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A Hybrid Structural Equation Modeling–Partial Least Square and Analytic Hierarchy Process Framework for Evidence-Based Safety Management in High-Risk Electricity Industry Operations

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ABSTRACT

Evidence-based safety management strategies that combine strong analytical techniques with context-specific decision support are necessary for high-risk electrical activities, especially during live working operations, i.e., work under voltage conditions (WUVC). This study aims to identify, validate, and rank factors contributing to safety risks in the electricity distribution industry in Indonesia by developing a hybrid framework that combines Structural Equation Modeling–Partial Least Square (SEM-PLS) and the Analytic Hierarchy Process (AHP) approaches. The links between safety factors, accident history, personal and environmental components, safety climate, and safety threats were examined using SEM-PLS analysis of survey data from 200 WUVC operators at PT XYZ. Strategic improvement rankings were then produced by incorporating significant latent variables into an AHP-based prioritizing process, including five national experts. The results demonstrate that safety factors, safety climate, and accident history all have a significant impact on safety hazards; however, the AHP results suggest that safety factors are the most important (weight = 0.255; Consistency Ratio (CR) = 0.04). Establishing specialized institutional structures for WUVC operations, improving the safety climate, and regularly updating Standard Operating Procedures (SOPs) and safety signage are the top strategic recommendations. The SEM-PLS data were used to create a KPI-based handbook, which was piloted with thirty operators, demonstrating its usefulness for field-level safety assessment. In high-voltage live working environments, the suggested hybrid approach provides a structured, data-driven foundation for enhancing safety performance.

1. INTRODUCTION

The electricity sector plays a vital role in driving Indonesia's economic development; however, it also presents considerable challenges, particularly in terms of Occupational Health and Safety (OHS). This industry encompasses the expansion of power generation, distribution networks, and electricity sales. Indonesia's electricity supply is generated by both state-owned PT Perusahaan Listrik Negara (PLN) and independent power plants. Between 2017 and 2024, national electricity capacity grew significantly, from 62,202.94 MW to 106,649 MW [1, 2]. As a critical energy backbone for multiple sectors, the electricity industry requires serious attention to its potential risks for worker health and safety [3, 4].

The rapid development of infrastructure, including the construction of new power plants and the expansion of distribution networks, has heightened the risk of electricity-related workplace accidents. Common hazards in this field include electric shocks, power surges, and fire incidents caused by system failures [5, 6]. Based on the Occupational Safety and Health Administration (OSHA) scenario analysis, three primary factors contribute to such accidents: unsafe equipment, hazardous work environments, and risky operational procedures [7, 8] These risks are multifaceted, with their prevention closely linked to factors such as workers' competence and practical experience [9] OHS regulations in Indonesia have become increasingly stringent, reflecting the government's commitment to strengthening workplace safety standards. Companies in the electricity sector are required to ensure compliance with these regulations and embed them into their risk management frameworks. Key legal instruments governing OHS include Law No. 1 of 1970 on Occupational Safety, Law No. 13 of 2003 on Manpower, Law No. 11 of 2020 on Job Creation, and Government Regulation No. 50 of 2012 on the Implementation of Occupational Health and Safety Management Systems (OHSMS) [10].

At the same time, aligning OHS practices with technological advancements in Indonesia's electricity sector has become essential. Enhancing the capacity, efficiency, and reliability of power infrastructure demands continuous updates to OHS risk management models to anticipate and mitigate emerging risks. Technological innovations in this context may include the application of smart grids, intelligent sensors, remote monitoring systems, and automation, all of which can significantly reduce accident risks [1]. Earlier studies have tried to address OHS risk management in the electricity industry. Albert and Hallowell [11] stated that OHS management in the United States (U.S.) construction sector uses a cost–benefit approach. Their findings indicated that while specific strategies were effective in reducing injuries related to maintenance of transmission and distribution systems, these measures also entailed very high costs. Roberts [12] integrated OHS principles with risk management principles in electrical safety. The OHSMS framework achieved the most effective implementation of hazard-specific standard requirements. Following risk management principles guaranteed the systematic identification and hierarchical implementation of risk control methods. The emphasis on OHSMS and the integration of risk management principles into the 2015 editions of NFPA 70E and CSA Z462 made these standards more accessible to OHS professionals, providing companies with a method for continuous and sustainable improvement of OHS performance and ultimately benefiting all electrical workers. Castillo-Rosa et al. [13] highlighted in a study across three categories of activities in Spain's primary, secondary, and tertiary sectors, the consequences of electrical accidents—both direct and indirect—lead to different outcomes. Electrical accidents often result in a high proportion of severe and fatal incidents. One recommended strategy is to ensure that installations and work equipment fully comply with legislation regarding protection against electrical contact.

Li et al. [14] used Interpretative Structural Modeling (ISM) to investigate the relationship between hazards/risks (considered obstacles) and the adoption of appropriate OHS measures. This study also studied inside and across hazard/risk classes, developing a structural model to identify and prioritize their levels. The results indicate that insulation failure (B7) represents the most critical hazard and therefore should be prioritized before other OHS actions are implemented in coal-fired thermal power plants. The second barrier in the ISM hierarchy, fire (plant/pool/jet) (B6), along with other identified hazards, requires further evaluation. Meanwhile, Wang et al. [15] developed a model for detecting safety hazards based on a lightweight MobileNet architecture, which proved to be accurate and efficient in identifying hazards in key resource sites. The model utilized a dataset of 1,440 images, covering both normal power plant conditions and associated facilities. Nurhayati et al. [16] used the Partial Least Squares–Structural Equation Modeling (PLS-SEM) method to model OHS, people, and work environment variables that could cause occupational diseases in workers in an industry. The study found a link between occupational disease incidence and characteristics such as PPE use, years of service, airborne dust levels, disease history, and noise exposure. Furthermore, there was a link between OHS variables (PPE use and noise levels) and occupational diseases, as well as between individual characteristics (years of service and disease history) and work environment factors (airborne dust levels).

