Albahit Journal of Applied Sciences
"open-access, peer-reviewed biannual journal"
eISSN: 2708-8936, pISSN: 2708-244X
Volume 5, Issue 3, 2026
Page No: 125-145
***Website**: https://albahitjas.com.ly/index.php/albahit/en/index*

Reconstructing Electrical Safety Barriers in Indonesian Manufacturing SMEs Using Systems-Theoretic Process Analysis

Ali Mahmoud Assabri [1*], Naji Abdalaziz Ali [2], Ahmed S. Mohamed [3]
[1] Department of Engineering Management, College of Technical Sciences, Bani Walid, Libya
[2] Department of Mechanical Engineering, College of Technical Sciences, Bani Walid, Libya
[3] Department of Electrical and Electronic Engineering, College of Technical Sciences, Bani Walid, Libya
[*]*Corresponding author:* ***alimahmoudassabri@gmail.com***

Received: 22-04-2026	**Accepted:** 18-07-2026	**Published:** 02-08-2026

Abstract:
The International Labour Organization estimates that work-related diseases and injuries account for approximately 2.93 million deaths and 395 million non-fatal work injuries annually These figures do not isolate electrical events in Indonesia, but they underline the importance of prevention-oriented occupational safety and health (OSH) systems, particularly in small enterprises where specialist expertise, formal supervision, documentation, and maintenance resources may be limited. Electricity is indispensable to manufacturing, yet workers and enterprises may be exposed to electric shock, burns, arc-related injury, fire, equipment damage, and production interruption when an installation's condition or integrity is inadequate, or when protection, maintenance, or work control is weak. Indonesian public authorities have emphasized electrical-fire prevention, residual-current protection, and compliance with applicable workplace requirements .
This paper reports a secondary-data, theory-informed STPA case reconstruction. The numerical values are reported from the source thesis rather than independently re-estimated in the present study. The reconstruction does not test the effectiveness of the proposed constraints, estimate accident probabilities, or establish event-level causal relationships. Its purpose is to organize available barrier evidence into a transparent control structure and to identify propositions and field-validation requirements. The reconstruction specified six hazards, ten high-level safety constraints, twelve unsafe control actions, and six causal-scenario families. These outputs are analytical constructs proposed for field validation; they are not empirically verified causal findings.

Keywords: electrical safety; STAMP; STPA; manufacturing SMEs; occupational safety and health; Indonesia; residual-current protection; safety barriers; human and organizational performance.

إعادة بناء حواجز السلامة الكهربائية في المنشآت الصناعية الصغيرة والمتوسطة الإندونيسية باستخدام تحليل العمليات النظمي النظري (*STPA*)

علي محمود الصابري[1]، ناجي عبد العزيز علي[2]، احمد صالح محمد[3]
[1] قسم الإدارة الهندسية، كلية العلوم التقنية، بني وليد، ليبيا
[2] قسم الهندسة الميكانيكية، كلية العلوم التقنية، بني وليد، ليبيا
[3] قسم الهندسة الكهربائية والإلكترونية، كلية العلوم التقنية، بني وليد، ليبيا.

الملخص
تُقدّر منظمة العمل الدولية أن الأمراض والإصابات المرتبطة بالعمل تؤدي إلى ما يقارب **2.93مليون حالة وفاة** و **395 مليون إصابة غير مميتة**.
ولا تفصل هذه الأرقام الحوادث الكهربائية في إندونيسيا بشكل خاص، إلا أنها تؤكد أهمية أنظمة السلامة والصحة المهنية القائمة على الوقاية، وخاصة في المنشآت الصغيرة والمتوسطة، حيث قد تكون الخبرات المتخصصة، والإشراف الرسمي، والتوثيق، وموارد الصيانة محدودة.
تُعد الكهرباء عنصرًا أساسيًا في العمليات التصنيعية، إلا أن العاملين والمنشآت قد يتعرضون لمخاطر مثل **الصدمات الكهربائية، والحروق، والإصابات الناتجة عن القوس الكهربائي، والحرائق، وتلف المعدات، وانقطاع الإنتاج** عندما تكون حالة التركيبات الكهربائية أو سلامتها غير كافية، أو عندما تكون أنظمة الحماية والصيانة وضوابط العمل ضعيفة. وقد أكدت الجهات الرسمية الإندونيسية أهمية الوقاية من الحرائق الكهربائية، واستخدام أنظمة الحماية من التيار المتبقي (Residual Current Protection)، والالتزام بالمتطلبات التنظيمية المعمول بها في أماكن العمل .
تقدم هذه الدراسة **إعادة بناء لحالة باستخدام تحليل العمليات النظمي النظري STPA** بالاعتماد على بيانات ثانوية ومنهج قائم على النظرية. وقد تم نقل القيم العددية من الرسالة المصدرية دون إعادة تقديرها بشكل مستقل في هذه الدراسة الحالية. ولا تهدف عملية إعادة البناء إلى اختبار فعالية القيود المقترحة، أو تقدير احتمالات وقوع الحوادث، أو إثبات العلاقات السببية على مستوى الأحداث الفردية.
يتمثل الهدف الأساسي في **تنظيم الأدلة المتعلقة بحواجز السلامة ضمن هيكل تحكم شفاف**، وتحديد المقترحات ومتطلبات التحقق الميداني المستقبلية. وقد حددت عملية إعادة البناء **ستة مخاطر، وعشرة قيود سلامة عالية المستوى، واثني عشر إجراءً غير آمن للتحكم، وست عائلات من السيناريوهات السببية** .وتمثل هذه المخرجات **نماذج تحليلية مقترحة للتحقق الميداني** وليست نتائج سببية مثبتة تجريبيًا.

الكلمات المفتاحية: السلامة الكهربائية؛ المنشآت الصناعية الصغيرة والمتوسطة؛ السلامة والصحة المهنية؛ إندونيسيا؛ الحماية من التيار المتبقي؛ حواجز السلامة؛ الأداء البشري والتنظيمي.

1.Introduction

A safe and healthy working environment is recognized as a fundamental principle and right at work. The International Labour Organization estimates that work-related diseases and injuries account for approximately 2.93 million deaths and 395 million non-fatal work injuries annually [1]. These estimates do not isolate electrical events in Indonesia, but they underline the importance of prevention-oriented occupational safety and health (OSH) systems, particularly in small enterprises where specialist expertise, formal supervision, documentation, and maintenance resources may be limited.

Electricity is indispensable to manufacturing. It also creates exposure to electric shock, burns, arc-related injury, fire, equipment damage, and production interruption when the installation is defective or when protection, maintenance, or work control is inadequate. Indonesian public authorities have continued to emphasize electrical-fire prevention and the use of residual-current protection [2, 3]. Such records provide an important public context, but they do not replace an organizational analysis of how safety decisions are made, communicated, authorized, and reviewed.

The organizational evidence for the present study is drawn from a master's thesis that examined electrical-OSH in Yogyakarta manufacturing SMEs using a structured questionnaire, field observations, and interviews [15]. The thesis identified broad barrier groups and proposed

management interventions involving policy, planning, implementation, inspection, and auditing. The current study develops a distinct analytical contribution by representing those barriers within a systems-theoretic control structure. STPA asks not only whether a training program, protective device, or written rule exists, but also whether the associated control action is assigned to the right controller, delivered at the right time, technically adequate, understood by the recipient, and connected to feedback [7, 8].

