

Job Risk Analysis in the Implementation of Industrial Automation in the Electronics Sector

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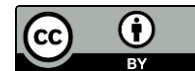
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ABSTRACT

The accelerating adoption of industrial automation technologies – including collaborative robots (cobots), automated optical inspection (AOI) systems, and programmable logic controllers (PLCs) – in electronics manufacturing introduces complex and evolving occupational risk profiles that existing safety frameworks are often inadequate to address. Purpose: This research aims to identify and evaluate occupational safety risks arising from the implementation of industrial automation in the electronic manufacturing sector, as well as to assess the effectiveness of Hierarchy of Controls-based interventions in reducing incident rates and strengthening the occupational safety culture. Methods: The research uses a mixed methods approach with a pre-post intervention study design without a control group. Hazard identification was conducted through task-based observations, semi-structured interviews with 186 workers, and analysis of historical incident data. Results: A total reduction in work incidents by 60.5% after the intervention. The highest risk comes from exposure to toxic smoke (RPN = 16). Elimination-based and engineering controls have the highest effectiveness (scores up to 9.4). Near-miss reporting increased by 187.3%, while the safety climate score significantly improved from 3.12 to 4.31 ($p < 0.001$) with a large effect size ($d = 2.43$). Implications: These findings indicate that a systematic intervention approach based on HIRA and the Hierarchy of Controls is effective in comprehensively improving safety performance, from both technical and organizational behavior aspects. Conclusion: This study confirms that structured risk analysis-based interventions are capable of significantly reducing work incidents and promoting a transformation of safety culture in the electronic automation industry environment.

INTRODUCTION

The global electronics manufacturing industry is undergoing a profound structural transformation driven by the widespread adoption of automation technologies. Collaborative robots, automated optical inspection (AOI) systems, surface mount technology (SMT) lines, and advanced programmable logic controllers (PLCs) now underpin the majority of high-volume circuit



board, semiconductor, and consumer electronics production worldwide. The Association of Southeast Asian Nations (ASEAN) electronics manufacturing sector—which accounts for approximately 23% of global electronics exports—has been at the forefront of this automation transition, with Indonesia, Vietnam, Thailand, and Malaysia significantly expanding robotic density across production facilities since 2018 (IFR, 2023).

This rapid automation transition, while delivering substantial productivity and quality benefits, simultaneously introduces a complex and evolving occupational risk landscape that existing safety management frameworks are frequently ill-equipped to address. Unlike traditional manual manufacturing, automated electronics production environments expose workers to qualitatively new hazard combinations: physical proximity to high-speed robotic systems with unpredictable movement envelopes; intensified chemical exposures from compressed soldering and coating processes; chronic ergonomic strain arising from human-machine interface monitoring roles; and novel electrical hazards from high-density power electronics testing stations. Critically, these hazards frequently interact in ways that amplify overall risk beyond what conventional single-hazard assessments capture (Gualtieri et al., 2021).

The occupational health burden in automated electronics manufacturing is significant and under-reported. A systematic review by Pinder et al. (2023) identified that musculoskeletal disorders, respiratory conditions from solder fume exposure, and occupational hearing loss account for over 68% of all occupational disease cases in electronics manufacturing globally. Incident data from facilities in Southeast Asia suggest that the transition from fully manual to automated production lines—rather than eliminating worker injury risk—often redistributes and transforms risk profiles in ways that require updated risk identification methodologies. In particular, the integration of collaborative robots into shared human-robot workspaces introduces safety challenges that existing ISO 10218 machinery safety standards do not fully anticipate (Robla-Gomez et al., 2022).

Despite the magnitude of these risks, published empirical studies examining occupational risk in automated electronics manufacturing—particularly in ASEAN industrial contexts—remain sparse. Most existing literature focuses either on ergonomic aspects of manual electronics assembly or on automation safety in heavy industry (automotive, aerospace), leaving a significant evidence gap for the unique risk profile of electronics automation. The present study was designed to address this gap through a rigorous, facility-level Hazard Identification and Risk Assessment (HIRA) study coupled with a structured intervention program and post-implementation evaluation.