Haroun and Ghomari [17] conducted an integrated approach and Spatial Data Visualization for the Occupational Health and Safety Management System (SDIVA-OHSMS) at the Algerian electricity and gas company (Sonelgaz). SDIVA-OHSMS provides a practical framework for organizations managing OHS services to adopt data-driven decision-making solutions that incorporate spatial and semantic aspects. Its effectiveness was evaluated through a case study drawing on expert judgments and software implementation. The results indicated that experts concluded that the SDIVA-OHSMS system provided a more comprehensive and accurate picture of occupational health issues and guided further prevention policies. Esmaeilli et al. [18] conducted research on the influence of Safety Performance Indicators (SPI) on the performance of the Health, Safety, and Environment (HSE) management system and the impact of the spread of COVID-19 on these indicators in the electricity industry. Safety indicators had been identified based on comprehensive safety indicators that were available in the industry and expert opinions. Subsequently, they had been ranked, weighted, and prioritized through the Analytic Hierarchy Process (AHP), which was followed by a calculation and comparison process during the periods before and after the COVID-19 outbreak. The findings showed that the indicators and their analyses before and after the COVID-19 outbreak, as well as the safety performance of the HSE unit, were not significantly influenced by the pandemic. This outcome is attributed to the fact that the electricity industry under study had not fully incorporated several indicators, and that routine performance assessments played a major role in driving continuous improvement.

Otitolaiye and Abd Aziz [19] explored the factors that influenced the safety performance of power and electricity distribution companies in Nigeria by applying McGrath's input-process-output model as a theoretical framework using SmartPLS 3.0 and SPSS Version 23. The results indicated that employee involvement, safety training, working conditions, management commitment, safety communication, safety champions, and government regulations were significant factors that influenced safety performance through their impact on working conditions. Organizational and regulatory elements played a crucial role in shaping safety performance in high-risk environments.

The reviewed paper indicated that the electricity distribution industry had a high occupational risk, especially during live working operations, i.e., work under voltage conditions (WUVC). Electric shock, arc flash, equipment failure, and unstable climatic conditions were just a few of the risks that workers faced due to Indonesia's energy infrastructure's rapid expansion. Empirical studies demonstrated that efficient modeling of hazardous situations significantly reduced accident rates in energy systems, and electrical hazard detection evolved with ongoing technical improvements. In distribution environments, where employees had to work directly on energized wires in dynamic field conditions, those dangers were significantly increased. In high-risk electricity industry operations, safety performance is closely related to human behavior and compliance with operational procedures. Based on this insight, evidence-based safety management requires analytical approaches that can systematically evaluate human and organizational factors and prioritize safety-critical elements, which supports the integration of Structural Equation Modeling–Partial Least Square (SEM-PLS) and AHP frameworks in this study by Suwandi et al. [20].

Research indicated that workers' perceptions of risk and adherence to safety procedures in high-risk occupations were influenced by safety climate, leadership, workload, and previous accident experience. Furthermore, research in the Indonesian electricity industry indicated that latent variables such as environmental factors, personal characteristics, and safety factors had a significant impact on safety hazards [21-24]. Therefore, the AHP gained recognition as a powerful multi-criteria decision-making tool for addressing complex safety management issues by allowing for the quantification and prioritization of risk factors based on expert judgment and empirical data. To enhance occupational hazard assessments and strategic safety planning in high-risk industries, such as power distribution, recent research demonstrated the integration of AHP with fuzzy logic, Delphi techniques, and machine learning.

However, the majority of current research focuses on global contexts or general industrial applications, with limited adaptation of these techniques to Indonesia's unique electrical sector environment, particularly live working operations known as WUVC. To obtain a comprehensive understanding of latent safety variables and their prioritization in intervention methods, there is also a research need for combining sophisticated latent variable analysis approaches, such as SEM-PLS, with AHP.

To close these gaps, this work proposes a hybrid model that combines SEM-PLS to identify key latent variables influencing occupational safety and AHP to prioritize improvement measures tailored to the specific challenges faced by the Indonesian power distribution industry. The innovation lies in combining both qualitative expert judgment and quantitative statistical modeling in a localized setting to enhance the efficacy of decision-making. This study aims to (1) use SEM-PLS analysis to identify important factors influencing occupational safety hazards in the Indonesian electricity industry; (2) apply AHP to prioritize safety improvement strategies based on identified factors and expert input; and (3) develop and validate an implementation framework that supports focused safety interventions in real-world working environments. By achieving these objectives, the study supports Indonesia's continued industrial expansion with lower occupational risks while also advancing academic understanding and practical safety management.

2. LITERATURE REVIEW

2.1 Occupational Health and Safety

OHS is an essential requirement for both Micro, Small, and Medium Enterprises (MSMEs) and large companies in carrying out their business activities. The central objective of OHS implementation is to create a safe and healthy work environment, not only for employees but also for their families, customers, and others who may be affected by workplace conditions. Because OHS is closely related to production performance, industries must properly control the risks of accidents and occupational illnesses to avoid productivity losses [25-27].

The importance of OHS arises from moral, legal, and financial considerations. Organizations are obligated to ensure the safety of their workers and all related stakeholders at all times. OHS practices encompass preventive measures, sanctions, compensation, medical treatment, health care, and leave for sick employees. Safety efforts aim to mitigate risks that may lead to fatalities, illnesses, or stress, whether in the workplace or beyond. Meanwhile, health emphasizes ensuring employees remain free from both physical and psychological illnesses [28, 29].

Workplace safety refers to the protective measures organizations undertake to prevent occupational accidents during task performance. These measures protect workers' physical, mental, and social well-being by preventing work and environment-related health problems or conditions, as well as common illnesses that could result in losses in the workplace. A safe working condition enables employees to perform their duties without accidents, thereby improving productivity and overall performance [25].

2.2 Safety hazards

Safety hazards refer to potential conditions that may pose a risk to workers' safety, particularly in sectors with high-risk operations. Such risks may be realized through workplace accidents, exposure to toxic or hazardous materials, or ergonomic disorders that have implications for employees' long-term health. Managing such hazards effectively is essential to minimize injuries or accidents that could bring harm not only to workers but also to the organization. Therefore, identifying potential hazards in a structured way becomes a fundamental step toward building a safer workplace [30, 31].

Risk management provides the core framework for handling safety hazards in industrial environments. The process typically starts with thorough hazard identification, followed by risk assessment and the application of preventive and corrective actions. When applied correctly, risk management not only reduces the likelihood of hazards but also strengthens workers' awareness and preparedness to adopt safe practices, which in turn decreases the probability of workplace accidents [30, 32].