This perspective is suitable for SMEs because responsibility is frequently distributed across owners, supervisors, workers, competent electricians, external contractors, regulators, and emergency responders. A hazard can therefore persist even when individual precautions are present. For example, a circuit breaker may be installed but not tested; a repair may be authorized but not preceded by verified isolation; or a worker may report a recurring trip without receiving corrective feedback. The central issue is the integrity of the control loop.

1.1. Knowledge gap and independent contribution

Prior studies have identified safety-management barriers in Indonesian SMEs, and systems-theoretic methods have been applied across several safety-critical domains. However, the available evidence has rarely been reconstructed as an interactive electrical-safety control system for manufacturing SMEs. This leaves a gap between barrier inventories and actionable control structures. A barrier inventory indicates which safety-related activities or conditions are present; it does not, by itself, specify who controls the activity, what information is required, how the action is timed, or how corrective feedback changes subsequent decisions. The present paper addresses this analytical gap rather than claiming to provide a new population estimate of electrical accidents.

The source study provides the organizational and measurement context for the present paper. The current paper contributes a different analytical product: a hierarchical control structure, an explicit set of unsafe control actions, causal-scenario families, safety constraints, and a proposed implementation sequence for field validation. STPA is used because it represents distributed responsibility, feedback, process models, and control interactions more directly than a conventional administrative list of barriers [6, 7]. The resulting framework is theory-informed. It does not reproduce the source study's management inventory, nor does it function as a validated accident-prediction model.

1.2. Research questions

RQ1: How can secondary-data barrier evidence be represented as a hierarchical control structure for Indonesian manufacturing SMEs?

RQ2: What unsafe control actions and causal-scenario families emerge from this structure?

RQ3: What safety constraints and implementation stages support proportionate field validation?

1.3. Propositions for future empirical testing

The following propositions are offered as testable directions for a subsequent empirical phase. They are not findings established by the present secondary analysis. Future studies could operationalize the propositions through GPAS/RCBO test completion and feedback time, worker-report response time, the proportion of corrective actions closed by their due dates, and observed compliance with authorization and isolation-verification steps.

P1: In Indonesian manufacturing SMEs, the absence of GPAS/RCBO testing feedback is expected to be associated with a higher prevalence of undetected leakage conditions than the absence of the device alone.

P2: Worker-reporting channels without visible management response are expected to be associated with more frequent normalization of workaround behaviors.

P3: The integrity of the electrical-safety control loop is expected to be associated with the coupling of authorization, verification, and corrective-action closure more strongly than with the presence of any single administrative measure.

2. Conceptual background

2.1. STAMP and STPA

STAMP is a systems-theoretic accident causality model in which safety is treated as an emergent property of hierarchical control relationships rather than as the outcome of a single linear chain of component failures [6, 7]. A safety control structure contains controllers, control actions, a controlled process, actuators, sensors, feedback, and the process models used by controllers. STPA is the proactive hazard-analysis technique derived from this perspective. It defines system losses and hazards, models the safety-control structure, identifies unsafe control actions and controller constraints, develops causal scenarios, and derives scenario-level safety requirements [6].

A control action may be unsafe because it is not provided, is provided when it should not be, is provided too early or too late, is stopped too soon, is applied for too long, or is delivered in an inadequate form [7]. Electrical work provides clear examples. An isolation instruction, authorization to repair, protection-device reset, emergency warning, or restoration decision may be unsafe even when no component has visibly failed. The analytical focus is consequently placed on the interaction between controllers, the controlled electrical process, feedback, and the process models used to make decisions. STPA does not, by itself, provide a quantitative accident probability; its value in this study lies in making control responsibilities and missing feedback explicit.

2.2. Electrical safety as a layered control problem

Electrical safety involves technical, organizational, and regulatory layers. Technical layers include installation integrity, insulation, earthing, overcurrent protection, residual-current protection, enclosures, warning signs, and emergency equipment. Organizational layers include competence assurance, work authorization, isolation and verification, maintenance, inspection, supervision, documentation, worker reporting, and learning. Regulatory and standards-based layers define requirements and oversight mechanisms that influence both practice and accountability.

The distinction between miniature circuit breakers (MCBs) and residual-current devices is particularly important. MCBs primarily address overload and short-circuit conditions, whereas Gawai Proteksi Arus Sisa (GPAS) devices and residual-current circuit-breakers with integral overcurrent protection (RCBOs) address leakage-current hazards while providing the functions defined by their respective technical specifications [2–5, 18–21]. In this paper, GPAS denotes the Indonesian residual-current protection function; the exact device configuration remains subject to applicable installation, product, and voltage requirements [23]. The presence of an MCB therefore does not demonstrate that leakage-current protection is suitable, tested, and maintained. Conversely, a residual-current device cannot compensate for poor earthing, an uncontrolled work boundary, or a process in which every trip is reset without investigation. Protection status, test results, outage information, damaged-cable reports, and worker observations should operate as feedback signals within the safety-control system.

2.3. HOP as an interpretive lens

Human and Organizational Performance (HOP) is used as an interpretive lens rather than as a replacement for engineering controls, competence requirements, or legal compliance. It was not applied as a separate data-collection or coding method in this study. Instead, three questions guide the interpretation of work as performed: what conditions made the action appear reasonable at the time; what information or feedback was unavailable; and what change would improve the work system rather than merely demand better behavior [11–13].

This distinction is relevant when a worker resets a nuisance trip, repairs a failed circuit after an outage, or continues with damaged equipment. The worker may be the last visible actor, while the conditions shaping the action include unclear authority, missing competence, production

pressure, unreliable protection, inadequate maintenance, or a reporting channel that produces no response. HOP therefore complements STPA: STPA identifies the control action and the required constraint, whereas HOP helps interpret the organizational conditions under which the action was omitted, mistimed, or adapted.

2.4. Positioning STPA among complementary methods

HAZOP examines deviations from design intent, often by applying guidewords to process parameters. Fault Tree Analysis traces logical combinations of contributing failures leading to a defined top event. Both methods are valuable when the analytical boundary and the available technical evidence suit the question. STPA begins from losses, hazards, control actions, and feedback. It is consequently able to represent missing commands, contradictory authority, weak process models, contractor interfaces, and control conflicts even when no single component has failed [17].

The methods are complementary rather than mutually exclusive. In the present study, STPA provides the organizing framework for the organizational analysis, while HAZOP-like examination, FTA logic, installation inspection, and protection-device testing remain appropriate during subsequent field validation. Recent work has applied STAMP-based safety-management construction to industrial and trade enterprises [8, 24], developed system-theoretic fuzzy analysis for systemic safety assessment [9, 25], examined hybrid STAMP-based causal analysis [26], and compared STPA with other hazard-analysis methods [10, 17]. Comparable systems-theoretic hazard analyses have also been reported in construction safety [16], while SME occupational-safety research highlights the importance of organizational capacity in smaller enterprises [22]. Recent STAMP work on dynamic risk assessment further illustrates the value of examining evolving control conditions, although that quantitative extension is outside the present study [27]. These studies support the relevance of feedback and control interactions, but they are not treated as direct evidence about the Indonesian SME sample. STPA is therefore selected here because it fits the specific analytical question concerning distributed authority, feedback, process models, and control conflicts; it is not presented as universally superior to HAZOP, FTA, FMEA, or FRAM.