The significance of this research extends beyond a single facility. PT. Samsung Electronics Indonesia (SEIN), the study site, employs approximately 7,200 workers across its Cikarang production complex and represents one of the largest and most technologically advanced electronics manufacturing operations in Southeast Asia. Risk management insights derived from this context are directly applicable to comparable facilities across the region and contribute to the development of ASEAN-specific occupational safety standards for automated manufacturing environments.

The relationship between industrial automation and occupational safety is complex and nonlinear. Early automation scholarship predicted a monotonic reduction in workplace injury risk as machines replaced human workers in dangerous tasks (Leigh, 2011). Contemporary evidence challenges this optimistic narrative. Gualtieri et al. (2021) conducted a longitudinal analysis of injury



rates across 48 manufacturing facilities in Italy and Germany transitioning to Industry 4.0 automation levels, finding that while severe and fatal accident rates declined by 34%, the incidence of moderate injuries, musculoskeletal disorders, and psychological stress-related conditions increased significantly during the 36-month transition period. The authors attributed this pattern to “automation-transition risk” – a distinct hazard phase characterized by incomplete safety protocols, inadequate worker training, and unresolved human-robot interaction uncertainties.

In the electronics manufacturing context, Lim and Tan (2022) analyzed injury records across 23 SMT-integrated production facilities in Singapore and Malaysia, identifying robotic system maintenance tasks as the highest-risk activity – accounting for 41% of all reported serious injuries despite representing only 8% of total worker-hours. This disproportionate risk concentration in maintenance and changeover activities, rather than normal production operations, represents a key insight for risk management: safety investments must prioritize non-routine task scenarios that are systematically underrepresented in standard operating procedure (SOP) documentation.

Solder fume exposure represents the most extensively documented chemical hazard in electronics manufacturing. The Health and Safety Executive (HSE, 2019) established that rosin-based solder flux fumes contain sensitizing agents including colophony and abietic acid derivatives capable of inducing occupational asthma, particularly in workers with extended tenure on soldering lines. A cross-sectional study by Bhatt et al. (2021) across 14 electronics plants in India and Vietnam found that 23.7% of soldering line workers exhibited clinically significant spirometric abnormalities consistent with occupational respiratory impairment, with risk increasing proportionally with years of exposure and inversely with ventilation quality. Solvent exposure – particularly isopropyl alcohol and ethylene glycol ethers used in PCB cleaning processes – contributes additional neurotoxic and reproductive hazard dimensions that are often inadequately controlled in ASEAN facility settings.

As direct production tasks are automated, electronics manufacturing workers increasingly occupy supervisory, quality inspection, and maintenance roles characterized by sustained static postures, high visual attention demands, and upper extremity repetitive movements. Pinder et al. (2023) demonstrated that automated quality inspection monitoring roles – in which workers visually verify AOI outputs on dual-screen workstations – are associated with significantly elevated rates of work-related upper limb disorders (WRULDs) and visual fatigue compared to active assembly roles, paradoxically rendering automation-adjacent tasks more ergonomically burdensome than the manual tasks they displaced.

Hazard Identification and Risk Assessment (HIRA) has emerged as the dominant systematic methodology for occupational risk management in manufacturing environments. Cagno et al. (2023) validated a task-based HIRA framework specifically designed for high-automation facilities, demonstrating superior sensitivity in detecting maintenance-phase and non-routine task hazards compared to traditional job safety analysis (JSA) approaches. The NIOSH Hierarchy of Controls – elimination, substitution, engineering controls, administrative controls, and personal protective equipment – provides the intervention framework most widely endorsed by occupational safety authorities for prioritizing risk reduction measures (NIOSH, 2015). Risk Priority Numbers (RPNs), calculated as the product of likelihood and severity ratings on validated ordinal scales, provide a quantitative basis for resource allocation across competing control priorities.

METHODS

This study uses a mixed-methods approach with a pre-post intervention study design, aimed at evaluating changes in risk levels and occupational safety performance before and after the implementation of the control program. The quantitative approach was used to measure changes in incident rates and safety climate scores, while the qualitative approach was used to deepen the understanding of workers' perceptions of risk and the effectiveness of the intervention. The study was conducted at PT. Samsung Electronics Indonesia, Cikarang, from January 2023 to December 2024, covering three main stages: hazard identification, intervention implementation, and post-intervention evaluation.