Advances in technology further enhance the ability to manage safety risks. Human-Machine Interface (HMI) systems, for instance, enable real-time monitoring of operations, allowing for the detection of early warning signs of danger before they develop into serious incidents. Similarly, automated sensors and data-driven monitoring systems enable the quick identification of abnormal conditions, allowing for a rapid response that improves both accident prevention and operational efficiency.

These innovations also contribute to stricter oversight of processes with high risk levels [33, 34].

In addition, fostering a strong safety culture within the workplace is equally vital. Embedding safety values into everyday practices motivates employees to take greater responsibility for their own protection and that of their colleagues. Organizations that successfully cultivate such a culture tend to achieve better compliance with safety protocols and experience fewer accidents. Greater awareness and a heightened sense of responsibility encourage workers to take a more proactive role in attending safety training and following prescribed guidelines, thereby fostering a safer and more sustainable workplace [35].

2.3 Structural Equation Modeling–Partial Least Square

SEM served as a powerful multivariate statistical technique that researchers utilized to assess how well their proposed hypothetical models aligned with collected empirical data and a theoretical framework [36-38]. The two primary approaches within SEM are: PLS-SEM and Covariance-Based Structural Equation Modeling (CB-SEM). PLS-SEM offers several distinct advantages over CB-SEM, making it a widely adopted method [39, 40]:

a. Flexibility in specification: PLS-SEM provides greater flexibility in defining the relationships between the observed items (indicators) and the unobserved constructs (latent variables).

b. Sample size: It performs well with various sample sizes, provided the basic minimum requirements are met.
c. Complex relationships: PLS-SEM is particularly suitable for testing hypotheses involving complex effects among variables within the model.
d. Construct operationalization: It works with constructs (composites or latent variables) where the measurement models can be specified using different operationalizations: Mode A (also known as reflective measurement), Mode B (also known as formative measurement), and Common factor.

This combination of features explains the widespread use of the PLS-SEM approach among researchers. Several significant advantages associated with the PLS-SEM approach render it particularly valuable for applications in social science research. Core Benefits of PLS-SEM are that the methodology of PLS-SEM allows for robust verification of theoretical models [41]; PLS-SEM is highly effective for reliably estimating complex hypothetical models. It performs well even in scenarios with many latent variables (constructs) and numerous indicators (items). PLS-SEM can be reliably used even with relatively small sample sizes. While capable of handling complexity, the underlying goal of PLS-SEM is to arrive at models that are as parsimonious (simple and concise) as possible, while still explaining the target constructs effectively [38].

Due to these advantages, PLS-SEM is a technique successfully applied across various domains within social science research, including: the construction industry, studies on competitive performance, hospitality management, and research concerning organization and the environment [40, 42-44]. Consequently, the PLS-SEM approach was selected to test and verify the 11 hypotheses proposed in our study.

The guidelines for conducting a PLS-SEM analysis are structured around four key aspects. These aspects define the typical, systematic process identified as relevant in prior research on PLS-SEM usage. The four core steps in the structured PLS-SEM analysis process are [38]:

a. Determining the research goal: Clearly defining the purpose and objectives of the analysis.
b. Structural model specification: Defining the hypothesized relationships (paths) between the latent variables (constructs).
c. Measurement model specification: Determining how the latent variables are measured by their observed indicators (i.e., specifying whether they are reflective or formative).
d. Results evaluation: Assessing the quality of the measurement and structural models and interpreting the findings relative to the research goal.

2.4 Analytic Hierarchy Process

This study formulated priority strategies for improving safety in Indonesia's electrical power industry. The AHP was employed as a tool to rank and prioritize various strategic alternatives, thereby enabling decision-makers to select the most appropriate option. AHP was a decision-support model developed by Saaty [45], a professor at the University of Pittsburgh, which was designed to assist decision-making in situations involving multiple factors or criteria. This model broke down complex, multi-criteria problems into a hierarchical structure, which made them more manageable and systematically organized [45, 46].

Table 1. Pairwise comparison n scale [47]

Intensity of Importance	Definition	Description
1	Equal importance.	Both elements have an equal influence on the goal.
3	One element is slightly more important than the other.	Experience and judgment slightly favor one aspect over the other.
5	One element is more important than the other.	Experience and judgment strongly support one element over the other.
7	One element is absolutely more important than the other.	One element is strongly supported and clearly dominant in practice.
9	One element is absolutely more important than the other.	The evidence supporting one element over the other has the highest possible level of affirmation.
2, 4, 6, 8	Intermediate values between the two adjacent judgments.	This value is assigned when a compromise is reached between two alternatives.
Reciprocal value	If activity i is assigned a certain value when compared to activity j, then activity j will have the reciprocal value when compared to activity.	

The AHP method employs a functional hierarchy model, where human judgment serves as the primary input. These judgments are expressed through pairwise comparisons of the relative importance of attributes and the evaluation of available alternatives [46]. According to Saaty [46], a hierarchy represents a complex problem in a multi-level structure, where the top level defines the main objective, followed by factors, criteria, sub-criteria, and finally the lowest level, which consists of alternatives. By structuring problems in this way, complex issues can be broken down into smaller groups, allowing for a more systematic and transparent analysis. Syukron [48] highlighted three key principles for analysis using AHP, including:

a. Hierarchy construction: Complex realities are broken down into fundamental elements, which are then further divided into sub-elements, resulting in a hierarchical structure.
b. Priority setting: Priorities are determined based on the perspectives of experts or relevant stakeholders, either directly or indirectly, in the decision-making process.
c. Logical consistency: This principle ensures that both qualitative and quantitative aspects are considered. Quantitative judgments are expressed numerically to reflect preferences, while qualitative aspects define the problem and guide the hierarchical structuring.

The steps in applying AHP can be summarized as follows

[49]:

a. Problem definition and goal setting, followed by the development of a hierarchical structure consisting of the overall goal, relevant factors, actors, and alternative strategies to be ranked.
b. Establishing pairwise comparison matrices to represent the relative contribution or influence of each element toward the elements at the higher level. These comparisons are based on the judgments of decision-makers, who evaluate the importance of one element relative to another. Saaty [46] proposed a nine-point scale (1–9) to measure these comparisons, where each value represents a specific level of relative importance. The numerical scale can be supported with qualitative interpretations, as typically presented in an analytical weighting table (Table 1).
c. Calculating the eigenvector of each pairwise comparison matrix. The eigenvector value represents the weight of each element. This step is carried out to synthesize the alternatives in determining the priority of elements, from the lowest level of the hierarchy up to the achievement of the overall goal.