3. Materials and methods

3.1. Research design and analytical boundary

The study used a secondary-data, theory-informed STPA case-reconstruction design. It did not collect a new survey or conduct a new incident investigation. Instead, it reinterpreted secondary organizational evidence from the source study within a systems-theoretic framework and placed that evidence alongside relevant public outcome records and peer-reviewed safety literature. The principal organizational context was the electrical-safety management of manufacturing SMEs in Yogyakarta. The study is not a mixed-methods prevalence study, a causal model, or an intervention evaluation.

The analytical boundary is intentionally conservative. Values from the source thesis are treated as reported contextual evidence; public records are used as contextual motivation; and the STPA outputs are treated as proposed analytical constructs requiring field validation. The present analysis does not test whether any safety constraint reduces incidents, does not estimate accident likelihood, and does not establish that a listed causal scenario occurred in any specific enterprise.

The system boundary includes national and local authorities, the utility or distribution interface, SME management, the designated electrical-OSH responsibility, workers, competent electricians and contractors, electrical installations, MCB and GPAS/RCBO protection, inspection and maintenance processes, and emergency response. Informal control paths are also considered because an SME may assign several safety functions to one manager or rely on an external competent person.

3.2. Source-study organizational evidence

The organizational basis comprises 27 manufacturing SMEs in the Yogyakarta region and 135 completed responses to a 36-item ordinal instrument reported in the master's thesis [15]. The instrument used a five-point response scale. According to the source thesis, the factor procedure excluded items Q1, Q15, Q18, Q19, and Q20, leaving 31 items for the reduced component analysis. The present paper reports these values from the source thesis; it does not claim to have independently re-run the PCA. The source-study information used in the reconstruction is summarized in Table 1.

Table 1. Source-study organizational evidence used in the STPA reconstruction.

Evidence element	Value used in the present study
Organizational setting	27 manufacturing SMEs in Yogyakarta
Completed responses	135
Original instrument	36 ordinal items on a five-point scale
Items retained for component analysis	31 items
Items excluded	Q1, Q15, Q18, Q19, Q20
Sampling adequacy	KMO = 0.746
Sphericity	Bartlett's $\chi^2(465) = 965.413$, $p < .001$
Extraction context	Principal Component Analysis with Varimax rotation
Retained components	Nine components with eigenvalues > 1
Cumulative explained variance	56.28% in the standardized correlation-matrix solution

The component results are interpreted as descriptive organizational context rather than as a validated latent-factor model, independent estimates of accident probability, or an accident-prediction model. PCA is a data-dependent dimensionality-reduction procedure; therefore, a complete replication would require the item-level data, the correlation matrix, the loading matrix, the missing-data treatment, the retention criterion, and the software output [28]. Those materials were not available for independent reanalysis in the present study. The nine barrier groups retained for interpretation were safe behavior, electrical-OSH expertise, motivation, knowledge, risk anticipation, safety signs, awareness, electrical-OSH responsibility, and safety-equipment maintenance.

3.3. External evidence and analytical safeguards

Public Indonesian records were used only to provide contemporary outcome context and to motivate field-validation scenarios. The Yogyakarta fire report records 63 citywide fires during 2025 and identifies electrical short circuit as the dominant reported cause at 49% [2]. A Ministry of Energy and Mineral Resources release reports 1,017 electrical-factor fires among 1,656 fires in DKI Jakarta during 2025, approximately 61.4% [3]. These figures describe different geographic, institutional, and reporting contexts; they are not pooled into an occupational-injury rate and do not estimate the risk of electrical events in manufacturing SMEs. A public report from Klaten concerning a fatal electric shock during domestic repair was used only as a qualitative prompt for examining the outage-to-repair transition [14].

Three safeguards were applied. First, source-study organizational evidence, public outcome context, peer-reviewed theory, and analytical propositions were kept conceptually distinct. Second, reported statistics were not presented as proof of specific causal mechanisms. Third, STPA outputs were formulated as control gaps and field-validation targets rather than as confirmed explanations of individual incidents. No new participants were recruited for this

secondary analysis. The temporal mismatch between the 2017 source thesis and the 2025–2026 public records is therefore treated as a contextual boundary rather than as a longitudinal dataset.

Table 2. Summary of Evidence Streams, Analytical Use, and Inference Boundaries in the STPA Case Reconstruction

Evidence stream	Period	Unit of analysis	Use in this paper	Inference boundary
Source thesis	2017 source study	27 Yogyakarta manufacturing SMEs; 135 responses	Organizational barrier context and reported PCA summary	Not an independently re-estimated dataset or accident-risk model
Yogyakarta fire record	2025	Citywide reported fire incidents	Contextual motivation for electrical-fire scenarios	Not SME-specific and not an occupational-injury rate
DKI Jakarta electricity-related fire record	2025	Reported fires in DKI Jakarta	Contextual motivation for protection and prevention questions	Different geography and reporting context; not pooled with Yogyakarta
Klaten public report	2026	One publicly reported domestic electric-shock fatality	Qualitative prompt for outage-to-repair transition	Not an incident investigation and not representative evidence
Peer-reviewed and standards literature	Various	Published methods, standards, and prior applications	Conceptual and technical grounding	Does not constitute evidence about the 27 SMEs

3.4. STPA procedure

The reconstruction followed five stages consistent with the STPA literature: defining system losses, hazards, and high-level constraints; constructing a hierarchical control structure; identifying UCAs using the standard unsafe-control-action categories; developing causal-scenario families; and formulating preventive constraints and a proposed implementation sequence [6]. The structure was built around regulators, management, the designated safety function, electricians, workers, the electrical installation, protective devices, and feedback channels. The nine source-study barrier groups were then mapped to STPA elements. Each mapping is interpretive and is presented as a field-validation pathway rather than as a statistical association. The resulting hazards, constraints, UCAs, and scenarios were generated through analyst interpretation of the mapped evidence; they were not statistically inferred from the source-study responses.

Analytical credibility was addressed through explicit traceability rather than through a claim of independent validation. The manuscript identifies the controller, control action, unsafe type, relevant hazard, process-model weakness, causal-scenario family, safety constraint, and field evidence required for each UCA. Because no new participants were recruited and no independent field audit was conducted, the reconstruction should be treated as a transparent analyst-generated framework. Independent review by electrical-safety and STPA specialists remains a recommended next step.

The nine source-study barrier groups were mapped to STPA elements as follows: safe behavior was treated as a front-line control function; expertise as controller capability; motivation as

management resource allocation; knowledge and safety signs as process-model and interface functions; risk anticipation as hazard and emergency control; awareness as monitoring and learning; electrical-OSH responsibility as the organizational controller; and safety-equipment maintenance as a protective-layer reliability function. These mappings are analytical interpretations, not psychometric factor-to-control equivalences.

Table 3. Mapping matrix from source-study components to STPA elements. The links identify analytical pathways for field validation; they are not statistical associations or causal estimates.

