



Development Of an ARC-Flash Hazard Mitigation Framework for Brownfield Industrial Power Distribution Retrofits in U.S. Manufacturing

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Doi: [10.63125/vhqjgm79](https://doi.org/10.63125/vhqjgm79)

Received: 04 February 2025; Revised: 21 March 2025; Accepted: 19 April 2025; Published: 19 May 2025;

Abstract

This study examined the development of an arc-flash hazard mitigation framework for brownfield industrial power distribution retrofits in U.S. manufacturing facilities. The problem addressed in the study is that many brownfield manufacturing environments operate with aging switchgear, outdated circuit protection, undocumented modifications, incomplete electrical drawings, limited shutdown windows, and inconsistent safety practices, which increase uncertainty in arc-flash assessment and expose workers to high incident energy, delayed fault clearing, poor hazard labeling, and unsafe energized work conditions. The purpose of the study was to assess how technical, organizational, planning, and maintenance-related factors influence arc-flash hazard mitigation effectiveness and electrical safety performance. A quantitative, cross-sectional, case-based research design was adopted, using structured questionnaire data collected from 220 valid respondents out of 260 distributed questionnaires, representing an 84.6% response rate. The sample included electrical engineers, maintenance engineers, safety managers, facility managers, plant or project engineers, and technical supervisors involved in enterprise-scale brownfield manufacturing retrofit and safety decisions. The key variables were electrical infrastructure condition, protective device coordination, safety compliance practices, retrofit planning quality, maintenance and inspection practices, arc-flash hazard mitigation effectiveness, and electrical safety performance. Data were analyzed using descriptive statistics, Cronbach's alpha reliability testing, Pearson correlation, and multiple regression modeling. The findings showed high agreement across all major variables, with safety compliance practices recording the highest mean score of 4.12, followed by arc-flash mitigation effectiveness at 4.10 and protective device coordination at 4.08. The regression model was significant, $F(5,214) = 46.82$, $p < 0.001$, and explained 52.2% of the variance in mitigation effectiveness. Safety compliance practices were the strongest predictor, $\beta = 0.29$, followed by protective device coordination, $\beta = 0.24$, maintenance and inspection practices, $\beta = 0.21$, retrofit planning quality, $\beta = 0.18$, and electrical infrastructure condition, $\beta = 0.15$. Arc-flash mitigation effectiveness also significantly improved electrical safety performance, $\beta = 0.34$, $p < 0.001$. The study implies that safer brownfield retrofits require integrated engineering controls, compliance discipline, maintenance verification, accurate documentation, and structured retrofit planning.

Keywords

Arc-Flash Hazard Mitigation; Brownfield Industrial Retrofit; Protective Device Coordination; Electrical Safety Compliance; U.S. Manufacturing.

INTRODUCTION

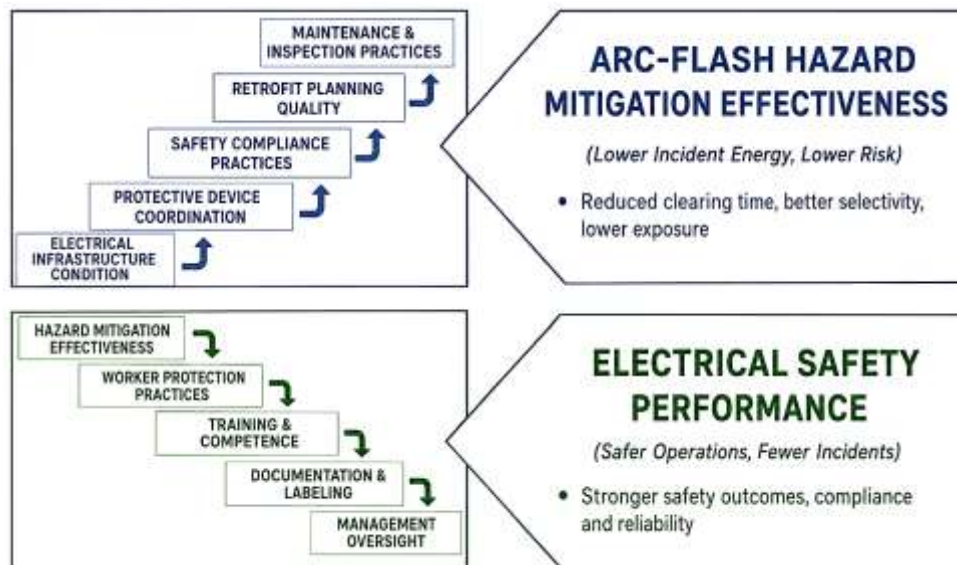
Arc flash refers to a high-energy electrical discharge that occurs when electric current travels through air between conductors, between a conductor and ground, or across an unintended low-impedance path within electrical equipment. In industrial power systems, this event can release intense thermal radiation, molten metal, pressure waves, acoustic energy, and toxic vapors within milliseconds, making it one of the most severe hazards associated with energized electrical work. Arc-flash hazard mitigation refers to the organized set of engineering, administrative, maintenance, and safety-control measures used to reduce the likelihood, severity, exposure, and consequences of such events. In brownfield industrial power distribution systems, the term “brownfield” describes existing facilities with legacy electrical infrastructure, aged switchgear, older motor control centers, limited spare capacity, outdated documentation, and operational constraints that restrict full system replacement. A retrofit refers to the modification, modernization, upgrading, or reconfiguration of existing electrical assets without constructing an entirely new facility. These definitions are central to the present study because arc-flash risk in brownfield U.S. manufacturing facilities is not only an electrical calculation problem; it is also a systems-safety problem involving aging equipment, protective device performance, maintenance history, human exposure, safety procedures, and compliance maturity. The international importance of arc-flash mitigation is supported by the global use of technical calculation models, workplace electrical safety programs, and incident-energy assessment methods that guide engineers and safety professionals in industrial settings. Technical literature on arc-flash hazard assessment has shown that incident energy is strongly associated with arcing current, system voltage, working distance, equipment configuration, and fault clearing time, making protective device coordination and faster interruption central to hazard reduction ([Ammerman et al., 2007](#); [IEEE, 2018](#); [Mohla et al., 2005](#)). These technical foundations support the need for a quantitative study that measures how electrical infrastructure condition, protective coordination, safety compliance, retrofit planning quality, and maintenance practices influence arc-flash hazard mitigation effectiveness in existing manufacturing facilities.

The international significance of arc-flash hazard mitigation has grown because industrial electrical systems are becoming more interconnected, energy-intensive, and reliability-dependent, while many manufacturing plants continue to operate legacy distribution equipment installed under earlier design assumptions. Arc-flash events are relevant in low-voltage, medium-voltage, AC, and DC systems, and the literature shows that hazard estimation varies depending on arc behavior, enclosure configuration, voltage level, electrode arrangement, available fault current, and protective clearing time ([Ammerman et al., 2010](#); [Doan, 2010](#); [Eblen & Short, 2017](#); [Parise & Scarpino, 2021](#)). In manufacturing environments, these technical conditions are linked to production continuity because the same switchgear, breakers, motor control centers, transformers, and bus systems that support production may also become points of hazardous energy release during fault conditions or maintenance activities. Studies on DC arc modeling and exposure calculations show that arc behavior can be complex and that limited data can affect incident-energy estimation, especially in systems involving batteries, drives, rectifiers, and industrial DC loads ([Ammerman et al., 2010](#); [Doan, 2010](#)). Low-voltage arc sustainability research further shows that some assumptions about lower-voltage equipment require careful review because arc duration and equipment configuration influence whether a hazardous arc can persist long enough to create dangerous thermal exposure ([Eblen & Short, 2017](#); [Lang & Jones, 2011](#)). Arc-blast studies add another dimension by showing that arc-flash consequences include pressure effects and door ejection hazards, not only thermal burns ([Hoagland et al., 2017, 2020](#)). These studies establish that arc-flash mitigation in brownfield facilities requires more than selecting personal protective equipment; it requires a structured framework that connects system modeling, equipment condition, protective device coordination, hazard labeling, maintenance verification, worker safety practices, and retrofit prioritization. The industrial relevance is especially strong in U.S. manufacturing, where electrical distribution systems often remain in service for decades while production requirements, load profiles, automation systems, and safety expectations continue to evolve.