Testing the consistency of the hierarchy using the Consistency Ratio (CR), which must be less than 0.10. If this requirement is not met, the assessment must be repeated.

3. METHOD

The focus of this research is the distribution unit of PT XYZ, and the study participants consist of operators who work under energized conditions (WUVC) within this unit. The criteria for selecting respondents include WUVC operators with a minimum of three years of experience, aged between 25 and 45 years, and in good physical and mental condition. The workflow of this study is illustrated in Figure 1.

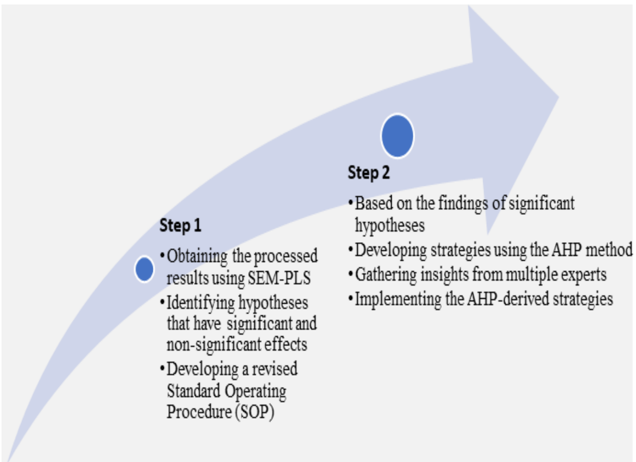

Figure 1. Roadmap research

The research plan has been comprehensively executed, beginning with the formulation of research questions, followed by literature searching and review, engineering design, cost estimation, and the completion of the production process along with its outputs [50]. Building on a paper previously published in IJSSE, the data employed and the statistical analyses were derived from earlier work; consequently, this subsequent study explores the AHP from the standpoint of implementation strategy.

This study consists of 11 hypotheses based on a conceptual model (Figure 2). The hypotheses are categorized into causal hypotheses (direct effects) and mediation hypotheses (indirect effects).

The hypotheses in this study were formulated to examine the relationships among factors that affect workplace safety, particularly within the PT XYZ distribution unit. The study commenced with a literature review of previous research concerning safety hazard models. This stage was followed by interviews and Focus Group Discussions (FGDs) involving five stakeholders at Expert Electrical Company, including representatives from OSHE as well as training centers in the transmission and distribution sectors. The data obtained from these interviews and FGDs were analyzed employing thematic analysis. Based on insights from both the literature and FGDs, a conceptual framework was developed for advancing the safety hazard model in the electricity sector [50]. The subsequent step was the development of a questionnaire based on the latent variables derived from the conceptual framework. This questionnaire served as the main instrument for designing the safety hazard model in the electricity industry. Data were then collected from 200 WUVC operators working in PT XYZ's distribution units.

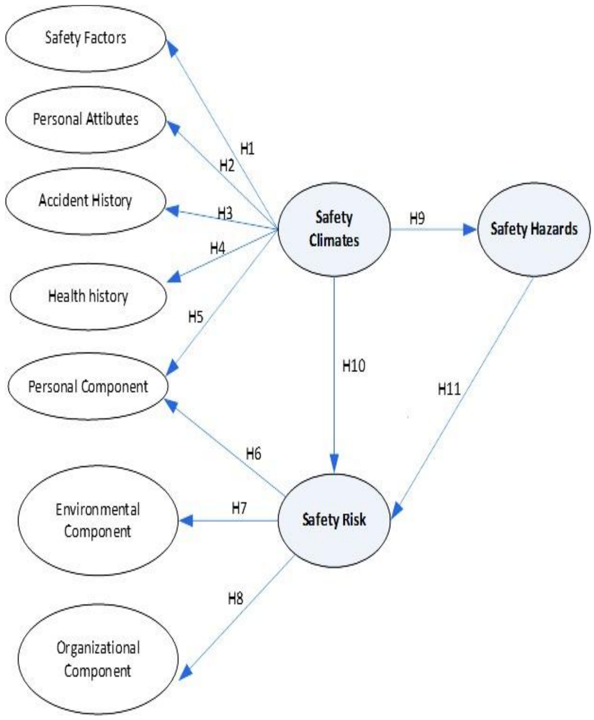

Figure 2. The research hypotheses of the new model

The collected survey data were processed employing the SEM-PLS technique utilizing SMART-PLS 3. Following the development of the model, a guideline was formulated for evaluating Key Performance Indicators (KPIs) derived from the significant latent variables within the model. This manual was then piloted to assess the KPIs of WUVC workers at the Electrical Education Company in Semarang. The trial, involving 30 WUVC operators, was conducted over a period of one month.

Following the pilot phase, validity tests were carried out on the KPI results obtained using the manual. A comparison test was subsequently performed to evaluate the significance of the differences between the new manual and the current manual. Figure 3 shows the research framework.