Source-study component	STPA interpretation	Principal UCA links	Field-validation focus
Safe behavior	Front-line control action and operational constraint	UCA-8, UCA-9	Trip response, defect reporting, task observation
Electrical-OSH expertise	Controller capability and process-model accuracy	UCA-4, UCA-6	Competence matrix, authorization, supervision
Motivation	Management control algorithm and resource allocation	UCA-11, UCA-12	Action closure, budget, stop-work support
Knowledge	Shared process model and rule communication	UCA-1, UCA-7	Procedure comprehension, induction, hazard information
Risk anticipation	Hazard and emergency control	UCA-3, UCA-10	Pre-work review, isolation planning, emergency drill
Safety signs	Human–machine interface and boundary visibility	UCA-4, UCA-7	Labels, isolation points, cable routes
Awareness	Monitoring, reporting, and learning	UCA-8, UCA-9, UCA-11	Trip logs, near-miss review, audit feedback
Electrical-OSH responsibility	Organizational controller	UCA-2, UCA-3, UCA-11, UCA-12	Responsibility matrix, permits, corrective-action tracking
Safety-equipment maintenance	Protective-layer reliability and feedback	UCA-5, UCA-8	GPAS/RCBO tests, PPE and emergency-equipment records

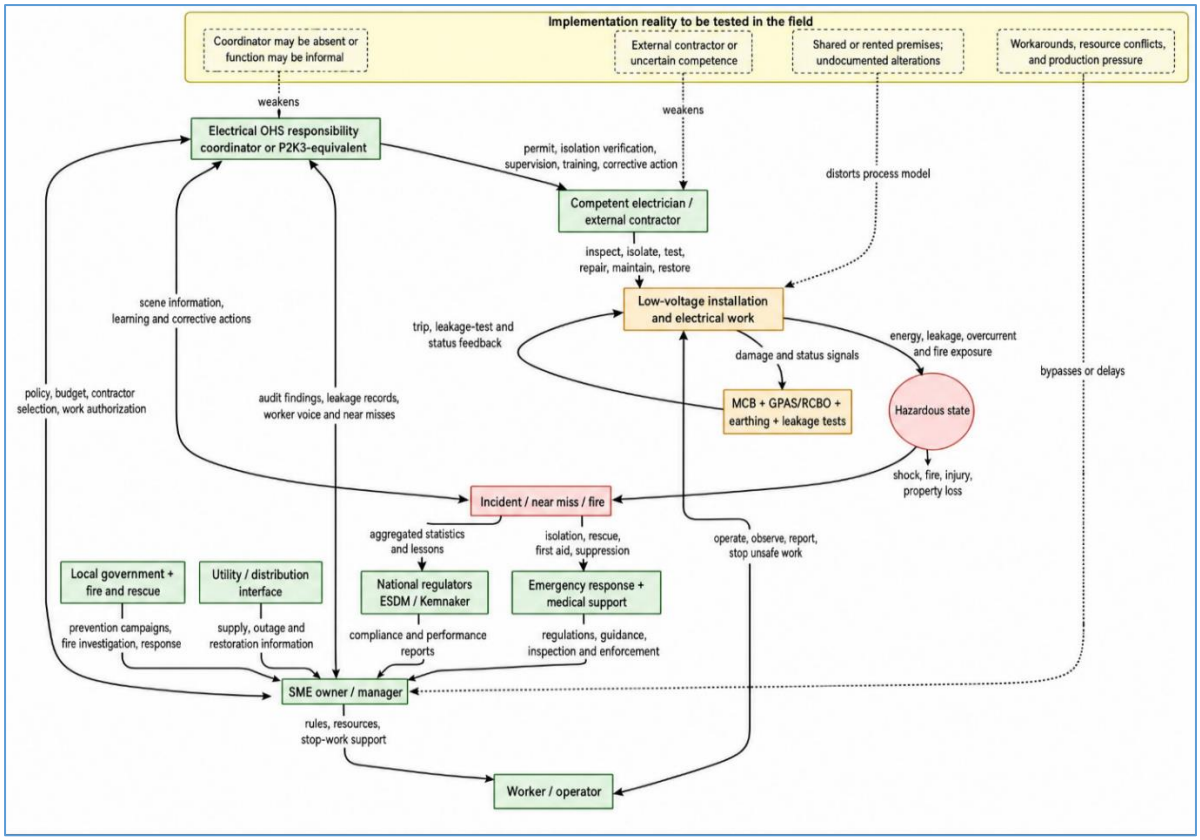

Figure 1. Data-informed STPA control structure.

Downward arrows represent control actions such as policy, resource allocation, work authorization, isolation verification, maintenance, and restoration. Upward arrows represent feedback including worker reports, inspection findings, leakage-test results, protection trips, incident information, and corrective-action learning. The diagram is a normative target structure; its presence and effectiveness require field verification.

4. Results

The hazards, safety constraints, UCAs, and causal-scenario families reported below are analyst-generated normative constructs derived from the source-study barrier groups, STPA logic, and the cited technical context. They are not direct observations of the 27 enterprises and should be treated as propositions for field validation.

The analysis defined five system losses: fatality or permanent disability; non-fatal injury; asset and production loss; unsafe restoration or delayed response; and organizational or regulatory loss. Six hazards were then specified: hazardous electrical contact, undetected leakage, ignition-prone electrical condition, uncontrolled repair or maintenance, missing safety feedback, and ineffective emergency control.

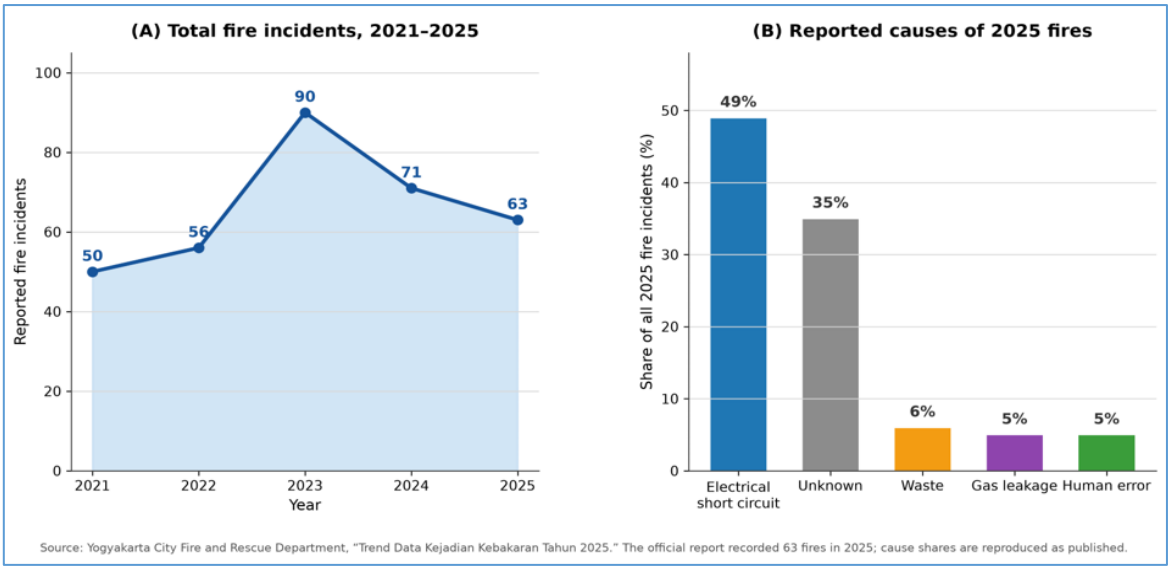

Figure 2. Yogyakarta City fire evidence used as public outcome context.