Brownfield industrial power distribution systems create a distinct research context because retrofit decisions must be made within the constraints of existing layouts, aging assets, limited shutdown windows, production schedules, and incomplete historical documentation. In a new facility, power

distribution design can be organized around present-day safety standards, modern equipment ratings, digital relays, arc-resistant designs, and coordinated engineering documentation. In a brownfield facility, engineers often work with older switchboards, legacy breakers, undocumented field modifications, unavailable spare parts, degraded insulation, inconsistent maintenance records, and electrical one-line diagrams that may not fully match the installed system. These conditions increase uncertainty in short-circuit studies, protective device coordination, and incident-energy calculations. Research on safety by design and prevention through design shows that hazards are easier to control when they are considered during design and planning rather than after systems are already installed and operating (Behm, 2005; Gambatese et al., 2008). For brownfield retrofits, this means arc-flash mitigation must be incorporated into the planning process before equipment upgrades, load additions, protection adjustments, or panel modifications occur. Maintenance research also supports this position because equipment condition, maintenance quality, and reliability practices affect operational performance and safety outcomes in industrial systems (Alsyouf, 2007; Muchiri & Pintelon, 2008). A breaker or relay may appear properly selected in a study, but if the device is poorly maintained, incorrectly set, mechanically degraded, or unable to clear a fault within the expected time, the actual hazard may differ from the calculated hazard. This relationship makes maintenance and inspection practices a major variable in the proposed research. The brownfield environment also requires case-study-based attention because each facility has its own distribution architecture, load composition, production criticality, and retrofit constraints. Therefore, a quantitative cross-sectional study can help identify common relationships across professional responses while still recognizing the practical realities of brownfield manufacturing retrofits.

Figure 1: Arc-Flash Hazard Mitigation Framework for Brownfield Manufacturing Facilities



Arc-flash mitigation is closely connected to protective device coordination because incident energy is strongly influenced by how quickly a protective device detects and clears an arcing fault. Protective device coordination involves selecting and setting breakers, relays, fuses, current-limiting devices, and trip functions so that faults are interrupted selectively, rapidly, and safely. In industrial facilities, coordination decisions often balance competing goals: maintaining selective operation to avoid unnecessary plant shutdowns while also reducing clearing time to lower arc-flash energy. The literature shows that arc-flash energy depends heavily on clearing time and that mitigation strategies may include instantaneous trip settings, maintenance switches, zone-selective interlocking, differential protection, optical arc detection, current limitation, and equipment modernization (Ammerman et al., 2007; Mohla et al., 2005; Zhao et al., 2020). Light-based and spectrum-based arc fault detection studies indicate that detection speed and sensor reliability can improve the response of arc-flash protection

systems, especially when conventional overcurrent detection alone may not provide the fastest or most selective response (Zhao et al., 2020). The updated arc-flash calculation model also emphasizes that equipment configuration, enclosure size, electrode orientation, voltage, working distance, arcing current, and protective clearing time must be considered in incident-energy estimation (IEEE, 2018). These technical variables matter in brownfield manufacturing because existing equipment may not have been designed for modern mitigation features, and retrofit teams may need to decide whether to adjust settings, replace protective devices, install relays, add remote operation, improve labeling, or upgrade switchgear. Protective coordination is therefore not only an engineering calculation; it is a decision-making process involving risk tolerance, production continuity, equipment limitations, and worker exposure. In this study, protective device coordination is treated as an independent variable because it is expected to influence arc-flash hazard mitigation effectiveness through reduced clearing time, improved fault isolation, better selectivity, and stronger confidence in electrical safety controls. Electrical safety compliance and workforce protection practices form another major foundation of this research because arc-flash risk is not fully controlled through engineering calculations alone. Workplace safety studies show that safety climate, safety management practices, training, leadership commitment, worker participation, and procedural discipline are associated with safer behavior and lower accident risk (Christian et al., 2009; Neal & Griffin, 2006; Vinodkumar & Bhasi, 2010; Zohar & Luria, 2005). These findings are highly relevant to arc-flash mitigation because electrical workers and maintenance personnel must apply safe work practices when performing inspections, troubleshooting, switching, testing, racking, and energized tasks. Safety compliance practices may include arc-flash labeling, personal protective equipment selection, energized work permits, lockout/tagout procedures, electrical safety training, maintenance documentation, job hazard analysis, and audit systems. Research on safety management systems indicates that formalized safety practices can influence organizational safety performance when they are integrated into leadership commitment, employee involvement, risk assessment, training, and continuous monitoring (Fernández-Muñiz et al., 2009; Wachter & Yorio, 2014). For brownfield manufacturing facilities, compliance maturity becomes especially important because legacy systems may require workers to interact with older equipment that has limited arc-resistant features, restricted working clearances, or uncertain maintenance histories. A technically accurate arc-flash study can lose practical value if labels are outdated, workers are not trained, PPE is inconsistently selected, energized work is poorly controlled, or maintenance records are incomplete. Internationally, electrical safety programs increasingly combine calculation-based hazard assessment with safety management practices because the hazard involves both physical energy release and human exposure control. In the present study, safety compliance practices are therefore measured as a core independent variable. This allows the research to examine whether stronger compliance practices are statistically associated with higher arc-flash mitigation effectiveness and improved electrical safety performance among professionals involved in brownfield industrial power distribution retrofits. A systems-based understanding is necessary because arc-flash hazards emerge from interactions among technical assets, protection systems, maintenance practices, human decisions, and organizational controls. Systems Safety Theory provides a strong theoretical foundation for this study because it treats accidents as outcomes of weaknesses in system design, control, feedback, procedures, equipment condition, and organizational decision-making rather than isolated worker errors or single equipment failures. Risk research supports the need to analyze uncertainty, system interactions, control barriers, and decision quality when assessing hazardous technical systems (Aven, 2011, 2016; Marhaviilas et al., 2011). Applied to arc-flash mitigation, Systems Safety Theory suggests that effective risk reduction depends on multiple layers of defense: accurate system data, updated one-line diagrams, short-circuit analysis, incident-energy calculation, protective device coordination, equipment maintenance, worker training, PPE, labeling, access control, and management oversight. This theoretical perspective is especially suitable for brownfield retrofits because the risks are shaped by legacy equipment, undocumented modifications, changing load profiles, production pressures, and varying levels of safety compliance. The conceptual foundation of the study can therefore be organized around electrical infrastructure condition, protective device coordination, safety compliance practices, retrofit planning quality, and maintenance and inspection practices as predictors of arc-flash hazard mitigation effectiveness. Electrical safety performance can be positioned as an outcome associated with

mitigation effectiveness. This variable structure fits the quantitative, cross-sectional, case-study-based design because each construct can be measured through a five-point Likert-scale instrument and analyzed using descriptive statistics, correlation analysis, and regression modeling. The theoretical and conceptual framing also supports the development of unique result sections such as an Arc-Flash Retrofit Readiness Index and an Arc-Flash Mitigation Priority Matrix. These sections allow the thesis to connect statistical findings with practical retrofit decision-making in manufacturing facilities.

The purpose of this research is to develop and assess an arc-flash hazard mitigation framework for brownfield industrial power distribution retrofits in U.S. manufacturing by examining the relationships among infrastructure condition, protective coordination, compliance practices, retrofit planning quality, maintenance practices, mitigation effectiveness, and electrical safety performance. The study is designed as quantitative, cross-sectional, and case-study-based because the research problem requires measurable evidence from professionals who understand industrial electrical systems, safety programs, maintenance, and retrofit planning. Likert-scale data can capture professional perceptions of technical and organizational conditions, while descriptive statistics can summarize the maturity of arc-flash practices across respondents. Correlation analysis can identify whether stronger infrastructure condition, coordination practices, compliance maturity, retrofit planning, and maintenance discipline are associated with stronger mitigation effectiveness. Regression modeling can identify which predictors have the strongest effect when the variables are considered together. This research design is supported by previous quantitative safety and risk studies that used survey-based constructs to connect organizational practices, safety behavior, risk controls, and performance outcomes (Christian et al., 2009; Fernández-Muñiz et al., 2009; Vinodkumar & Bhasi, 2010; Wachter & Yorio, 2014). It is also aligned with arc-flash engineering literature that treats incident energy, equipment configuration, fault current, detection speed, and clearing time as measurable factors affecting hazard severity (IEEE, 2018; Parise & Scarpino, 2021; Zhao et al., 2020). The research contributes a focused structure for brownfield manufacturing environments because it does not examine arc flash as a generic electrical hazard only. Instead, it positions arc-flash mitigation as a retrofit-readiness and systems-safety issue involving aging assets, coordination limitations, documentation quality, compliance practices, maintenance reliability, and engineering decision priorities. This framing supports the development of a practical mitigation framework that can be evaluated statistically and presented in a way that is specific to brownfield industrial power distribution retrofits in U.S. manufacturing.