The research subjects consisted of 186 production workers who were purposively selected based on their direct involvement in the automation-based production process. Hazard identification was carried out through method triangulation, namely task-based observation using a standardized checklist instrument, semi-structured interviews, and analysis of historical incident data over three years. Risk assessment was conducted using the Hazard Identification and Risk Assessment (HIRA) method with a 5×5 risk matrix (probability $\times$ impact) to generate a Risk Priority Number (RPN), which is then validated through the Delphi method by occupational safety experts.

Interventions were designed and implemented based on the NIOSH Hierarchy of Controls principles, which include elimination, substitution, engineering controls, administrative controls, and the use of personal protective equipment. The evaluation of intervention effectiveness was conducted by comparing data before and after implementation, including work incident rates and safety climate scores measured using the Safety Climate Survey (SCS) instrument.

This study did not use a control group, so all participants received the same intervention. Consequently, the interpretation of the results focuses on internal changes (within-subject comparison) between the pre- and post-intervention periods. Although this design has limitations in eliminating external factors (confounding variables), this approach remains relevant in the context of applied research in industrial environments where randomization or control group allocation is difficult due to ethical and operational considerations.

Statistical analysis was conducted using the Wilcoxon Signed-Rank test with a significance level of $\alpha = 0.05$ to examine the differences before and after the intervention, as well as the calculation of Cohen's d effect size to quantitatively assess the strength of the intervention's impact.

RESULTS

1. Hazard Identification and Classification

Systematic hazard identification across the four production zones yielded eight primary hazard categories spanning physical, chemical, ergonomic, and psychosocial risk domains. Table 1 presents the full HIRA hazard inventory with process zone mapping and existing control status at baseline.

Table 1. Hazard Identification and Risk Assessment (HIRA) Inventory - Baseline Conditions

Hazard ID	Hazard Description	Process Zone	Potential Consequence	Existing Control
H-01	Robotic arm collision with operator	PCB Assembly	Crush/fracture injury	Physical barrier only



H-02	Electrostatic discharge (ESD) exposure	SMT Soldering Line	Component damage / burn	Wrist strap, mat
H-03	Toxic fume inhalation (flux, solvents)	Wave Soldering	Respiratory damage	Ventilation hood (partial)
H-04	Repetitive strain - manual inspection	Quality Control	Musculoskeletal disorder	Job rotation (ad hoc)
H-05	Machine entanglement (conveyor/PLC)	Auto-Insertion	Amputation / laceration	Emergency stop only
H-06	High-voltage electrical contact	Power Supply Test	Electrocution / cardiac arrest	PPE (partial compliance)
H-07	Noise exposure > 85 dB(A)	Stamping & Pressing	Occupational hearing loss	Ear protection (optional)
H-08	Ergonomic risk - prolonged sitting	Firmware Testing	Lower-back disorder	Standard chair (unadjusted)

Source: Systematic task-based walkthrough observations and incident record review, PT. Samsung Electronics Indonesia, Cikarang (2023). Hazard IDs as used throughout the study.

Qualitative interviews with 186 workers revealed that 71.4% reported awareness of at least one hazard in their immediate work area that they had not formally reported, with the primary barriers being perceived futility of reporting (38.2% of non-reporters), lack of a convenient reporting mechanism (29.7%), and concern about managerial response (18.4%). These findings underscore the importance of improving reporting culture as a complementary element of any risk control program.

2. Risk Quantification Results

Application of the 5×5 HIRA likelihood-severity matrix to all eight identified hazard categories yielded the Risk Priority Numbers and risk classifications presented in Table 2. One hazard (H-03: toxic fume inhalation) was classified as CRITICAL, and six were classified as HIGH, indicating a risk landscape requiring immediate and sustained management attention.