The figure reproduces the reported citywide fire totals for 2021–2025 and the reported cause shares for 2025. It is not an SME-specific risk estimate and does not establish event-level causation [2].

The hazards are system states, not allegations about particular enterprises. For example, "undetected leakage" refers to the persistence of leakage current without timely detection and interruption. "Uncontrolled repair" refers to electrical work proceeding without verified isolation, competent authorization, or safe restoration. These definitions allow the analysis to connect technical conditions with organizational controls.

4.1. High-level safety constraints

Ten high-level safety constraints were derived from the control structure. They are stated as system conditions rather than as instructions directed at workers alone.

Table 4. High-level safety constraints derived from the STPA control structure.

ID	High-level safety constraint
SC-1	Electrical installations shall comply with applicable Indonesian requirements, including PUIL and relevant SNI provisions.
SC-2	Electrical work shall be allocated to competent and appropriately authorized personnel.
SC-3	Intrusive work shall not begin until isolation, absence of voltage, and controlled re-energization have been verified.
SC-4	Leakage-current and overcurrent protection shall be selected, tested, maintained, and investigated after operation.
SC-5	SMEs shall maintain understandable electrical-safety rules, task procedures, PPE requirements, warnings, and task-specific training.
SC-6	Protective and emergency equipment shall be inspected, maintained, and recorded at defined intervals.
SC-7	A designated electrical-OSH responsibility shall coordinate hazard identification, work authorization, supervision, and corrective-action closure.
SC-8	Workers shall receive usable hazard information and have a protected route to report defects, near misses, workarounds, and work-pressure conflicts.
SC-9	Inspections, tests, incident investigations, and worker reports shall update the safety process model and lead to verifiable corrective action.
SC-10	Emergency arrangements shall support rapid isolation, first aid, fire response, and communication of electrical status to responders.

4.2. Unsafe Control Actions (UCAs)

Twelve Unsafe Control Actions (UCAs) were identified through the STPA reconstruction. These UCAs are treated as **control conditions that should be prevented, detected, or corrected**, rather than as confirmed causes of specific electrical fires or injuries. The following points summarize the traceability relationships between each UCA, the responsible controller, unsafe control condition, associated hazards, process-model weaknesses, causal-scenario families, safety constraints, and required field-validation evidence.

UCA-1: Failure to provide accessible electrical safety implementation guidance

- **Controller:** Regulators / local authorities.
- **Control action:** Provide accessible guidance for electrical safety implementation.
- **Unsafe control type:** Not provided.
- **Relevant hazards:**
  - Uncontrolled electrical repair.
  - Missing safety feedback.
- **Process-model weakness:**
  - SME managers lack a practical interpretation of requirements and escalation pathways.
- **Causal scenario:**
  - Different interpretations of installation requirements, competency expectations, and reporting procedures persist due to insufficient technical support.
- **Related safety constraints:** SC-1, SC-5, SC-8.
- **Required field evidence:**
  - Availability of guidance documents.
  - Manager interviews.
  - Documented escalation routes.
  - Inspection records.

UCA-2: Incorrect verification of electrical installation condition and integrity

- **Controller:** Inspector / certifier.
- **Control action:** Verify installation condition, integrity, protection systems, competence, and corrective-action closure.
- **Unsafe control type:** Provided incorrectly.
- **Relevant hazards:**
  - Undetected leakage.
  - Ignition-prone electrical conditions.
  - Missing safety feedback.
- **Process-model weakness:**
  - The inspection model does not incorporate protection testing, competence evidence, or verification of corrective-action closure.
- **Causal scenario:**
  - Inspection approval or certification is issued while significant defects or overdue corrective actions remain unresolved.
- **Related safety constraints:** SC-1, SC-2, SC-4, SC-9.
- **Required field evidence:**
  - Inspection scope.
  - Test certificates.
  - Competence records.
  - Corrective-action closure evidence.

UCA-3: Authorizing repair after outage without verified isolation

- **Controller:** SME management.
- **Control action:** Authorize repair activities following electrical outages.
- **Unsafe control type:** Provided incorrectly; wrong timing.
- **Relevant hazards:**
  - Hazardous electrical contact.
  - Uncontrolled repair activities.
- **Process-model weakness:**
  - The organization assumes that power interruption is equivalent to verified isolation.
- **Causal scenario:**
  - Production pressure leads to repair work before isolation, absence-of-voltage testing, and controlled re-energization are confirmed.
- **Related safety constraints:** SC-2, SC-3, SC-5.
- **Required field evidence:**
  - Work permits.
  - Authorization records.
  - Outage-to-repair observations.
  - Isolation verification records.

UCA-4: Failure to isolate, secure, test, and communicate electrical boundaries

- **Controller:** Safety function / electrician.
- **Control action:** Isolate, secure, test, and communicate the electrical work boundary.
- **Unsafe control type:** Not provided; wrong timing.
- **Relevant hazard:**
  - Hazardous electrical contact during repair.
- **Process-model weakness:**
  - The process model does not consider alternative energy sources, restoration risks, or communication of work boundaries.
- **Causal scenario:**
  - Repair proceeds based only on local switching assumptions while another energy source or restoration pathway remains possible.
- **Related safety constraints:** SC-2, SC-3, SC-8.
- **Required field evidence:**
  - Isolation diagrams.
  - Test-before-touch records.
  - Permit samples.
  - Task observations.

UCA-5: Incorrect installation, testing, or maintenance of electrical protection systems

- **Controller:** Management / contractor.
- **Control action:** Install, test, and maintain appropriate GPAS/RCBO protection.
- **Unsafe control type:** Not provided; provided incorrectly.
- **Relevant hazards:**
  - Undetected leakage.
  - Ignition-prone electrical conditions.
- **Process-model weakness:**
  - Protection selection and testing are not linked to actual installation conditions, leakage exposure, or post-trip investigation.

- **Causal scenario:**
  - An MCB is considered sufficient, or residual-current protection is installed but unsuitable, bypassed, untested, or repeatedly reset.
- **Related safety constraints:** SC-1, SC-4, SC-6.
- **Required field evidence:**
  - Protection inventory.
  - Test records.
  - Trip logs.
  - Installation inspections.

UCA-6: Assigning high-risk electrical work to insufficiently competent personnel

- **Controller:** SME management.
- **Control action:** Assign high-risk work to competent personnel with appropriate PPE and tools.
- **Unsafe control type:** Not provided; provided incorrectly.
- **Relevant hazards:**
  - Hazardous electrical contact.
  - Uncontrolled repair.
- **Process-model weakness:**
  - Competence decisions are based on familiarity or availability rather than task-specific authorization.
- **Causal scenario:**
  - Workers or contractors perform intrusive electrical work without adequate competence, equipment, or supervision.
- **Related safety constraints:** SC-2, SC-5.
- **Required field evidence:**
  - Competence matrix.
  - Authorization records.
  - PPE/tool inspections.
  - Supervision observations.