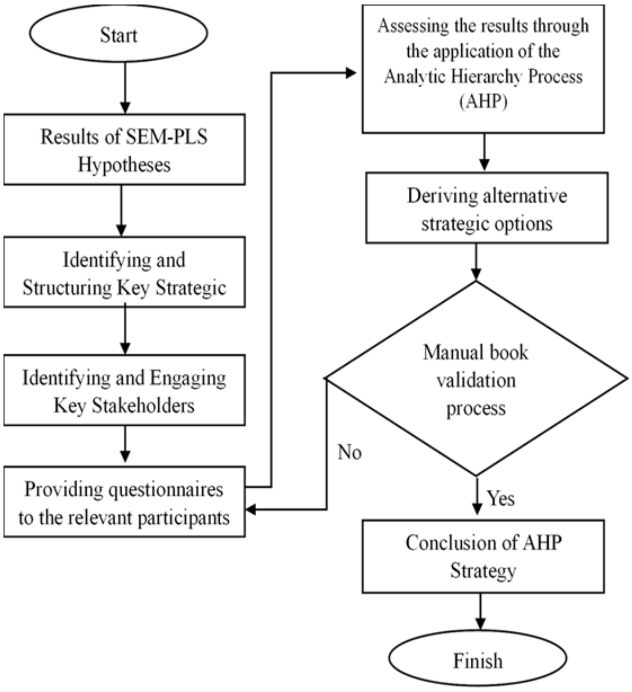

Figure 3. Research framework

4. DISCUSSION

4.1 Bibliometrics analysis

Bibliometric analysis is a multidisciplinary research approach that utilizes mathematical and statistical techniques to assess the quantitative characteristics of academic publications and other knowledge sources. Its main aim is to generate a detailed and comprehensive depiction of the intellectual landscape within a particular field of study by Su et al. [47]. This is achieved by analyzing influential publications and citation networks, which allows for the exploration of the domain's historical evolution, current state, and potential future development [51]. The primary source of information used in this study is the research database published in Scopus. Researchers often use Scopus to collect literature because it is an open source that provides a comprehensive database on various scientific topics. This study uses a methodology to organize and analyze a hybrid framework that combines SEM-PLS and the AHP approaches for evidence-based safety management in high-risk live working operations of the electricity industry. The database published (metadata) in Scopus was then downloaded as a comma-separated value (CSV) dataset, a specific file format that can be generated and modified in Excel. The CSV file was subsequently analyzed using Vos Viewer, a commonly employed bibliometric tool that utilizes bibliographic data, filtered by co-occurrences of all keywords and quantified by occurrences (full counting) [51, 52].

The metadata exported from Scopus in CSV format was analyzed using Vos Viewer. The mapping process was carried out through keyword filtering by setting a minimum threshold of 20 documents. Of the 14,974 keywords identified, 104 met this criterion. The analysis results showed that the keyword "structural equation modeling" was the most dominant, appearing in 480 documents with a total link strength of 314, indicating its relationship with 314 other keywords. Meanwhile, the keyword SEM-PLS was found in 161 documents and was related to 147 other keywords. The keyword "risk management" appeared in 63 documents and was linked to 51 other keywords. The overlay visualization of the co-occurrence map is shown in Figure 4. Based on these results, the keywords "Analytic Hierarchy Process" and "electricity industry" do not appear in the co-occurrence map, which indicates that the number of publications combining these two keywords—as formulated in the G5 search combination ("structural equation modeling" OR "SEM-PLS" OR "partial least squares") AND ("Analytic Hierarchy Process" OR "AHP") AND ("safety management" OR "risk management" OR "decision-making") AND "electricity industry" OR "power system" OR "live working" OR "high-risk operation")) On Scopus—is still very limited.

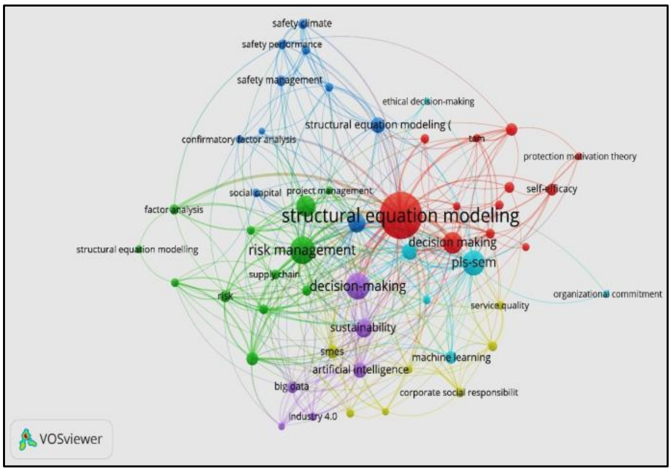

Figure 4. The overlay visualization of the co-occurrence map

The resulting co-occurrence map was then analyzed qualitatively by observing the thickness of the links between keywords and terms. The thicker the links, the stronger the connection between one keyword and another. The keyword mapping results showed the formation of four main clusters. The first cluster represents the group of keywords with the strongest level of interconnection, while the fourth cluster illustrates relatively weaker relationships [53].

Cluster 1 consists of keywords such as SME, decision making, PLS, and the technology acceptance model. Cluster 2 includes keywords such as risk management, risk assessment, supply chain management, structural equation model, and factor analysis. Cluster 3 contains keywords such as decision-making, PLS-SEM, sustainability, and artificial intelligence. Meanwhile, cluster 4 includes keywords such as SMEs, sustainable development, corporate social responsibility, and customer satisfaction. These four clusters demonstrate the significant development of research related to SEM-PLS in the domains of decision-making, organizational behavior, risk management, sustainability, and intelligent technology. The detailed illustrations are shown in Figure 5. However, the absence of keywords such as "Analytic Hierarchy Process" or "electricity industry" in the co-occurrence map confirms that the integration of SEM– PLS and AHP in the context of high-risk electricity operations is still very limited. This conclusion opens up new research opportunities and demonstrates the potential of this study to fill this gap.

In addition to generating visual overlays from co-occurrence maps, Vos Viewer also serves as an effective tool for analyzing the dynamics of research development, knowledge dissemination patterns, and global scientific and technological collaboration [54]. Figure 6 displays the collaborative research network between countries contributing to the topic of a hybrid framework integrating the SEM–PLS and AHP approaches for evidence-based safety management in high-risk work operations in the electrical industry during the period 2010–2025.

Although the SEM–PLS and AHP approaches have been widely applied separately in studies of decision-making, risk management, and organizational performance evaluation, their integration in the context of evidence-based occupational safety in the electricity industry—particularly in high-risk live working activities—has not been widely explored. Bibliometric analysis shows no significant correlation between the keywords "Analytic Hierarchy Process" and "electricity industry," indicating a lack of research combining quantitative methods based on structural models and multi-criteria assessment techniques in this domain. Furthermore, the limited research contributions from developing countries, including Indonesia, highlight the need for a more comprehensive methodological approach to improve the understanding of safety factors in high-risk electricity operations.