Background of the Study

Arc-flash hazard mitigation has become an important concern in industrial power distribution systems because manufacturing facilities depend heavily on continuous, safe, and reliable electrical energy to support production equipment, motor control systems, automation lines, lighting, process controls, and facility operations. An arc flash occurs when electrical energy is suddenly released through the air due to a fault between energized conductors or between an energized conductor and ground. This event can generate extreme heat, intense light, molten metal, pressure waves, and explosive forces that may cause severe injury, equipment damage, fire, production interruption, and financial loss. In brownfield manufacturing facilities, the problem becomes more complex because the electrical systems are often older, modified several times, and operated under conditions different from their original design assumptions. Many existing facilities contain legacy switchgear, aging circuit breakers, outdated protection devices, incomplete electrical drawings, limited working clearances, and equipment that may no longer fully support modern safety expectations. As manufacturing plants expand production capacity and integrate advanced machinery, robotics, automation, and high-demand electrical loads, existing power distribution systems may face additional stress. Retrofitting these systems is necessary, but brownfield retrofits are often difficult because facilities must maintain production continuity while improving safety and system reliability. Arc-flash mitigation in such environments requires more than the use of personal protective equipment. It requires a structured approach that includes system assessment, updated documentation, short-circuit analysis, protective device coordination, equipment modernization, safety compliance, maintenance planning, employee training, hazard labeling, and continuous monitoring. The present study focuses on developing an arc-flash hazard mitigation framework for brownfield industrial power distribution retrofits in U.S. manufacturing. This topic is

important because manufacturing facilities need practical and evidence-based methods to identify arc-flash risk factors, prioritize mitigation actions, and improve safety outcomes during electrical modernization projects. By using a quantitative, cross-sectional, case-study-based design, the study will measure how infrastructure condition, protective coordination, safety compliance, retrofit planning, and maintenance practices influence arc-flash hazard mitigation effectiveness.

Problem Statement

Brownfield manufacturing facilities in the United States often operate with electrical distribution systems that were designed, installed, and expanded over many years of production activity. These systems may include aging switchgear, outdated circuit protection, undocumented modifications, obsolete components, limited spare capacity, and electrical drawings that do not fully reflect actual field conditions. Such conditions can increase uncertainty in arc-flash hazard assessment and make mitigation planning more difficult. Although arc-flash analysis, protective device coordination, safety labeling, electrical maintenance, training, and compliance procedures are widely recognized as important safety practices, their implementation in brownfield retrofit environments is often inconsistent. Many facilities face practical constraints such as limited downtime, budget limitations, production pressure, shortage of skilled personnel, old equipment that cannot easily be upgraded, and incomplete historical maintenance records. These challenges can create a gap between formal electrical safety expectations and actual workplace conditions. As a result, workers may remain exposed to high incident energy levels, delayed fault clearing, outdated warning labels, inadequate personal protective equipment selection, and unsafe energized work conditions. Another major problem is that existing studies and safety practices often address arc-flash mitigation from a technical calculation perspective, while brownfield retrofit projects require an integrated framework that combines technical, organizational, maintenance, and compliance-related factors. In many manufacturing facilities, decisions about arc-flash reduction are made separately by engineers, safety managers, maintenance teams, and plant managers, which may reduce the effectiveness of hazard control. There is also a need for a quantitative assessment of which factors most strongly influence arc-flash mitigation effectiveness in brownfield industrial power distribution retrofits. Without such evidence, facility managers may not know whether to prioritize protective device coordination, equipment replacement, workforce training, documentation improvement, maintenance inspection, or retrofit planning. Therefore, the problem addressed in this study is the lack of a structured, measurable, and context-specific arc-flash hazard mitigation framework for brownfield industrial power distribution retrofits in U.S. manufacturing. This study responds to that problem by examining the relationships among key technical and organizational factors and by developing a practical framework that supports safer retrofit decision-making.

Objectives of The Study

The main objective of this study is to develop and evaluate an arc-flash hazard mitigation framework for brownfield industrial power distribution retrofits in U.S. manufacturing facilities. This objective is based on the need to understand how different technical, organizational, and maintenance-related factors contribute to arc-flash hazard reduction in existing industrial electrical systems. The study will first examine the condition of electrical infrastructure in brownfield manufacturing facilities, including the age and reliability of equipment, quality of electrical documentation, availability of updated system studies, and suitability of existing power distribution assets for modern safety requirements. It will also assess the role of protective device coordination in reducing arc-flash risk by examining how circuit breakers, relays, fuses, trip settings, fault clearing time, and selective coordination practices contribute to mitigation effectiveness. Another objective is to evaluate the influence of safety compliance practices on arc-flash hazard mitigation, especially in relation to worker training, hazard labeling, personal protective equipment use, energized work controls, lockout/tagout procedures, and safety audits. The study will also investigate how retrofit planning quality affects mitigation outcomes by considering engineering planning, outage coordination, management support, budget readiness, risk assessment, and implementation control. In addition, maintenance and inspection practices will be examined as a key objective because the performance of protective devices and electrical equipment depends heavily on their physical condition, testing history, and maintenance discipline. The study will use descriptive statistics to summarize the level of agreement among respondents, correlation analysis to examine

relationships among variables, and regression modeling to determine which factors significantly predict arc-flash hazard mitigation effectiveness. The objective-based focus of this research is also connected to the development of two study-specific analytical outputs: an Arc-Flash Retrofit Readiness Index and an Arc-Flash Mitigation Priority Matrix. These outputs will help translate the statistical results into practical retrofit guidance. Overall, the objectives of the study are designed to support a measurable and practical understanding of arc-flash hazard mitigation in brownfield U.S. manufacturing environments.

Research Hypotheses

The research hypotheses of this study are designed to test the expected relationships between the major independent variables and arc-flash hazard mitigation effectiveness in brownfield industrial power distribution retrofits. Since the study uses a quantitative, cross-sectional, case-study-based design, the hypotheses will be tested using survey data collected through a five-point Likert scale and analyzed through correlation and regression modeling. The first hypothesis states that electrical infrastructure condition has a significant positive effect on arc-flash hazard mitigation effectiveness. This means that facilities with better-maintained equipment, updated documentation, reliable switchgear, accurate one-line diagrams, and modernized distribution assets are expected to achieve stronger mitigation outcomes. The second hypothesis states that protective device coordination has a significant positive effect on arc-flash hazard mitigation effectiveness. This is based on the expectation that properly selected, tested, and coordinated breakers, relays, fuses, and trip settings can reduce fault clearing time and improve hazard control. The third hypothesis states that safety compliance practices have a significant positive effect on arc-flash hazard mitigation effectiveness. This means that facilities with stronger training, labeling, PPE use, energized work control, lockout/tagout procedures, and audit practices are expected to report better mitigation performance. The fourth hypothesis states that retrofit planning quality has a significant positive effect on arc-flash hazard mitigation effectiveness. This suggests that structured planning, management support, risk assessment, outage coordination, and budget readiness can improve the success of arc-flash mitigation during brownfield retrofit projects. The fifth hypothesis states that maintenance and inspection practices have a significant positive effect on arc-flash hazard mitigation effectiveness. This means that regular testing, inspection, preventive maintenance, and corrective actions are expected to strengthen equipment reliability and protection system performance. The sixth hypothesis states that arc-flash hazard mitigation effectiveness has a significant positive effect on electrical safety performance in brownfield manufacturing facilities. Together, these hypotheses provide a clear statistical pathway for examining how technical infrastructure, engineering controls, compliance behavior, planning quality, and maintenance discipline contribute to safer industrial power distribution retrofits.

Significance of the Research

- i. This research is significant for U.S. manufacturing facilities because it provides a structured way to understand and reduce arc-flash hazards in brownfield industrial power distribution systems. Many manufacturing plants operate with older electrical infrastructure that cannot be completely replaced at once. Therefore, a practical mitigation framework can help organizations improve safety while managing production continuity, budget limitations, and retrofit constraints.
- ii. This research is significant for electrical engineers because it connects arc-flash hazard mitigation with infrastructure condition, protective device coordination, retrofit planning, and maintenance practices. It can help engineers identify which technical factors should be prioritized during electrical system assessments, short-circuit studies, coordination studies, equipment upgrades, and incident-energy reduction planning.
- iii. This research is significant for safety managers because it highlights the role of safety compliance practices in arc-flash risk reduction. The study can support better decisions regarding worker training, hazard communication, arc-flash labeling, personal protective equipment, energized work permits, lockout/tagout procedures, and electrical safety audits.
- iv. This research is significant for facility managers and plant managers because it provides evidence that arc-flash mitigation is not only a compliance requirement but also a production reliability and risk management issue. Effective mitigation can reduce downtime, equipment damage, injury risk, maintenance disruption, and operational uncertainty during retrofit projects.

v. This research is significant for maintenance teams because it emphasizes the role of inspection, testing, and preventive maintenance in sustaining electrical safety. Poorly maintained breakers, relays, switchgear, and distribution components can weaken arc-flash mitigation even when formal studies have been completed.

vi. This research is significant for academic researchers because it contributes a quantitative, case-study-based model for examining arc-flash hazard mitigation in brownfield manufacturing environments. The use of descriptive statistics, correlation analysis, regression modeling, a Retrofit Readiness Index, and a Mitigation Priority Matrix makes the study more measurable, practical, and specific to the research context.

vii. This research is significant for policymakers and compliance stakeholders because it can support stronger awareness of electrical safety risks in aging industrial facilities. The study may help encourage better guidance, enforcement, and safety planning for brownfield manufacturing retrofits.