UCA-7: Failure to provide warnings, labels, and task-specific electrical information

- **Controller:** Safety function / supervisor.
- **Control action:** Provide warnings, labels, safe cable routing, and operational information.
- **Unsafe control type:** Not provided; provided incorrectly.
- **Relevant hazards:**
  - Hazardous electrical contact.
  - Ignition-prone electrical conditions.
- **Process-model weakness:**
  - Hazards, isolation points, cable routes, and equipment status are not sufficiently visible.
- **Causal scenario:**
  - Workers interpret unclear electrical boundaries or damaged routes differently from the intended safe configuration.
- **Related safety constraints:** SC-5, SC-8.
- **Required field evidence:**
  - Signage audits.
  - Cable-route inspections.
  - Worker comprehension checks.

- Photographic evidence.

UCA-8: Resetting or bypassing protective devices without investigation

- **Controller:** Worker / supervisor.
- **Control action:** Reset or bypass protective trips.
- **Unsafe control type:** Provided incorrectly; stopped too soon.
- **Relevant hazards:**
  - Undetected leakage.
  - Ignition-prone electrical conditions.
  - Missing safety feedback.
- **Process-model weakness:**
  - Protective trips are treated as operational interruptions rather than safety signals requiring diagnosis.
- **Causal scenario:**
  - Repeated trips are reset without isolation, investigation, or corrective action.
- **Related safety constraints:** SC-4, SC-9.
- **Required field evidence:**
  - Trip logs.
  - Reset records.
  - Defect investigations.

UCA-9: Failure to report electrical defects and unsafe conditions

- **Controller:** Worker / supervisor.
- **Control action:** Report leakage, damaged insulation, repeated trips, and near misses.
- **Unsafe control type:** Not provided.
- **Relevant hazards:**
  - Missing safety feedback.
  - Ignition-prone electrical conditions.
- **Process-model weakness:**
  - Workers lack effective reporting channels or expect that reporting will not lead to action.
- **Causal scenario:**
  - Repeated defects become normalized because reports are delayed, ignored, or closed without feedback.
- **Related safety constraints:** SC-8, SC-9.
- **Required field evidence:**
  - Reporting records.
  - Response-time data.
  - Near-miss logs.
  - Worker interviews.

UCA-10: Failure to communicate circuit status and isolation points during emergencies

- **Controller:** Emergency coordinator.
- **Control action:** Communicate electrical status and isolation locations to responders.
- **Unsafe control type:** Provided incorrectly; wrong timing.
- **Relevant hazards:**
  - Ineffective emergency response.
  - Hazardous electrical contact.
- **Process-model weakness:**
  - Emergency responders lack an updated model of electrical hazards and isolation points.
- **Causal scenario:**

    - Rescue or firefighting begins before electrical status confirmation.
- **Related safety constraint:** SC-10.
- **Required field evidence:**
    - Emergency plans.
    - Drills.
    - Isolation-point maps.
    - Responder interviews.

UCA-11: Incomplete verification of corrective-action closure

- **Controller:** Auditor / management.
- **Control action:** Assign, verify, and close corrective actions and update procedures.
- **Unsafe control type:** Stopped too soon; applied too long.
- **Relevant hazards:**
    - Missing safety feedback.
    - Organizational control failure.
- **Process-model weakness:**
    - Audit processes do not distinguish temporary containment from permanent verified closure.
- **Causal scenario:**
    - Findings are closed without evidence, or outdated controls remain after conditions change.
- **Related safety constraints:** SC-6, SC-7, SC-9.
- **Required field evidence:**
    - Audit reports.
    - Action trackers.
    - Closure evidence.
    - Procedure revision history.

UCA-12: Failure to integrate worker feedback into safety decisions

- **Controller:** Management / safety function.
- **Control action:** Incorporate worker information regarding workarounds and resource conflicts.
- **Unsafe control type:** Not provided; provided incorrectly.
- **Relevant hazards:**
    - Missing safety feedback.
    - Uncontrolled repair.
- **Process-model weakness:**
    - Management decisions rely only on formal procedures and exclude information from actual work practices.
- **Causal scenario:**
    - Differences between work-as-imagined and work-as-performed are not incorporated into the safety control system.
- **Related safety constraints:** SC-7, SC-8, SC-9.
- **Required field evidence:**
    - Worker feedback records.
    - Management review minutes.
    - Resource-conflict logs.
    - Procedure updates.

4.3. Causal-scenario families

Six causal-scenario families connect the UCAs to plausible pathways that should be tested in the field. The first concerns a leakage-protection and installation-control gap. Damaged

insulation, loose connections, excessive loading, or other leakage paths may coexist with a functioning MCB. If the MCB is treated as sufficient while GPAS/RCBO protection is absent, unsuitable, untested, or bypassed, the protection layer does not match the hazard. Installation inspection and leakage-current testing are required to evaluate this pathway.

The second family concerns the transition from outage to repair. A power outage can create pressure to restore production or service. If "the power is off" is treated as equivalent to verified isolation, repair may begin while a circuit remains energized or can be re-energized from another source. The required control is an isolate–secure–test–communicate–restore sequence supported by authorization.

The third family concerns a mismatch between competence, supervision, and production pressure. The source-study barrier groups point to the importance of expertise, knowledge, motivation, safe behavior, and responsibility. A familiar workaround may appear efficient when instructions are unclear or competent support is unavailable. The control response is task-specific authorization, a competence matrix, stop-work authority, and supervisor verification.

The fourth family concerns weak organizational control and resource allocation. When responsibility is not clearly assigned, safety resources are insufficient, or audits are symbolic, downstream controls become fragile. A small enterprise does not require a large safety department, but it does require an explicitly assigned function with authority, resources, and feedback.

The fifth family concerns emergency response without prevention feedback. Emergency response can reduce consequences without removing the precursor condition. If incident information and electrical-isolation data do not return to management and inspection functions, recurring conditions may remain unresolved. The final family concerns worker participation and normalization of workarounds. Repeated trips, damaged cables, informal repairs, and resource conflicts may become routine when reporting is unreliable or produces no visible action.

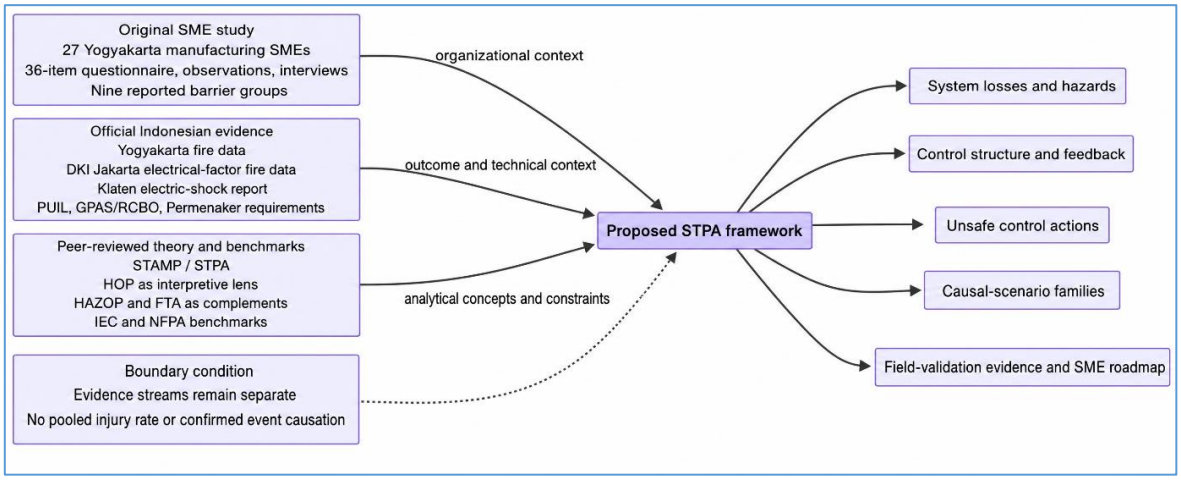

Figure 3. Evidence-to-framework map.