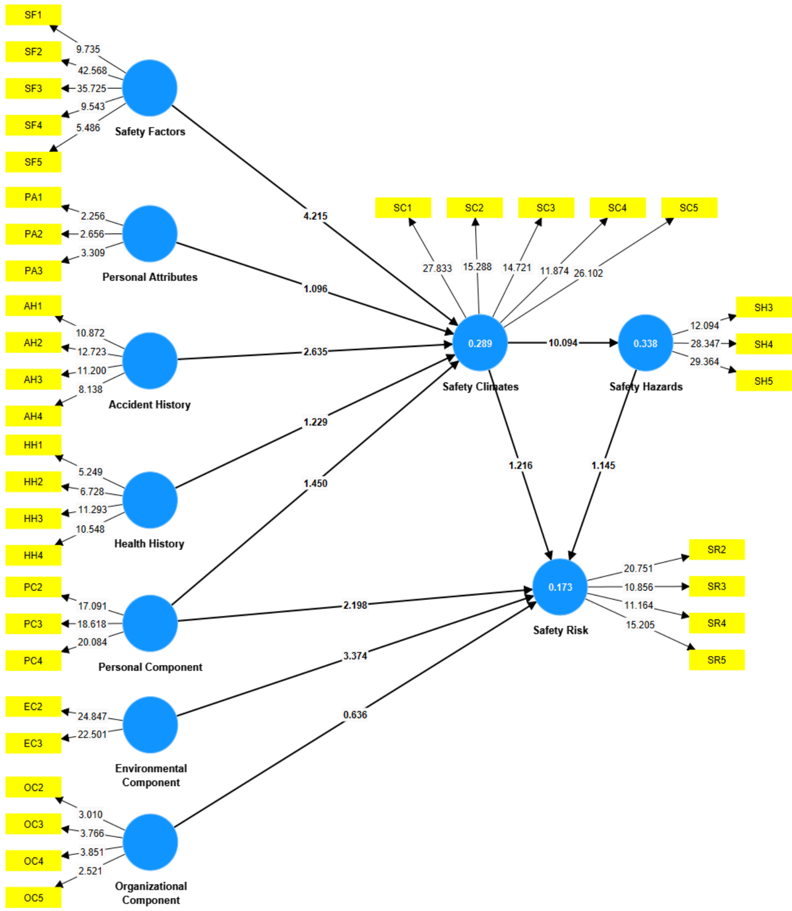

Figure 5. Final T-statistic values of Structural Equation Modeling–Partial Least Square (SEM-PLS)

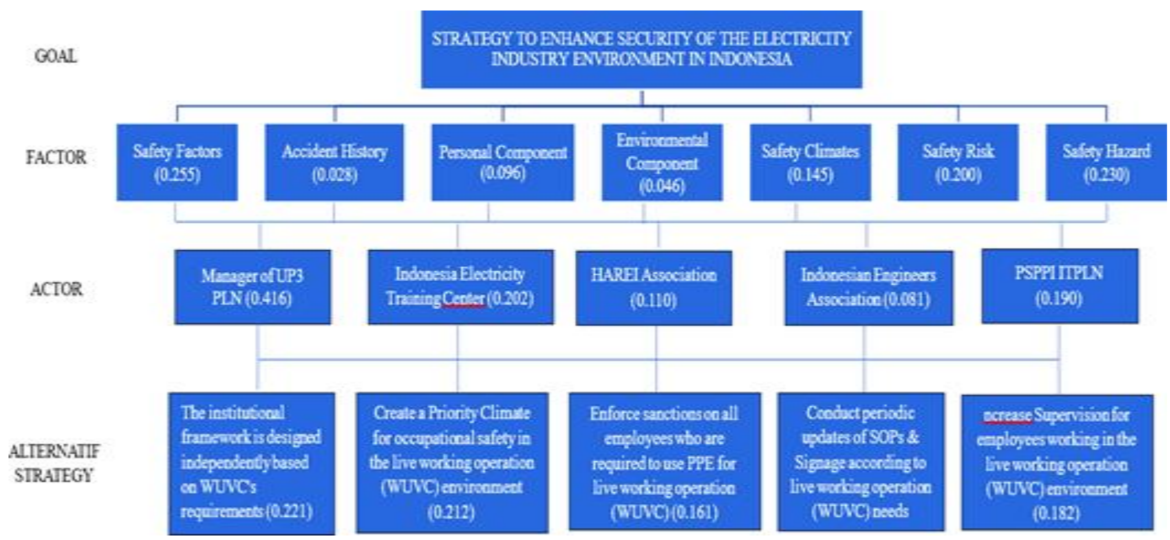

Figure 6. Hierarchy of strategies to enhance safety in the Indonesian electricity industry

4.2 Structural Equation Modeling–Partial Least Square findings

Theoretically, this result supports both Safety Culture Theory and Organizational Climate Theory, which highlight that observable safety practices and management's explicit commitment to safety are fundamental in forming employees' shared safety perceptions. When safety provisions and procedures are sufficient and consistently applied, employees develop trust in the organization's prioritization of safety. Such a climate promotes collective responsibility and increases adherence to safety regulations, ultimately reducing workplace accidents and injuries. From a practical perspective, the finding stresses the necessity of continual improvement in safety facilities, training effectiveness, and communication mechanisms. Regular safety audits, refresher training, and active employee participation are recommended to ensure that these safety dimensions are sustained and perceived positively across the workforce.

These findings indicate that the safety climate is shaped mainly by organizational conditions and safety management practices, rather than by individual employee characteristics. In line with Social Cognitive Theory, safety climate represents a collective perception that is largely driven by shared experiences, leadership behaviors, and organizational policies, rather than demographic variations among workers. Although individual attributes such as age or education may influence personal behavior and risk perception, they do not significantly impact the overall safety climate of the workplace. The final SEM-PLS flowchart is presented in Figure 5.

Practically, the results emphasize that organizational safety initiatives should be directed toward structural interventions, including strengthened managerial commitment, enhanced safety communication mechanisms, and uniform application of safety policies, instead of relying predominantly on demographic attributes to forecast or improve safety climate. Through organizational-level reform, firms can establish a comprehensive and equitable safety environment that benefits employees across diverse backgrounds [50]. From the paper previously published in IJSSE, the data used, and the statistical test results were built upon prior work; therefore, this follow-up study examines the AHP from the perspective of implementation strategy.

4.3 Analytic Hierarchy Process factor prioritization

The findings of the model development indicate that the variables of safety factors, accident history, personal components, environmental components, and safety climate significantly influence safety hazards. The first finding indicates that safety factors and accident history among WUVC operators influence the safety climate. This occurs because the formation of a safety climate arises from the interaction between safety factors and accident history, which together establish the foundation of safety culture and foster proactive attitudes among WUVC workers toward occupational risks. Safety factors refer to the policies, procedures, and resources provided by company management to ensure the safety of workers. Within the WUVC team, this factor is crucial, as the availability of PPE, intensive simulated training, and strict Standard Operating Procedures (SOPs) form the foundation of a positive safety climate. WUVC workers feel valued and protected by the company, which motivates them to voluntarily and proactively comply with safety practices.