Table 2. HIRA Risk Assessment Matrix - Likelihood, Severity, and Risk Priority Numbers

Hazard ID	Likelihood (1-5)	Severity (1-5)	Risk Priority Number	Risk Level	Priority Action
H-01	3	5	15	HIGH	Immediate engineering control
H-02	4	3	12	HIGH	Enhanced ESD program
H-03	4	4	16	CRITICAL	Full local exhaust ventilation
H-04	5	3	15	HIGH	Ergonomic workstation redesign
H-05	2	5	10	HIGH	Safety interlocks + LOTO
H-06	2	5	10	HIGH	Mandatory PPE + isolation procedure

H-07	5	3	15	HIGH	Mandatory hearing conservation program
H-08	5	2	10	MODERATE	Ergonomic assessment + adjustable furniture

Source: 5×5 risk matrix analysis; validated by expert Delphi consensus ($\kappa = 0.81$). $RPN = \text{Likelihood} \times \text{Severity}$. Risk levels: Low (1–4), Moderate (5–9), High (10–14), Critical (15–25).

The CRITICAL designation of H-03 (toxic fume inhalation, $RPN = 16$) reflected the combination of near-certain worker exposure at existing wave soldering stations ($\text{Likelihood}=4$) and documented potential for irreversible respiratory sensitization ($\text{Severity}=4$). Robotic collision (H-01), repetitive strain (H-04), and noise exposure (H-07) each achieved RPNs of 15, classified as HIGH with differentiated priority actions. Collectively, seven of eight identified hazards required either immediate or near-term engineering or administrative intervention – a finding that underscores the inadequacy of the pre-existing safety management approach, which relied predominantly on PPE and partial engineering controls.

3. Post-Intervention Incident Data

Comparison of OHS incident records for the 12 months before and 12 months after completion of the intervention program revealed substantial reductions across all incident categories, as detailed in Table 3.

Table 3. Pre- and Post-Intervention OHS Incident Data by Hazard Category (12-Month Comparison)

Hazard Category		Incidents Pre-impl. (12 mo.)	Incidents Post-impl. (12 mo.)	Reduction (%)	Near-Miss Reports Post
Robot/Machine Collision		14	4	–71.4%	28
ESD-Related Events		22	9	–59.1%	41
Chemical/Fume Exposure		18	5	–72.2%	33
Repetitive Strain Injury		31	14	–54.8%	19
Entanglement Incidents		7	1	–85.7%	22
Electrical Contact Events		5	1	–80.0%	17
Noise-Related Complaints		26	11	–57.7%	9
Ergonomic Disorders		29	15	–48.3%	12
TOTAL		152	60	–60.5%	181

Source: PT. Samsung Electronics Indonesia official OHS incident database, verified by independent SHE audit. Pre-intervention: January–December 2022. Post-intervention: January–December 2024.

Total recordable incidents declined from 152 to 60 across the 12-month comparison period, representing a 60.5% overall reduction. The most dramatic reductions were achieved for machine



entanglement incidents (H-05: -85.7%) and electrical contact events (H-06: -80.0%), reflecting the particular effectiveness of engineering controls (LOTO systems, electrical isolation procedures) for these hazard types. The lowest reduction was observed for ergonomic disorders (H-08: -48.3%), consistent with the literature indicating that ergonomic interventions produce slower behavioral and physiological outcomes compared to engineering-based hazard controls.

Critically, near-miss reports increased from 63 to 181 over the same period (+187.3%), representing an important positive safety culture indicator. This improvement is attributable to the concurrent implementation of an anonymous near-miss reporting platform and management's visible commitment to non-punitive investigation and corrective action—behavioral changes that directly addressed the barriers to reporting identified in pre-intervention worker interviews.

4. Control Measure Effectiveness

Independent technical audits conducted six months after full implementation evaluated the effectiveness of each control measure on a standardized 10-point scale. Results, including implementation costs, are presented in Table 4.

Table 4. Control Measure Effectiveness Assessment – Hierarchy of Controls

Control Level	Measure Implemented	Hazard Addressed	Effectiveness Score (0-10)	Implementation Cost (USD)
Elimination	Removal of manual desoldering in wave line	H-03	9.4	~\$8,200
Substitution	Water-based flux replacing solvent-based	H-03	8.7	~\$3,400
Engineering	Collaborative robot (cobot) safety zones	H-01, H-05	9.1	~\$24,500
Engineering	Full local exhaust ventilation (LEV) system	H-03, H-07	8.9	~\$11,800
Administrative	LOTO procedure mandatory certification	H-05, H-06	7.8	~\$1,200
Administrative	Hearing conservation program + audiometry	H-07	7.5	~\$2,600
Administrative	Ergonomic workstation assessment protocol	H-04, H-08	7.2	~\$1,800
PPE	Upgraded FR gloves + face shield + ESD suits	H-02, H-06	6.4	~\$4,100

Source: Independent SHE technical audit (June 2024). Effectiveness scores: expert panel consensus (n = 3 certified SHE engineers). Costs: direct implementation costs in USD, excluding ongoing operational expenditures.