LITERATURE REVIEW

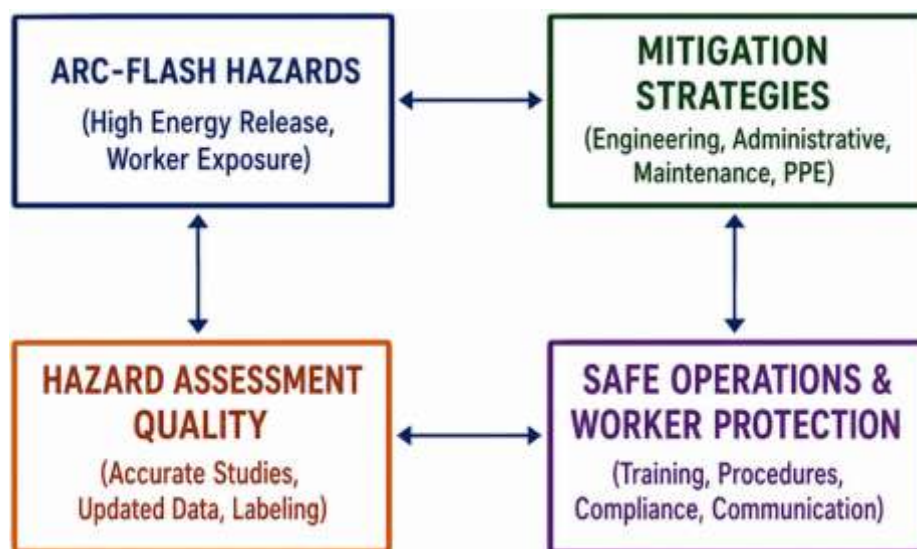
The literature on arc-flash hazard mitigation, industrial electrical safety, and brownfield power distribution retrofits provides the foundation for understanding why this study is necessary and how its variables are connected. Arc-flash hazards are usually examined through technical factors such as incident energy, arcing current, voltage level, equipment configuration, working distance, and protective device clearing time. These factors are important because they determine the severity of thermal exposure and the level of risk faced by workers during energized electrical tasks. However, the literature also shows that arc-flash mitigation is not only a technical calculation process. It is also connected to safety management, maintenance quality, workforce behavior, regulatory compliance, and organizational decision-making. In brownfield manufacturing facilities, the relationship between technical and organizational factors becomes especially important because older electrical systems often contain legacy switchgear, outdated protection devices, incomplete documentation, and equipment that may have been modified several times during facility expansion. Literature on brownfield retrofits highlights the complexity of improving safety in facilities that must remain operational while electrical upgrades are being planned or implemented. This creates challenges related to outage scheduling, budget control, risk prioritization, production continuity, and system reliability. Studies on protective device coordination emphasize that arc-flash hazard reduction depends heavily on the ability of protective devices to detect and clear faults quickly while maintaining selective operation. Maintenance-related literature further suggests that the condition and reliability of electrical equipment influence whether protection systems perform as expected during fault conditions. Safety management literature adds another layer by showing that training, hazard communication, PPE compliance, lockout/tagout practices, and leadership commitment shape worker protection outcomes. Therefore, the literature review for this study will examine six major areas: arc-flash hazards in industrial power distribution systems, brownfield manufacturing retrofit challenges, protective device coordination and engineering controls, electrical safety compliance and workforce protection practices, Systems Safety Theory as the theoretical framework, and the conceptual framework linking infrastructure condition, coordination practices, compliance, retrofit planning, maintenance, mitigation effectiveness, and safety performance. Together, these areas support the development of a quantitative framework for arc-flash hazard mitigation in brownfield U.S. manufacturing facilities.

Arc-Flash Hazards in Industrial Power Distribution Systems

Arc-flash hazards in industrial power distribution systems represent a critical electrical safety concern because they combine sudden fault initiation, extremely rapid energy release, and direct human exposure during operation, troubleshooting, testing, switching, and maintenance activities. In manufacturing environments, the distribution system usually includes transformers, switchgear, switchboards, motor control centers, bus ducts, panelboards, feeders, drives, and large rotating equipment, all of which may become arc-flash locations when insulation failure, loose connections, contamination, equipment deterioration, human error, or abnormal operating conditions create an unintended conductive path. The severity of an arc-flash event is shaped by available fault current, system voltage, arc duration, equipment enclosure type, working distance, conductor gap, and the response of upstream protective devices. Industrial distribution systems were traditionally designed around functionality, continuity, capacity, selectivity, and cost, while arc-flash reduction was not

always treated as a central design objective in older facilities. This historical design condition is highly relevant to brownfield manufacturing plants because legacy systems may still operate with equipment arrangements that were acceptable when installed but are less aligned with modern hazard-reduction expectations. Design-focused research has shown that system configuration, transformer sizing, grounding arrangement, protective device selection, and distribution architecture can strongly influence incident energy and worker exposure during arcing faults (Das, 2005; Abdur & Iftekhar, 2021). Therefore, arc-flash hazards should be understood as system-level hazards rather than isolated equipment failures. In brownfield industrial settings, the same electrical assets that support production reliability may also create severe safety exposure when documentation is outdated, equipment has aged, or protective devices no longer match present operating conditions. This makes the study of arc-flash hazards particularly important for retrofit planning, where the aim is to reduce hazard severity while maintaining plant operations and equipment reliability, minimizing shutdown disruption, and ensuring that safety upgrades are compatible with existing electrical layouts and production requirements.

Figure 2: Relationship Between Arc-Flash Hazards, Assessment Quality, Mitigation Strategies, and Worker Protection



Industrial arc-flash hazard assessment also depends on the accuracy of system studies and the quality of safety improvement actions taken after those studies are completed. Arc-flash assessment normally requires updated one-line diagrams, equipment data, transformer information, conductor lengths, utility fault contribution, protective device settings, short-circuit calculations, coordination analysis, and incident-energy estimation. In practice, brownfield facilities may have incomplete drawings, undocumented field changes, mismatched protective settings, and aging equipment labels, which can weaken the reliability of hazard calculations. Large-scale industrial assessment experience has shown that arc-flash studies can lead to practical safety improvements such as revised protective settings, equipment labeling, reduced incident energy, improved work procedures, and better identification of high-risk locations (Golam & Amir, 2022; Doan et al., 2009). This is important for U.S. manufacturing facilities because retrofit projects often begin with uncertainty about actual system condition and then require engineering decisions based on both calculated hazard levels and operational constraints. Arc-flash risk is also multidimensional because the worker may be exposed to thermal energy, pressure effects, light radiation, molten material, and secondary injury pathways during the same event. Studies focusing on incident energy, personal protective equipment ratings, and burn injury have emphasized that numerical hazard values should be interpreted carefully because injury severity is affected by exposure conditions, body position, heat transfer, clothing performance, and the nature of the arcing event (Binayan & Shakhawat, 2022; Gammon et al., 2015). This perspective is useful for the present

study because it supports a broader understanding of arc-flash mitigation effectiveness. A facility should not be viewed as safe only because calculations and labels exist; the overall system must also include reliable equipment, accurate data, proper maintenance, trained personnel, suitable PPE, disciplined energized-work control, and clear communication between engineering, safety, and operations teams. Therefore, assessment quality and implementation quality must be treated together when evaluating arc-flash hazard management in brownfield manufacturing environments.