Meanwhile, accident history represents the experiences of WUVC workers with past incidents or accidents. For WUVC workers, even the occurrence of near misses has a significant psychological impact. Such incidents may generate positive effects by providing valuable lessons and strengthening workers' awareness of hazards in the workplace. Conversely, if incidents are ignored or concealed, they may result in a loss of trust in management and damage the workplace safety climate [55].

Safety climate in an organization reflects the collective perceptions of employees regarding the importance of workplace safety. This is consistent with Oah et al. [55], who stated that safety factors (e.g., workload) and accident history can influence workers' perceptions of occupational risks. Furthermore, safety climate can be improved if companies actively provide high-quality safety training and encourage supervisors to demonstrate safety leadership, thereby strengthening employees' positive perceptions and improving the organizational safety climate.

The next finding of the model indicates that both personal and environmental components influence safety risk. This occurs because WUVC operators' work requires extreme caution due to the direct hazards of handling high-voltage electricity. Individual components that may contribute to accidents include the knowledge, skills, and attitudes of operators during work. This aligned with Heinrich's research, which found that unsafe acts by individual workers caused 88% of industrial accidents, unsafe environments caused 10%, and 2% were unpreventable [53]. Such unsafe acts may result from insufficient or incomplete training, as well as physical or mental conditions such as fatigue or stress, which can reduce concentration and reaction time [56].

From an environmental component perspective, the physical conditions of the workplace and the availability of facilities play a crucial role. WUVC operators often face extreme working conditions, particularly when exposed to adverse weather such as rain and lightning. Additionally, challenging terrains such as elevated sites or wet areas also increase risks [57, 58]. Other environmental factors include inadequate vehicles, the presence of sparks, and extreme weather conditions, all of which are significant hazards. Moreover, the availability and condition of equipment and PPE serve as the last line of risk control. Unsafe conditions in the environment can be exacerbated if the company's OHS management system is inadequate [59].

The integration of personal and environmental components ultimately shapes the level of safety risk in the workplace. An effective OHSMS must be capable of identifying, evaluating, and controlling risks from both variables. Previous studies have indicated that weaknesses in management control systems are often the root cause of unsafe behaviors and unsafe conditions among workers. Furthermore, the importance of safety climate in influencing safety acts has been demonstrated in previous research, showing a significant relationship between safety climate and worker safety [60].

Five respondents were selected as decision-makers in this study. The respondents chosen as decision-makers are experts or specialists in fields related to the Indonesian electricity industry. The hierarchy of strategies for improving safety in the Indonesian electricity industry is presented in Figure 6.

This AHP analysis was conducted using the Expert Choice version 11 software. Expert Choice is an application that serves as a decision-making tool to assist decision-makers in determining the best course of action [61]. The software offers a range of features, including entering criteria data, selecting alternative options, and defining objectives. It is user-friendly due to its simple interface and is capable of performing both quantitative and qualitative analyses, ensuring rational outcomes.

a. Once all pairwise comparison matrices have been completed, the next step is to combine the responses from all experts. This is done by selecting Assessment → Combine Participants' Judgments/Data → Entire Hierarchy, as illustrated below (Figure 7).
b. After combining the assessments, the resulting weight values for each level (Goal, Factors, Actors, and Alternative Strategies) will be generated. The analysis requires that the inconsistency value or CR be less than 10%, which indicates that the decision-makers' evaluations are consistent and acceptable. The output of the weight values is presented as shown in the following example (Figure 8).

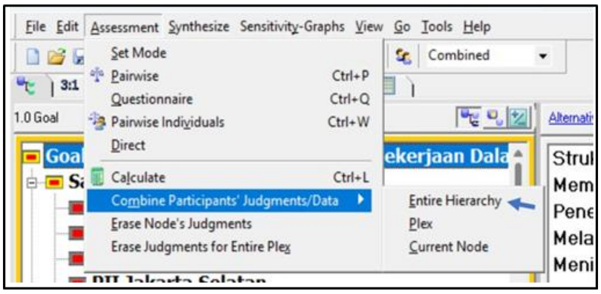

Figure 7. Combine the responses from all experts

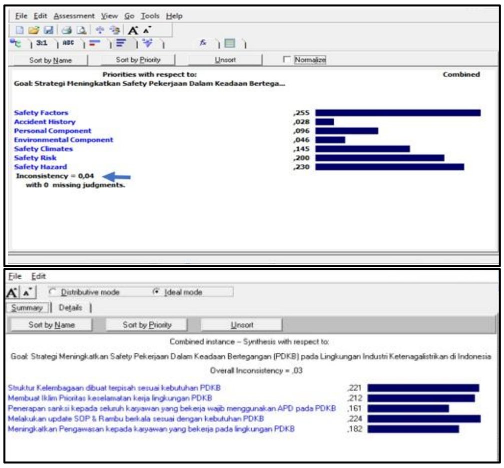

Figure 8. The output of the weight values

4.4 Synthesis of Structural Equation Modeling–Partial Least Square and Analytic Hierarchy Process results

The factor-level analysis produced a CR value of 0.04, which is below the threshold of 1, indicating that the assessments made by the decision-makers are consistent and therefore acceptable (Figure 9). The analysis further reveals that the safety factor holds the most significant weight (0.255), followed by safety hazard (0.230) and safety risk (0.200). These findings suggest that safety factors represent the top priority in enhancing the safety of the electricity industry environment in Indonesia, with safety hazards ranked second and safety risks third. The factor level of the weight values is presented as shown in the following example (Figure 9).

Furthermore, an analysis at the factor level for each factor was conducted to identify the dominant roles of actors based on the existing factors, aiming to enhance the safety of the electricity industry environment in Indonesia. At the factor level, based on each factor, the CR value was found to be < 1, indicating that the decision-makers' assessments were consistent and acceptable (Table 2). Overall, the results show that PT XYZ has the highest weight of 0.416, followed by the Indonesian Electricity Training Center (Expert Electrical Education) in second place with a weight of 0.202, and the expert electrical company in third place with a weight of 0.190. This indicates that PT XYZ plays a significant and dominant role in addressing the influencing factors to enhance the safety of the electricity industry environment in Indonesia.