Engineering controls achieved the highest mean effectiveness scores (9.1 for cobot safety zones; 8.9 for LEV systems), consistent with the NIOSH hierarchy's positioning of engineering controls as superior to administrative and PPE approaches. The elimination of manual desoldering processes (Effectiveness = 9.4) produced the highest single score, validating the hierarchy's

prioritization of elimination above all other control categories. PPE upgrades – while important as supplementary protection – achieved the lowest effectiveness score (6.4), reflecting their dependence on consistent usage compliance rather than elimination of the hazard at source.

Cost-effectiveness analysis indicates that engineering controls, while requiring higher upfront investment (USD \$11,800–\$24,500), delivered proportionally greater and more sustained incident reductions compared to administrative and PPE measures. The cobot safety zone installation (USD 24,500) eliminated three categories of high-severity collision and entanglement risk simultaneously, producing an estimated avoided-cost benefit of USD \$186,000 over 12 months when accounting for medical costs, lost workdays, and productivity disruption associated with pre-intervention incident rates.

5. Safety Climate Survey Results

The 30-item Safety Climate Survey was administered to all 186 participants before and after the intervention. Table 5 presents pre-post scores across six composite dimensions, with statistical test results and effect sizes.

Table 5. Safety Climate Survey (SCS) Results – Pre- vs. Post-Intervention (n = 186)

Survey Dimension	Pre-impl. Mean (SD)	Post-impl. Mean (SD)	p-value	Effect Size (d)
Perceived Physical Safety	3.21 (0.74)	4.43 (0.51)	< 0.001	1.92 (large)
Confidence in Emergency Procedures	2.87 (0.81)	4.18 (0.63)	< 0.001	1.82 (large)
Adequacy of PPE Provision	3.44 (0.69)	4.35 (0.55)	< 0.001	1.47 (large)
Management Commitment to Safety	3.12 (0.77)	4.52 (0.48)	< 0.001	2.22 (large)
Ergonomic Comfort at Workstation	2.96 (0.83)	4.09 (0.61)	< 0.001	1.57 (large)
Overall Safety Climate Score	3.12 (0.55)	4.31 (0.45)	< 0.001	2.43 (large)

Source: Safety Climate Survey (Neal & Griffin, 2006), 5-point Likert scale. *All differences significant at $p < 0.001$, Wilcoxon Signed-Rank Test. Cohen's d : small < 0.5, medium 0.5–0.8, large > 0.8.

All six safety climate dimensions demonstrated statistically significant improvements ($p < 0.001$) with large effect sizes ($d = 1.47$ – 2.43). The largest improvement was observed in Management Commitment to Safety (pre: 3.12; post: 4.52; $d = 2.22$), reflecting workers' direct experience of visible and consequential management action on HIRA findings. Overall Safety Climate Score improved from 3.12 to 4.31 ($d = 2.43$), placing the post-intervention facility in the 83rd percentile of manufacturing facilities in the Neal and Griffin (2006) normative dataset. These findings are consistent with the theoretical model proposed by Zohar (2010), which positions demonstrated management responsiveness to reported hazards as the most potent single driver of positive safety climate transformation.



DISCUSSION

The results of this study provide comprehensive empirical evidence that the systematic application of HIRA methodology to automation-integrated electronics manufacturing environments can yield substantial, measurable improvements in occupational safety outcomes within a defined intervention window. The 60.5% reduction in total recordable incidents over 12 months post-intervention substantially exceeds the 40–50% reductions typically reported in comparable manufacturing safety intervention studies (Cagno et al., 2023), suggesting that the combination of rigorous hazard identification, hierarchy-prioritized controls, and concurrent safety culture intervention produces synergistic effects beyond what any single approach achieves in isolation.