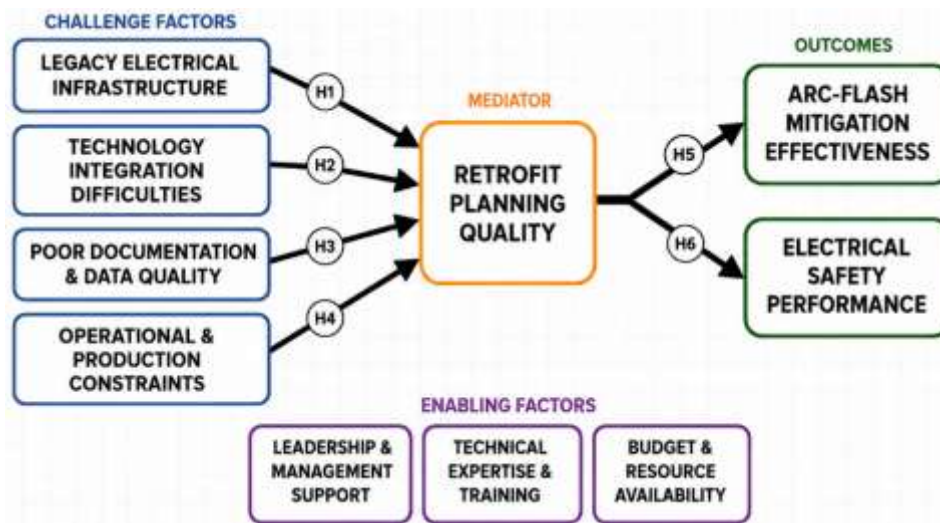
Arc-flash mitigation in industrial power distribution systems requires a coordinated safety approach that combines engineering controls, administrative controls, maintenance practices, and worker-protection measures. A total-system perspective is important because no single technology can fully address all arc-flash and shock hazards across a complex manufacturing facility. Mitigation options may include high-resistance grounding, current-limiting devices, arc-resistant equipment, faster relaying, zone-selective interlocking, maintenance switches, remote operation, differential protection, optical detection, improved labeling, and stronger electrical safety procedures. Research on total-system protection has emphasized that personnel and equipment safety improve when mitigation technologies are selected according to the overall electrical system configuration rather than applied as isolated solutions (Hamer et al., 2012; Hasan & Uddin, 2022). This view fits brownfield retrofits because existing equipment may limit the feasibility of full replacement, making staged and prioritized mitigation necessary. Arc-flash incident-energy analysis also requires periodic review because changes in equipment, loads, utility source capacity, protective settings, and distribution topology can alter the level of hazard over time. Renewal-focused research has highlighted the importance of reviewing incident-energy analyses when system changes occur and maintaining periodic reassessment to prevent outdated studies from guiding unsafe decisions (Hossain & Uddin, 2022; Sullivan et al., 2021). For brownfield manufacturing facilities, this concern is especially relevant because retrofit work often modifies feeders, breakers, transformers, loads, and operating modes. Consequently, arc-flash hazards in industrial power distribution systems should be reviewed as dynamic hazards shaped by system condition, operating changes, protection performance, and human interaction. This literature supports the present study's focus on infrastructure condition, protective device coordination, compliance practices, retrofit planning quality, maintenance discipline, and mitigation effectiveness as measurable elements of an arc-flash hazard mitigation framework. It also supports the need for readiness and priority-based analysis, because retrofit teams must identify which controls provide the greatest safety value within practical plant constraints.

Brownfield Manufacturing Facilities and Power Distribution Retrofit Challenges

Brownfield manufacturing facilities refer to existing industrial plants where production systems, electrical infrastructure, machinery, control systems, and facility services have already been installed and operated over a long period. In these facilities, retrofit work is different from new construction because engineers and managers must improve existing systems while the plant continues to support production, safety, maintenance, and business operations. Brownfield power distribution retrofits are especially challenging because electrical systems may include legacy switchgear, older motor control centers, aged transformers, obsolete circuit breakers, undocumented load additions, limited spare capacity, and electrical drawings that may not fully match actual field conditions. In manufacturing environments, these challenges become more serious because electrical systems are directly connected to production continuity, worker safety, asset protection, and operational reliability. Retrofitting is often selected because replacing an entire plant or installing a completely new electrical system can be financially and operationally difficult. However, the retrofit option requires careful assessment of existing equipment, available space, protection settings, system documentation, outage limitations, and compatibility between old and new technologies. Research on smart manufacturing retrofit has shown that brownfield systems often lack the communication, interoperability, and functional flexibility required by modern manufacturing environments, making structured retrofit planning necessary for upgrading legacy assets without full replacement (Etz et al., 2020; Sany & Siful, 2022). This finding is relevant to arc-flash mitigation because brownfield electrical systems may also lack modern safety-oriented features such as advanced protection relays, remote switching, arc-resistant equipment, updated labels, and accurate engineering data. Therefore, brownfield manufacturing facilities create a complex setting where arc-flash mitigation cannot be treated as a single technical activity. It must be

integrated into broader retrofit planning that considers system age, operational constraints, maintenance condition, worker exposure, documentation quality, and the need to maintain productivity during electrical modernization.

Figure 3: Brownfield Manufacturing Power Distribution Retrofit Challenges Model



A major challenge in brownfield manufacturing retrofits is the difficulty of integrating modern technologies into legacy systems that were not originally designed for digital monitoring, automated coordination, or real-time safety control. Many existing facilities contain machines, power distribution panels, controllers, sensors, and protection systems from different time periods and manufacturers. This heterogeneity can create problems during retrofit projects because different systems may use different communication protocols, control architectures, data formats, protection philosophies, and maintenance requirements. In power distribution retrofits, this challenge may appear when older circuit breakers are connected to newer relays, when protective settings must be changed without compromising selectivity, or when a facility attempts to add monitoring and safety functions to equipment with limited digital capability. The challenge is not only technical; it is also organizational because retrofit projects require cooperation among electrical engineers, maintenance personnel, safety managers, production managers, contractors, and plant leadership. Research on cyber-physical production system retrofitting has indicated that upgrading existing production systems requires a structured method for transforming legacy assets into more connected and intelligent systems while managing the limits of older equipment and existing processes (Lins & Oliveira, 2020; Binte & Iftekhhar, 2022). Studies on process plant retrofitting also show that old industrial plants can be upgraded to improve safety, maintainability, and technological performance when retrofit planning is organized around practical operational conditions rather than abstract modernization goals (Santolamazza et al., 2021; Taufiqur & Khalid, 2022). These findings support the present study because arc-flash mitigation in brownfield power distribution systems requires the same type of structured modernization logic. Existing electrical systems must first be assessed, then upgraded according to risk level, protection limitations, production constraints, safety requirements, and available resources. This makes retrofit planning quality an important variable in understanding arc-flash hazard mitigation effectiveness. Another important issue in brownfield manufacturing facilities is retrofit readiness, which refers to the technical and organizational capacity of a facility to implement improvements successfully. A facility may recognize the need for arc-flash mitigation, but implementation can be delayed or weakened by poor documentation, limited technical expertise, low digital maturity, inadequate budget, weak management support, lack of training, or uncertainty about how to prioritize electrical upgrades. Research on smart manufacturing maturity has shown that organizations often face difficulties when attempting to move from traditional industrial systems toward more advanced and integrated manufacturing environments, especially when they lack assessment models for readiness, capability,

and implementation planning (Iftekhar & Binayan, 2023; Mittal et al., 2018). Similarly, studies on Industry 4.0 adoption in small and medium-sized manufacturing contexts have highlighted that modernization requires practical management attention to technology, people, resources, strategy, and operational limitations (Hasan & Chapal, 2023; Moeuf et al., 2018). These insights are relevant to brownfield power distribution retrofits because arc-flash mitigation also depends on readiness across multiple dimensions. Electrical infrastructure condition determines whether the existing system can support mitigation actions. Protective device coordination determines whether fault clearing can be improved safely. Safety compliance practices determine whether workers understand and follow electrical hazard controls. Maintenance and inspection practices determine whether equipment can perform as expected during fault conditions. Retrofit planning quality determines whether upgrades can be completed without excessive disruption to production. In this way, brownfield manufacturing retrofit challenges are not limited to replacing old electrical equipment. They involve a wider decision-making process that includes technical diagnosis, safety prioritization, workforce capability, financial planning, shutdown coordination, and long-term reliability. For this reason, the present study includes the Arc-Flash Retrofit Readiness Index and Arc-Flash Mitigation Priority Matrix as unique result sections to connect quantitative findings with practical retrofit decisions in U.S. manufacturing facilities.