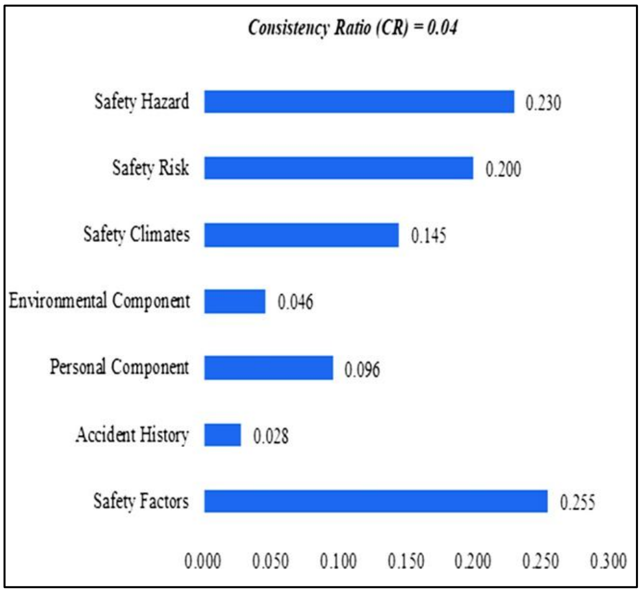

Figure 9. Factor-level weight values

Table 2. Actor-level weights based on factors

Actor	Factors							Result
	Safety Factor	Accident History	Personal Component	Environmental Component	Safety Climate	Safety Risk	Safety Hazard	
Expert Electrical Company	0.419	0.359	0.468	0.398	0.403	0.429	0.437	**0.416**
Expert Electrical Education	0.217	0.194	0.168	0.217	0.225	0.228	0.168	**0.202**
Expert HAREI	0.118	0.131	0.118	0.100	0.099	0.101	0.104	**0.110**
Expert PII	0.076	0.085	0.091	0.077	0.080	0.075	0.083	**0.081**
Expert PSPPI	0.170	0.231	0.155	0.208	0.193	0.167	0.208	**0.190**
Total	**1.000**	**1.000**	**1.000**	**1.000**	**1.000**	**1.000**	**1.000**	**1.000**
Consistency Ratio	**0.030**	**0.050**	**0.050**	**0.020**	**0.040**	**0.020**	**0.030**	

Table 3. Weight values of alternative strategy levels based on actors

Alternative Strategies	Actors					Result
	Expert Electrical Company	Expert Electrical Education	Expert HAREI	Expert PII	Expert PSPPI	
The institutional structure is established separately according to the needs of WUVC.	0.226	0.175	0.237	0.275	0.232	**0.221**
First work environment climate for WUVC.	0.174	0.263	0.231	0.158	0.259	**0.212**
Implementation of sanctions requiring all employees working in WUVC to use PPE.	0.198	0.190	0.093	0.060	0.111	**0.161**
Regular updates of SOPs and signage according to WUVC needs.	0.232	0.195	0.203	0.371	0.214	**0.224**
Enhancing employees' WUVC environment.	0.170	0.177	0.237	0.136	0.185	**0.182**
Total	**1.000**	**1.000**	**1.000**	**1.000**	**1.000**	**1.000**
Consistency Ratio	**0.030**	**0.020**	**0.050**	**0.030**	**0.010**	

Subsequently, an analysis was conducted at the strategy alternative level for each actor to map the strategic priorities based on the role of each actor in enhancing the safety of Indonesia's electricity industry environment. At the strategy alternative level for each actor, the CR value obtained was < 1, indicating that the decision-makers' assessments were consistent and acceptable (Table 2). Overall, the results show that the alternative strategy of regularly updating SOPs and safety signs according to the needs of WUVC holds the highest weight at 0.224, making it the top priority. This is followed by the alternative strategy of establishing a separate institutional structure tailored to WUVC needs, with a weight of 0.221. The third priority is fostering a safety climate within the WUVC work environment, with a weight of 0.212. The overall hierarchy, along with its corresponding weight values, is presented in Table 3.

5. CONCLUSIONS

This study developed an integrated analytical framework that combines the AHP and Structural SEM-PLS to enhance occupational safety management in Indonesia's electrical distribution industry. According to the SEM-PLS results, the creation of safety threats among WUVC operators is strongly influenced by safety factors, accident history, personal components, environmental components, and safety climate. These results highlight the crucial role that environmental factors, safety culture, and organizational safety procedures play in determining employees' risk exposure in high-voltage operating environments.

The AHP process was used to prioritize strategic actions based on expert judgment, building on these latent variable correlations. The robustness of expert judgments was confirmed by the factor-level analysis, which produced a CR of 0.04. The highest-priority domain was identified as safety considerations, followed by safety risks and hazards. PT XYZ was recognized as the most significant stakeholder in enhancing safety outcomes at the actor level, underscoring the vital importance of organizational leadership and resource allocation. The highest priority was given to upgrading SOPs and safety signage on a regular basis to meet WUVC's operating needs. This was followed by the creation of an institutional framework specifically for WUVC activities and the enhancement of the safety atmosphere.

A valuable tool for tracking worker safety performance and improving field-level decision-making is provided by the verified KPI-based manual derived from significant latent variables. When taken as a whole, the combined SEM-PLS–AHP methodology offers a methodical and fact-based basis for creating focused OHS enhancements in high-risk electrical situations.

The study's concentration on a single state-owned firm limits its generalizability, notwithstanding its contributions. To enhance model flexibility and accuracy, future research should consider a range of organizations and local contexts and utilize digital, real-time monitoring tools. Nevertheless, by offering a thorough, data-driven approach to reducing risks in the Indonesian power sector, the findings make a substantial contribution to both scholarly discussions and real-world safety management.

CONTRIBUTIONS

Conceptualization, P, HP, WNY, and AR; methodology, P and AR; software, P and AR; validation, HP and WNY; formal analysis, P and AR; investigation, P; resources, P and AR; data curation, P; writing—original draft preparation, P, HP, WNY, and AR; writing—review and editing, P and AR; visualization, P and AR; supervision, HP and WNY; project administration, P; funding acquisition, P. All authors have read and agreed to the published version of the manuscript.

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CONFLICTS OF INTEREST

The authors declare no conflicts of interest related to this study. All participants involved in the interviews provided informed consent prior to data collection, and their confidentiality has been maintained throughout the research process.

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