The figure shows how the source-study organizational evidence, official Indonesian public records, and peer-reviewed theory converge in the proposed STPA framework and lead to hazards, control structure, UCAs, causal scenarios, and field-validation outputs. The evidence streams remain analytically distinct.

5. Discussion

5.1. Contribution of the STPA reframing

The central contribution is the conversion of a barrier inventory into a control structure. Training is interpreted as a capability control; written procedures as control algorithms; signs

and PPE as human–machine interface support; installation integrity and GPAS/RCBO protection as controlled-process safeguards; and inspections, trips, worker reports, and incident investigations as feedback. Audits and management review provide mechanisms for updating the safety process model.

This reframing changes the practical question. Instead of asking whether an SME has a rule, device, or training activity, the analysis asks whether the associated control action is available, timely, understandable, technically adequate, and linked to corrective feedback. A written rule may exist without being usable. A protective device may exist without being tested. A reporting channel may exist without producing action. The traceability matrix makes these distinctions explicit.

The analysis also clarifies the role of HOP. STPA provides the formal structure for hazards, control actions, and constraints. HOP supports a disciplined interpretation of why work was adapted under the conditions that existed. Together, the approaches avoid reducing a complex electrical event to the last visible worker action while preserving the need for technically sound controls and competent work.

Compared with prior STPA applications in transportation, nuclear instrumentation, construction, and process safety, this paper differs in its unit of analysis and evidence base. It reconstructs SME electrical-safety controls from a prior organizational study and public contextual records, and its principal outputs are a traceability matrix and a field-validation roadmap rather than an incident explanation, quantitative risk ranking, or verified intervention effect.

5.2. Technical and organizational implications

A proposed implementation sequence begins with exposure reduction. SMEs can identify exposed or damaged conductors, unsafe enclosures, critical cable-routing defects, unsuitable protection, and unclear isolation points. Findings should be recorded in a defect register with responsible persons, interim controls, and closure dates. The sequence is proposed on the basis of direct exposure reduction and practical containment; it is not a statistically validated risk ranking. Assessment and testing should be performed by appropriately competent personnel in accordance with applicable Indonesian requirements [5].

The next proposed sequence is repair and restoration control. A concise procedure can be effective when it specifies who may authorize electrical work, how energy sources are isolated, how absence of voltage is verified, how the work boundary is communicated, and who may authorize restoration. Administrative simplicity is compatible with strong control when the critical verification steps are explicit. This sequence is a design proposal for field validation rather than an empirically proven intervention order.

A further proposed element is feedback. Protection trips, incidents, near misses, repeated defects, and worker concerns should be recorded in a form that is simple enough to use and specific enough to support action. The responsible safety function should determine whether immediate isolation is required, assign corrective action, and communicate the outcome. Useful future indicators include reporting response time, GPAS/RCBO test completion, time to corrective-action closure, and the proportion of repeated defects that receive documented investigation.

5.3. Proposed implementation sequence

The following sequence is proposed for field validation on the basis of direct exposure reduction, control-loop establishment, feedback quality, and practical feasibility. It should not be interpreted as a statistically validated risk ranking.

Table 5. Proposed implementation sequence for field validation in Indonesian manufacturing SMEs.

Stage	Time horizon	Proposed implementation actions	Evidence of completion
1. Stabilize immediate risks	0–30 days	Identify exposed or damaged parts; prohibit unqualified repair; mark isolation points; correct critical enclosure and routing defects; check emergency readiness.	Defect register, temporary controls, isolation map, emergency checklist
2. Establish core controls	1–3 months	Assign electrical-OSH responsibility; authorize repair; complete a competent baseline inspection; verify suitable protection; define PPE and task procedures.	Appointment record, SOP, inspection report, test records, authorization register
3. Build feedback and competence	3–6 months	Create worker reporting; provide task-specific training; record trips and tests; review recurring defects and workarounds.	Near-miss log, training matrix, GPAS/RCBO records, corrective-action status
4. Learn and improve	Ongoing	Audit action closure; review incidents; update controls; include worker input in management review.	Audit reports, closure evidence, updated procedures, feedback outcomes

5.4. Policy and research implications

The control structure suggests that SME support should connect regulation, technical guidance, competence pathways, inspection, emergency learning, and corrective-action closure. Proportionate support is preferable to simply transferring large-enterprise bureaucracy to small firms. Useful measures include accessible SME-oriented guidance, affordable testing, contractor-verification routes, simple reporting tools, and assistance with closing identified defects. The sequence should be evaluated empirically rather than treated as a validated priority ranking.

Future field research should test each of the six causal-scenario families through installation audits, protection-device test records, permit-to-work samples, maintenance logs, interviews, near-miss records, and direct observation of normal work. A subsequent quantitative phase could evaluate the relative priority of control actions only after the instrument, sampling frame, local control evidence, and measurement model have been documented sufficiently. The STPA reconstruction is therefore a basis for validation, not a substitute for field evidence.

6. Limitations

The present study is a secondary-data, theory-informed reconstruction rather than a complete incident investigation. Public fire records and fatality reports provide heterogeneous outcome contexts and do not disclose, for every event, the voltage level, protection-device condition, maintenance history, work authorization, competence status, or detailed causal sequence. They are therefore used to motivate control questions rather than to establish event-level causation.

The component results reported in the source thesis are used as descriptive organizational context. They identify a structured set of barrier groups and provide reported summary statistics, but they are not interpreted as a validated latent-factor model or as an accident-prediction model. The normative control structure represents relationships that should be established; its presence and effectiveness require field observation and technical verification.

7. Conclusion

This study reframed electrical-safety barriers in Indonesian manufacturing SMEs as a systems-control problem. Evidence reported in the source thesis from 27 SMEs and 135 completed responses provided the organizational basis for the analysis. The source thesis reports that the reduced 31-item component procedure yielded KMO = 0.746, Bartlett's $\chi^2(465) = 965.413$, $p < .001$, and a nine-component standardized solution explaining 56.28% of cumulative variance. These values were used to organize the barrier evidence rather than to estimate accident risk.

The STPA reconstruction identified six hazards, ten safety constraints, twelve unsafe control actions, and six causal-scenario families. Its principal insight is that electrical safety depends on connected control functions: protection must be technically suitable and tested; repair must be authorized and preceded by verified isolation; competence and supervision must match task complexity; worker information must reach decision-makers; and corrective actions must be closed and fed back into the safety process model.