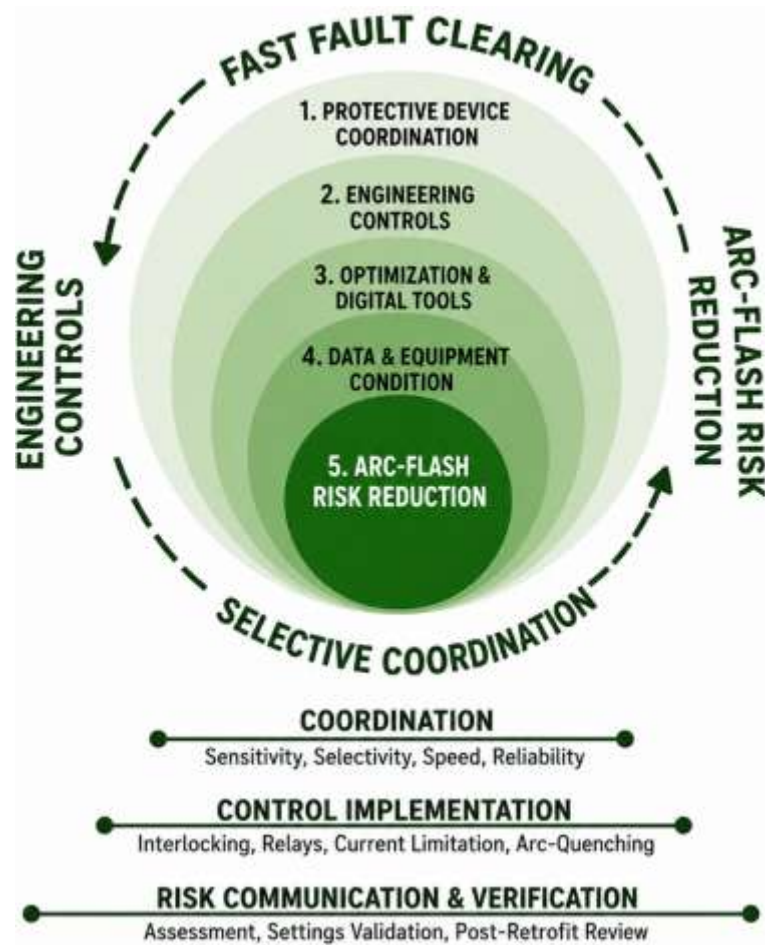
Protective Device Coordination, Engineering Controls, and Arc-Flash Risk Reduction

Protective device coordination is a central element of arc-flash risk reduction because the severity of an arc-flash event is strongly influenced by the length of time an arcing fault remains energized. In industrial power distribution systems, protective devices such as circuit breakers, fuses, relays, trip units, current transformers, and differential protection schemes are expected to detect abnormal current and isolate the faulted portion of the system. When these devices are properly coordinated, the device closest to the fault operates first, limiting the affected zone and preserving continuity for unaffected parts of the system. However, arc-flash mitigation introduces an important design tension because selective coordination may require intentional time delays, while worker protection often requires very fast fault clearing. In brownfield manufacturing facilities, this tension becomes more complex because older switchgear, legacy breakers, outdated relays, and undocumented setting changes may increase clearing time or reduce confidence in protection performance. Zone-selective interlocking has been presented as a practical method for reducing incident energy while maintaining selective coordination because downstream and upstream devices communicate during faults, allowing the upstream breaker to delay only when a downstream device is responding and to trip faster when the fault is within its own zone (Hodgson & Shipp, 2010; Aminul & Sheak, 2023). This is relevant to brownfield retrofits because ZSI can sometimes be implemented without replacing an entire distribution system, making it attractive for facilities with limited shutdown windows and budget restrictions. Therefore, protective device coordination in this study is not viewed only as a technical engineering study. It is treated as a measurable safety factor that connects fault detection, clearing time, selectivity, equipment condition, retrofit feasibility, and arc-flash hazard mitigation effectiveness in existing manufacturing facilities.

Engineering controls provide another major pathway for reducing arc-flash exposure because they attempt to reduce the hazard at the system level before relying on administrative procedures or personal protective equipment. Engineering controls may include instantaneous trip settings, energy-reducing maintenance switches, differential relaying, zone-selective interlocking, arc-flash relays, current-limiting devices, remote racking, remote switching, arc-resistant switchgear, and active arc-quenching systems. These measures are important because they can lower incident energy, reduce arc duration, restrict worker exposure, or physically redirect hazardous energy away from personnel. Advanced interlocking research has shown that protective-device interlocking can improve both protection and selectivity by reducing the traditional compromise between fast tripping and coordinated system operation (Shakhawat et al., 2023; Valdes & Dougherty, 2014). This is important in industrial settings where production continuity is important, but personnel safety cannot be sacrificed during maintenance or troubleshooting tasks. Active arc-flash mitigation systems also expand the engineering-control approach by sensing arc characteristics and reducing the energy released before a conventional upstream breaker can complete its clearing cycle. Current-limiting arc-quenching systems have been studied as a method for improving incident-energy reduction by creating a lower-impedance

controlled path and rapidly extinguishing the unintended arc, thereby reducing the amount of energy released into the equipment enclosure (Burns et al., 2019; Risha & Khalid, 2023). For brownfield industrial power distribution retrofits, the selection of engineering controls must consider equipment age, enclosure condition, available space, fault-current level, breaker capability, relay compatibility, maintenance access, and installation downtime. This makes engineering control selection a planning issue as well as a technical issue. In the present research, engineering controls are closely linked to protective coordination because both determine whether a facility can reduce incident energy without creating unacceptable operational disruption.

Figure 4: Relationship Between Protective Coordination, Engineering Controls, and Arc-Flash Mitigation Effectiveness



Protective coordination and engineering controls are also increasingly shaped by optimization methods, digital tools, and systematic decision-making models. Industrial power systems may contain multiple protective devices connected in series, and their settings must be selected so that sensitivity, selectivity, speed, and reliability are balanced across different fault scenarios. Directional overcurrent relay coordination has been widely treated as an optimization problem because relay operating times, time multiplier settings, pickup currents, coordination time intervals, and fault-current variations must be adjusted together to achieve reliable protection. Review-based research on soft computing methods has shown that optimization techniques can support protective device coordination by reducing computational difficulty and improving the search for suitable relay settings in complex systems (Draz et al., 2021; Sany & Uddin, 2023). Genetic-algorithm-based coordination research further demonstrates that optimal relay coordination can be formulated to improve selectivity and operating speed under different system conditions, which is relevant to arc-flash mitigation because faster and more reliable operation can reduce fault duration (Matthews et al., 2021). In brownfield manufacturing facilities,

these optimization ideas are valuable because existing electrical systems may have evolved through multiple expansions, making manual coordination difficult and increasing the risk of miscoordination. Modern software tools can support short-circuit studies, time-current curve analysis, arc-flash calculations, and protection setting evaluation, but these tools require accurate field data and reliable equipment information. Therefore, a retrofit framework must include data validation, protection assessment, engineering control selection, and post-retrofit verification. This literature supports the present study's decision to measure protective device coordination as a key predictor of arc-flash hazard mitigation effectiveness. It also supports the inclusion of an Arc-Flash Mitigation Priority Matrix because facilities need a practical method for identifying whether coordination settings, interlocking, relay upgrades, current limitation, arc-quenching systems, or maintenance controls should receive the highest retrofit priority.

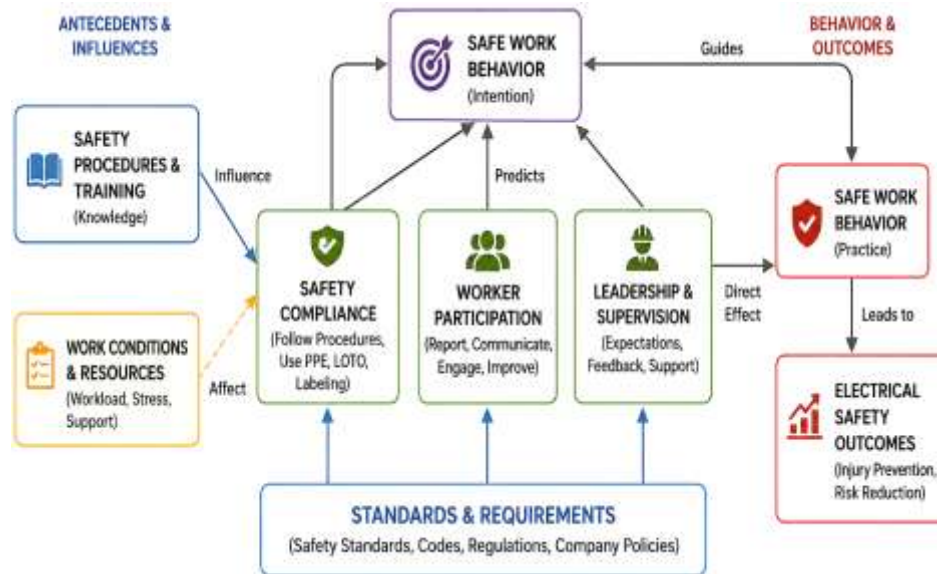
Electrical Safety Compliance, Standards, and Workforce Protection Practices

Electrical safety compliance is a major requirement in industrial power distribution systems because arc-flash hazards involve both technical energy exposure and human work behavior around energized equipment. In manufacturing facilities, workers may perform switching, troubleshooting, inspection, testing, racking, maintenance, and repair activities near electrical panels, switchgear, motor control centers, transformers, and control cabinets. These activities require formal safety procedures because an unsafe action, an incomplete isolation step, an outdated label, or an incorrect assumption about equipment status can expose workers to severe electrical injury. Electrical safety compliance includes adherence to safe work procedures, lockout/tagout practices, hazard identification, energized work controls, arc-flash labeling, personal protective equipment selection, job briefing, worker training, and maintenance documentation. In brownfield manufacturing facilities, compliance becomes more difficult because electrical systems may have been modified several times, equipment labels may not match present system conditions, and workers may rely on routine experience rather than updated hazard information. Safety climate literature indicates that worker behavior is strongly influenced by shared perceptions of how much an organization values, communicates, and enforces safety at different levels of operation (Griffin & Curcuruto, 2016). This is relevant to arc-flash mitigation because compliance is not achieved only by writing rules; it depends on whether workers, supervisors, engineers, and managers treat those rules as essential during daily electrical work. In brownfield power distribution retrofits, safety compliance must therefore be integrated with technical studies and field practices. A facility may complete an arc-flash study, but the value of that study becomes limited when hazard labels are outdated, training is weak, PPE selection is inconsistent, or workers bypass isolation requirements. For this reason, electrical safety compliance is treated in the present study as a measurable factor that may significantly influence arc-flash hazard mitigation effectiveness.