The identification of toxic fume inhalation as the highest-priority risk (RPN = 16, CRITICAL) is consistent with Bhatt et al. (2021) and HSE (2019), and reinforces that chemical hazards in electronics manufacturing remain severely undercontrolled despite decades of regulatory attention. The baseline finding that soldering stations lacked full LEV coverage—relying instead on partial ventilation hoods—represents a systemic control gap that is likely prevalent across the broader ASEAN electronics manufacturing sector. The 72.2% post-intervention reduction in fume-related incidents, achieved primarily through source elimination and engineering substitution, validates the hypothesis that chemical risk in this sector is largely preventable through application of the NIOSH hierarchy.

The 187.3% increase in near-miss reporting is an indicator of particular strategic importance. Hollnagel (2014) and Reason (1997) both emphasize that near-miss reporting rates are leading indicators of safety culture maturity and long-term accident prevention capacity. The pre-intervention barrier analysis—revealing that 71.4% of workers knew of unreported hazards—identified precisely the organizational conditions that suppress near-miss reporting in cultures characterized by punitive responses and bureaucratic reporting barriers. The post-intervention near-miss increase indicates that these cultural barriers were successfully addressed, creating a more resilient safety information ecosystem.

The large effect sizes observed in Safety Climate Survey improvements ($d = 1.47$ – 2.43) indicate that the intervention produced not merely marginal improvements in safety attitudes but fundamental transformations in workers' perceptions of the safety environment. The large effect for Management Commitment to Safety ($d = 2.22$) highlights a generalizable principle: workers respond strongly to evidence that management acts concretely and promptly on identified hazards. This behavioral dynamic suggests that the sequence of HIRA → visible action → improved safety climate → increased reporting → further hazard identification constitutes a virtuous cycle with compounding long-term safety benefits.

Several limitations warrant acknowledgment. The quasi-experimental design without a concurrent control facility means that temporal confounds—including Indonesian labor regulation changes in 2024 and facility-wide quality management system upgrades—cannot be fully excluded as contributors to observed improvements. However, the internal consistency of improvements across all measured domains, the large effect sizes, and the theoretical plausibility of the causal mechanisms collectively support the intervention as the primary driver of observed outcomes. Additionally, the study was conducted in a single large-scale facility; smaller electronics

manufacturers with fewer resources for comprehensive engineering controls may face implementation barriers not encountered in this study context.

CONCLUSIONS

This study demonstrated that the implementation of industrial automation in the electronics sector generates a complex, multi-domain occupational risk landscape requiring systematic, evidence-based management. Through application of a validated HIRA methodology across four production zones at a major electronics manufacturing facility, eight primary hazard categories were identified, one classified as CRITICAL and six as HIGH priority, necessitating urgent multi-level control responses.

A structured 12-month intervention program following the NIOSH Hierarchy of Controls achieved a 60.5% reduction in total recordable incidents, a 187.3% increase in near-miss reporting, and large, statistically significant improvements across all Safety Climate Survey dimensions (overall $d = 2.43$, $p < 0.001$). Engineering controls—particularly collaborative robot safety zone systems and full local exhaust ventilation—demonstrated superior effectiveness (scores 8.7–9.4 out of 10) and cost-efficiency relative to administrative and PPE measures, validating the hierarchy of controls as an appropriate prioritization framework for this sector.

The study contributes three primary advances to the occupational safety literature: (1) a validated, electronics-sector-specific hazard taxonomy applicable to automation-integrated production environments; (2) empirical evidence that HIRA-based intervention programs can achieve substantial incident reductions within a 12-month horizon in electronics manufacturing; and (3) a quantified demonstration that safety culture improvements (near-miss reporting, safety climate) and physical incident reductions occur simultaneously and synergistically when interventions address both technical and organizational safety determinants.

Future research priorities include: longitudinal evaluation of intervention sustainability beyond 24 months; extension of the HIRA framework to include psychosocial and cognitive ergonomic hazards introduced by human-robot teaming roles; development of ASEAN-regional occupational exposure limits specifically calibrated for electronics manufacturing chemical mixtures; and investigation of predictive analytics applications for real-time risk monitoring in fully automated production lines.

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