The proposed STPA framework, informed by HOP and grounded in STAMP, preserves the technical importance of installation integrity, residual-current protection, maintenance, PPE, emergency readiness, and applicable standards while making organizational interfaces explicit. Its practical value lies in supporting proportionate implementation and field validation in SMEs. It should be read as a structured analytical framework, not as a completed investigation of any individual incident.

References

[1] International Labour Organization. (2023, November 26). *Nearly 3 million people die of work-related accidents and diseases*. https://www.ilo.org/resource/news/nearly-3-million-people-die-work-related-accidents-and-diseases

[2] Dinas Pemadam Kebakaran dan Penyelamatan Kota Yogyakarta. (2026). *Trend Data Kejadian Kebakaran Tahun 2025*. Official municipal fire-service report.

[3] Ministry of Energy and Mineral Resources of the Republic of Indonesia, Directorate General of Electricity. (2026, July 9). *Cegah Kecelakaan Akibat Listrik, Kementerian ESDM Perkuat Penerapan GPAS*. https://www.esdm.go.id/en/media-center/news-archives/cegah-kecelakaan-akibat-listrik-kementerian-esdm-perkuat-penerapan-gpas

[4] Ministry of Energy and Mineral Resources of the Republic of Indonesia. (2024, October 5). Cegah Kebakaran Akibat Listrik, Dirjen Gatrik Sarankan Pakai RCBO.

[5] Ministry of Manpower of the Republic of Indonesia. (2015). *Peraturan Menteri Ketenagakerjaan Nomor 12 Tahun 2015 tentang Keselamatan dan Kesehatan Kerja Listrik di Tempat Kerja*. Official regulation.

[6] Patriarca, R., Chatzimichailidou, M. M., Karanikas, N., & Di Gravio, G. (2022). The past and present of System-Theoretic Accident Model And Processes (STAMP) and its associated techniques: A scoping review. *Safety Science, 146*, 105566. https://doi.org/10.1016/j.ssci.2021.105566

[7] Leveson, N. G. (2011). Engineering a safer world: Systems thinking applied to safety. MIT Press.

[8] Xu, X., Li, D., Huang, G., Wang, Z., Zhu, L., & Ni, X. (2024). Constructing safety management systems in modern industry and trade enterprises: A STAMP-based approach. Sustainability, 16 (24), 11238. https://doi.org/10.3390/su162411238.

[9] Ebrahimi, H., Zarei, E., Ansari, M., et al. (2024). A system theory based accident analysis model: STAMP-fuzzy DEMATEL. *Safety Science, 173*, 106445. https://doi.org/10.1016/j.ssci.2024.106445

[10] Shin, S.-M., Lee, S. H., Shin, S. K., Jang, I., & Park, J. (2021). STPA-based hazard and importance analysis on NPP safety I&C systems focusing on human–system interactions.

Reliability Engineering & System Safety, 213, 107698. https://doi.org/10.1016/j.ress.2021.107698
[11] Le Coze, J.-C. (2022). The “new view” of human error: Origins, ambiguities, successes and critiques. Safety Science, 154, 105853. https://doi.org/10.1016/j.ssci.2022.105853.
[12] European Agency for Safety and Health at Work. (2025). The concept of human error: Is it useful for the design of safe systems? OSHwiki. https://oshwiki.osha.europa.eu/en/safety-science-monitor/concept-human-error-it-useful-design-safe-systems
[13] Wachter, J. K., & Yorio, P. L. (2014). A system of safety management practices and worker engagement for reducing and preventing accidents: An empirical and theoretical investigation. Accident Analysis & Prevention, 68, 117–130. https://doi.org/10.1016/j.aap.2013.07.029.
[14] Government of Klaten Regency, Protocol and Communications Office. (2026, August 10). Bupati Klaten Sampaikan Belasungkawa kepada Keluarga Korban Tersengat Listrik di Mojayan.
[15] Assabri, A. M. A. A. (2017). *Pengembangan Model Manajemen K3 Listrik pada UKM untuk Meminimalkan Kecelakaan Kerja* [Master’s thesis, Universitas Islam Indonesia]. UII Repository.
[16] Clovis, D. G. J., & Park, J. Y. (2019). System theory based hazard analysis for construction site safety: A case study from Cameroon. *Safety Science, 118*, 783–794. https://doi.org/10.1016/j.ssci.2019.06.007
[17] Sun, L., Li, Y.-F., et al. (2022). Comparison of the HAZOP, FMEA, FRAM, and STPA methods for the hazard analysis of automatic emergency brake systems. ASCE-ASME Journal of Risk and Uncertainty in Engineering Systems, Part B: Mechanical Engineering, 8 (3), 031104. https://doi.org/10.1115/1.4051940.
[18] International Electrotechnical Commission. (2017). IEC 60364-4-41:2005/AMD1:2017: Low-voltage electrical installations—Protection against electric shock.
[19] International Electrotechnical Commission. (2024). IEC 61009-1:2024: Residual current operated circuit-breakers with integral overcurrent protection for household and similar uses.
[20] National Fire Protection Association. (2024). NFPA 70E: Standard for Electrical Safety in the Workplace.
[21] International Electrotechnical Commission. (2024). IEC 61008-1:2024: Residual current operated circuit-breakers without integral overcurrent protection for household and similar uses.
[22] Kongtip, P., Yoosook, W., & Chantanakul, S. (2008). Occupational health and safety management in small and medium-sized enterprises: An overview of the situation in Thailand. *Safety Science, 46*(8), 1359–1371. https://doi.org/10.1016/j.ssci.2007.09.001
[23] International Electrotechnical Commission. (2009, consolidated with Amendment 1:2021). *IEC 60038:2009+AMD1:2021: IEC standard voltages*.
[24] Hajibabaei, A. (2024). A Systems-Theoretic Approach to Safety Management System Assessment: A Case Study Applying STPA-Based Method in a Data Center Company [Master’s degree project, KTH Royal Institute of Technology]. DiVA portal. https://www.diva-portal.org/smash/get/diva2:1921044/FULLTEXT01.pdf.
[25] Nakhal, A. A. J., Patriarca, R., De Carlo, F., & Leoni, L. (2023). A System-Theoretic Fuzzy Analysis (STheFA) for systemic safety assessment. Process Safety and Environmental Protection, 177, 1181–1196. https://doi.org/10.1016/j.psep.2023.07.014.
[26] Dong, C., Zhang, Y., Wang, Z., Liu, J., & Zhang, J. (2024). The hybrid systems method integrating STAMP and HFACS for the causal analysis of road traffic accidents. Ergonomics, 67, 971–994. https://doi.org/10.1080/00140139.2023.2270783.
[27] Sun, H., Wang, H., Yang, M., & Reniers, G. (2024). Dynamic risk assessment of chemical process systems using the System-Theoretic Accident Model and Process approach (STAMP)

in combination with a cascading failure propagation model. Safety Science, 171, 106375. https://doi.org/10.1016/j.ssci.2023.106375.
[28] Jolliffe, I. T., & Cadima, J. (2016). Principal component analysis: A review and recent developments. Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences, 374(2065), 20150202. https://doi.org/10.1098/rsta.2015.0202

Compliance with ethical standards

Disclosure of conflict of interest

The authors declare that they have no conflict of interest.