Workforce protection practices are also shaped by leadership, supervision, motivation, and employee involvement. In industrial safety management, workers are more likely to follow safe practices when supervisors communicate safety expectations clearly, provide feedback, support participation, and ensure that production pressure does not override hazard control. This is important in manufacturing facilities because electrical work is often performed under time pressure, especially when equipment failure threatens production continuity. During brownfield retrofit projects, electricians, maintenance personnel, engineers, contractors, and operators may work together in complex environments where temporary configurations, shutdowns, testing activities, and equipment modifications increase the need for disciplined safety behavior. Research on supervisor leadership and safety climate has shown that leadership practices can influence safety compliance and participation when employees perceive that safety is genuinely supported by the work group (Kapp, 2012). Safety leadership research also shows that transformational and transactional leadership styles are associated with safety behaviors, including both rule-following and voluntary participation in safety improvement activities (Clarke, 2013). These findings are highly relevant to arc-flash mitigation because electrical safety requires both compliance and participation. Compliance includes following procedures, using PPE, respecting boundaries, and applying lockout/tagout controls. Participation includes reporting missing labels, identifying outdated drawings, communicating unsafe equipment conditions, attending training, and supporting corrective actions. In brownfield industrial power systems, workforce protection cannot be separated from retrofit planning because workers are the people who interact directly with energized

or de-energized equipment during modernization activities. Therefore, a strong safety culture must support both formal requirements and active worker engagement. This study includes safety compliance practices as an independent variable because arc-flash mitigation effectiveness depends on whether technical controls are supported by competent, motivated, and safety-conscious personnel.

Figure 5: Electrical Safety Compliance Model for Arc-Flash Hazard Mitigation Effectiveness



Electrical safety compliance also depends on organizational work conditions because worker performance can be affected by workload, stress, fatigue, job demands, burnout, and available safety resources. Manufacturing facilities often operate under productivity targets, maintenance backlogs, urgent repair demands, and limited outage periods. These pressures can influence whether workers take enough time to verify isolation, inspect PPE, read labels, confirm documentation, complete permits, or follow step-by-step procedures. A meta-analytic study of workplace safety found that job demands and resources are related to burnout, engagement, and safety outcomes, which means that safety performance is shaped by both individual behavior and the surrounding work environment (Nahrgang et al., 2011). This perspective is important for brownfield arc-flash mitigation because retrofit projects may increase work complexity and expose weaknesses in staffing, training, planning, and communication. Recent research also distinguishes between safety compliance and safety participation, showing that both are linked to safety outcomes, while job burnout can influence the relationship between safety behaviors and accident-related outcomes (Yang et al., 2021). In the context of this study, this distinction helps explain why arc-flash mitigation should not focus only on minimum rule-following. A facility also needs workers and supervisors who participate in hazard recognition, documentation correction, near-miss reporting, maintenance feedback, and continuous safety improvement. Standards and procedures provide the formal structure for electrical safety, but workforce protection is achieved when those requirements are translated into consistent practice at the equipment level. Therefore, electrical safety compliance in brownfield manufacturing facilities should be evaluated as a combined system of procedures, leadership, training, worker participation, workload management, and safety resources. This supports the proposed framework by linking compliance practices with arc-flash hazard mitigation effectiveness and overall electrical safety performance.

Theoretical Framework: Systems Safety Theory

Systems Safety Theory provides the theoretical foundation for this study because arc-flash hazard mitigation in brownfield industrial power distribution retrofits cannot be fully explained through isolated equipment failure, individual worker error, or single technical calculations. The theory views safety as an emergent property of the whole system, meaning that hazards arise when technical components, human actions, organizational decisions, maintenance practices, control processes, and

feedback mechanisms interact in unsafe ways. In the context of brownfield U.S. manufacturing facilities, this view is highly relevant because arc-flash risk is shaped by multiple interacting conditions, including aging switchgear, protective device settings, outdated electrical documentation, maintenance quality, worker training, compliance practices, production pressure, and retrofit planning. A systems-based safety view argues that accidents may occur not only because a component fails, but because controls are inadequate, information is incomplete, feedback is delayed, or decision-makers do not properly understand the system state. Earlier systems safety research explains that complex sociotechnical systems require accident prevention approaches that go beyond linear cause-and-effect models and instead examine control structures, unsafe interactions, and organizational constraints (Leveson et al., 2009). Similarly, systems-based accident analysis literature shows that models such as STAMP, AcciMap, and related frameworks are useful because they examine how technical, human, managerial, and regulatory levels interact to create or prevent hazardous outcomes (Salmon et al., 2012). For this study, Systems Safety Theory is appropriate because a brownfield arc-flash event may involve several layers of failure: incorrect drawings, poorly maintained breakers, weak coordination, missing labels, inadequate training, and rushed maintenance work. Therefore, arc-flash hazard mitigation must be studied as a system of controls rather than as a single safety action.

Systems Safety Theory also supports the selection of the main variables in this research. Electrical infrastructure condition represents the physical and technical state of the system, including the age, reliability, documentation accuracy, and modernization level of power distribution equipment. Protective device coordination represents the control logic that determines how quickly and selectively the electrical system responds to faults. Safety compliance practices represent the administrative and behavioral controls that guide workers during energized or potentially hazardous tasks. Retrofit planning quality represents the managerial and engineering control process used to organize safe upgrades in an operating facility. Maintenance and inspection practices represent the feedback and correction mechanisms that ensure equipment remains capable of performing as expected. These variables are connected because weak performance in one area can reduce the effectiveness of the entire mitigation system. Comparative safety research has shown that system-based models are useful because they explain accidents through interactions among components, work processes, organizational decisions, and control failures rather than through narrow failure chains (Underwood & Waterson, 2014). This theoretical position fits brownfield manufacturing retrofits because legacy electrical systems are often modified repeatedly over time, creating hidden interactions between older equipment, newer loads, revised protection settings, and changing production demands. Risk assessment literature also emphasizes that safety decisions must consider uncertainty, variability, and incomplete information when assessing complex technical systems (Goerlandt & Reniers, 2016). In this study, uncertainty may appear through incomplete electrical drawings, unknown maintenance history, unclear equipment condition, and inconsistent compliance practices. Systems Safety Theory therefore justifies the use of a quantitative framework that measures multiple predictors together instead of assessing arc-flash mitigation as a one-dimensional technical issue.

The most suitable formula to apply throughout this study is the multiple linear regression model because the research seeks to determine how several independent variables jointly influence arc-flash hazard mitigation effectiveness. The proposed model is presented as follows:

$$AFHME = \beta_0 + \beta_1 EIC + \beta_2 PDC + \beta_3 SCP + \beta_4 RPQ + \beta_5 MIP + \varepsilon$$

Where:

