challenge was the diversity of machines in terms of age, design, and operational function. Older machines often lacked compliant guarding, while newer machines showed

partial adherence to ISO and OSHA standards. This variability made uniform guarding impractical. To address this, machine-specific risk assessments were conducted, and customized guarding solutions such as fixed, adjustable, interlocked, and presence-sensing guards were selected based on individual hazard profiles. Limited workspace and ergonomic constraints posed another challenge, as conventional guard designs sometimes restricted visibility or operator movement. This was mitigated by integrating ergonomic principles into guard design, using transparent materials, compact interlocks, and adjustable or sliding guards, along with incorporating operator feedback during trial installations. Resistance to change and unsafe practices such as guard bypassing were significant human-factor challenges. Operators initially perceived upgraded guards as barriers to productivity. These issues were addressed through participatory training, awareness programs, enhanced supervision, tamper-resistant interlocks, and updated SOPs, which improved acceptance and compliance. Maintenance and reliability of advanced guarding systems also required attention due to sensor faults and mechanical wear. A structured preventive maintenance program supported by inspection logs and specialized maintenance training ensured long-term reliability. Inconsistent documentation and difficulty in measuring safety effectiveness were resolved by implementing standardized digital documentation and multi-metric performance indicators beyond accident data alone. Overall, these challenges were effectively addressed through a holistic approach combining customized engineering controls, ergonomic design, workforce engagement, structured documentation, and continuous monitoring, ensuring sustainable safety improvement without compromising productivity.

4.9. Performance Evaluation

Performance evaluation is a critical phase for assessing the effectiveness of safety interventions implemented through machine guard upgrades and comprehensive risk assessment. In this project, evaluation was conducted to measure improvements in workplace safety, regulatory compliance, and operational reliability resulting from engineering

controls, training programs, and continuous monitoring systems. The evaluation framework was designed in alignment with ISO 12100 risk reduction principles and OSHA's performance-based safety management approach. A balanced set of leading and lagging indicators was used. Lagging indicators included incident frequency rate, injury severity, accident-related downtime, and guard-related incidents, while leading indicators focused on near-miss reporting frequency, safety audit scores, operator compliance levels, training participation, and preventive maintenance completion rates. This dual approach provided a comprehensive and realistic assessment of safety performance. Baseline evaluation conducted prior to implementation revealed high exposure to mechanical hazards, inconsistent compliance, low near-miss reporting, reactive maintenance practices, and inadequate documentation. Post-implementation results showed a clear reduction in machine-related incidents and injury severity due to improved guarding systems that eliminated access to hazardous zones. Near-miss reporting initially increased, reflecting improved safety awareness, and later stabilized as actual risks were reduced. Operator compliance improved significantly, with reduced guard bypassing and better adherence to SOPs and emergency procedures. Evaluation of guard functionality confirmed reliable interlock performance, structural integrity, and ergonomic suitability. Training programs enhanced hazard recognition and proactive safety behavior. Additionally, accident-related downtime decreased, demonstrating that safety improvements positively contributed to productivity. Overall, the performance evaluation confirms that integrated safety optimization measures deliver measurable and sustainable improvements in industrial safety performance.

Conclusion

The project successfully demonstrates that systematic safety interventions can significantly reduce workplace hazards while maintaining operational efficiency. Combining structured risk assessment methodologies with targeted machine guarding upgrades, the study addresses critical mechanical, electrical, and human-factor risks commonly present

in industrial environments. The preliminary audit and compliance evaluation provided a clear understanding of existing safety gaps and non-conformities with ISO 12100 and OSHA standards. Risk assessment using a severity-likelihood matrix enabled effective prioritization of hazards and guided the selection of appropriate engineering controls. The implementation of upgraded guarding solutions including fixed enclosures, interlocked guards, adjustable barriers, and presence-sensing devices substantially reduced operator exposure to hazardous machine components. Operator training and awareness programs played a vital role in reinforcing safe work practices and improving compliance. Enhanced safety culture was evident through improved operator behavior, increased near-miss reporting, and proactive participation in safety initiatives. Comprehensive documentation and continuous monitoring further ensured traceability, accountability, and sustainability of safety improvements. Performance evaluation results confirmed a notable reduction in incident frequency, near-miss occurrences, and accident-related downtime. The findings highlight that safety optimization, when implemented through a holistic and data-driven approach, contributes not only to injury prevention but also to improved operational reliability and productivity. Overall, the project validates that integrating engineering controls with comprehensive risk assessment, training, and continuous monitoring is an effective strategy for achieving long-term workplace safety. The methodologies and outcomes of this study provide a scalable framework that can be adapted across various industrial settings, supporting continuous improvement and proactive safety management in line with modern safety standards.

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