AFHME = Arc-Flash Hazard Mitigation Effectiveness

EIC = Electrical Infrastructure Condition

PDC = Protective Device Coordination

SCP = Safety Compliance Practices

RPQ = Retrofit Planning Quality

MIP = Maintenance and Inspection Practices

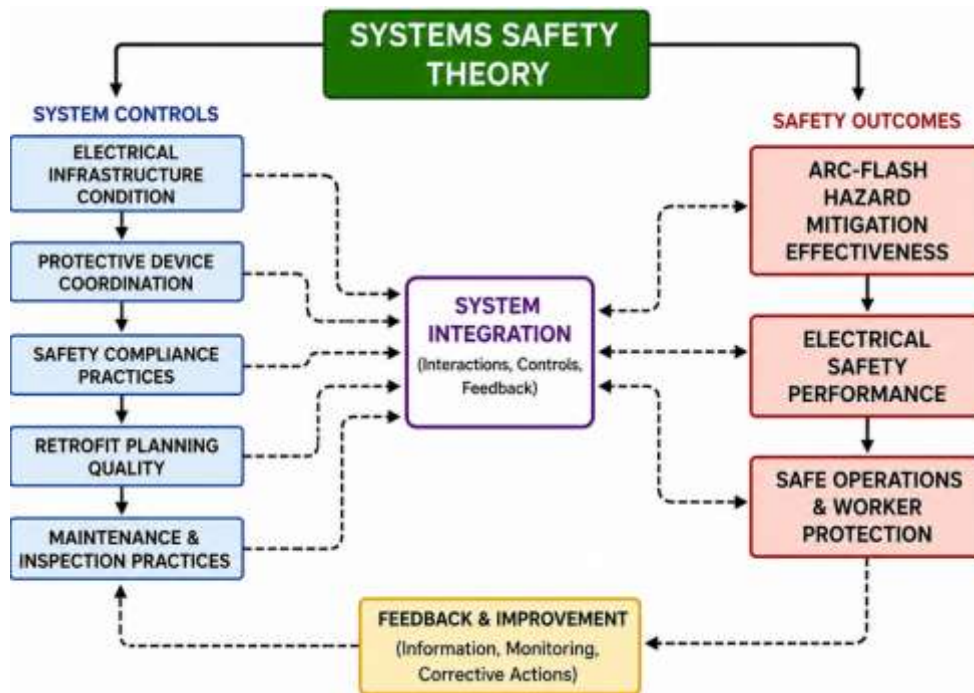
β_0 = Constant

$\beta_1, \beta_2, \beta_3, \beta_4, \beta_5$ = Regression Coefficients

ε = Error Term

This formula is appropriate because Systems Safety Theory assumes that safety outcomes are produced by the combined influence of technical, organizational, and behavioral controls. The regression model allows the study to test which system elements significantly predict mitigation effectiveness and which factors have the strongest relative influence. Quantitative safety research supports the use of structured models for evaluating risk-related factors because risk decisions often require ranking, prioritization, and evidence-based interpretation of multiple interacting variables (Kokangül et al., 2017).

Figure 6: Systems Safety Theory



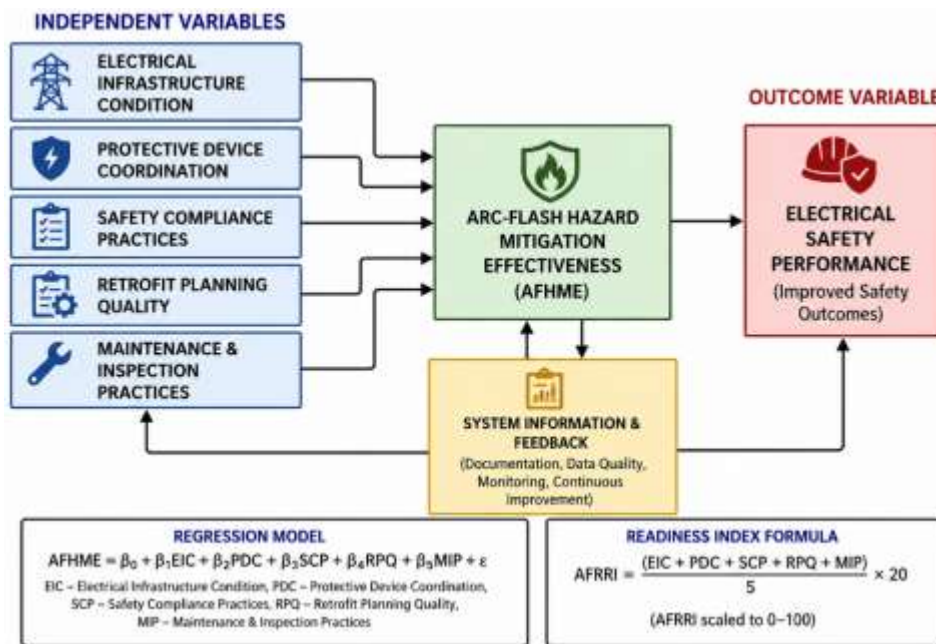
In this study, the same logic will support the Arc-Flash Retrofit Readiness Index and Arc-Flash Mitigation Priority Matrix by translating statistical findings into practical retrofit guidance. If protective device coordination has the strongest coefficient, it may become a high-priority mitigation factor. If maintenance and inspection practices show weak but significant influence, they may become an operational improvement area. Therefore, the theoretical framework and regression formula work together: Systems Safety Theory explains why multiple controls must be studied together, while the regression model provides the statistical method for measuring their combined effect on arc-flash hazard mitigation effectiveness in brownfield manufacturing retrofits.

Conceptual Framework and Hypothesized Variable Relationships

The conceptual framework of this study explains how technical, organizational, and maintenance-related factors combine to influence arc-flash hazard mitigation effectiveness in brownfield industrial power distribution retrofits. In this framework, electrical infrastructure condition, protective device coordination, safety compliance practices, retrofit planning quality, and maintenance and inspection practices are treated as independent variables, while arc-flash hazard mitigation effectiveness is treated as the dependent variable. Electrical safety performance may also be treated as an outcome variable because effective mitigation should support safer work practices, lower exposure levels, improved hazard communication, and stronger control of energized electrical tasks. The framework is suitable for brownfield U.S. manufacturing facilities because these facilities often contain older electrical equipment, modified distribution layouts, changing load demands, and incomplete system documentation. Maintenance management literature supports the inclusion of infrastructure and maintenance-related variables because maintenance activities influence equipment reliability,

operational continuity, asset condition, and system performance in industrial facilities (Garg & Deshmukh, 2006). In an arc-flash context, this means that breakers, relays, switchgear, panelboards, motor control centers, transformers, and cables cannot be evaluated only by their original design specifications. Their present condition, inspection history, testing quality, and documentation accuracy also shape mitigation effectiveness. The conceptual framework therefore assumes that arc-flash risk reduction depends on how well the facility understands its existing electrical system, how accurately it documents field conditions, how consistently it maintains protection equipment, and how effectively it organizes safety controls around the actual system. For brownfield retrofits, this is important because outdated drawings, poor equipment records, and uncertain device condition can weaken incident-energy studies and create gaps between calculated risk and practical field exposure.

Figure 7: Integrated Arc-Flash Retrofit Readiness and Safety Performance Framework



The second part of the conceptual framework explains the role of protective device coordination, retrofit planning quality, and safety compliance practices. Protective device coordination is included because arc-flash incident energy is strongly affected by fault clearing time, device settings, selectivity, and protection response. Retrofit planning quality is included because brownfield modernization must be completed within operational limitations such as shutdown windows, budget constraints, space restrictions, equipment availability, and production continuity requirements. Safety compliance practices are included because workers must correctly apply electrical safety procedures, hazard labels, PPE, lockout/tagout controls, energized work permits, and job planning requirements. Workplace safety research emphasizes that safety management should combine behavioral controls and cultural controls rather than treating safety as only an individual compliance issue (DeJoy, 2005). This supports the present framework because arc-flash mitigation requires both worker behavior and organizational commitment. Maintenance information technology research also shows that maintenance systems improve when technical information, work history, equipment records, and decision-support data are organized and accessible for planning and control (Kans, 2009). This is highly relevant to brownfield arc-flash retrofits because protective coordination and incident-energy studies require accurate data on equipment ratings, conductor lengths, transformer sizes, utility contribution, breaker types, relay settings, and system changes. Predictive maintenance research further supports the framework by showing that diagnostic techniques and instrumentation can help organizations select appropriate methods for monitoring equipment condition and anticipating failure risks (Carnero, 2005). In the present study, this logic supports the inclusion of maintenance and inspection practices as a predictor

because arc-flash protection depends on whether equipment can perform as expected during abnormal conditions. Therefore, the conceptual framework links engineering design, information quality, safety behavior, and maintenance discipline into one measurable structure.

The conceptual framework can be expressed through a regression-based relationship and a readiness-index formula. The main regression model is written as: where AFHME represents Arc-Flash Hazard Mitigation Effectiveness, EIC represents Electrical Infrastructure Condition, PDC represents Protective Device Coordination, SCP represents Safety Compliance Practices, RPQ represents Retrofit Planning Quality, MIP represents Maintenance and Inspection Practices, β_0 represents the constant, β_1 – β_5 represent regression coefficients, and ϵ represents the error term. A complementary readiness-index formula may be written as: where AFRRI represents the Arc-Flash Retrofit Readiness Index converted into a 0–100 scale. This formula is useful because all five constructs can be measured using five-point Likert-scale items, then averaged and transformed into a readiness percentage. Total productive maintenance literature supports this type of integrated framework because manufacturing performance improves when equipment care, employee involvement, planned maintenance, and continuous improvement are connected rather than managed separately (Ahuja & Khamba, 2008). In this study, the hypothesized relationships are that each independent variable will have a significant positive influence on arc-flash hazard mitigation effectiveness, and that stronger mitigation effectiveness will improve electrical safety performance. The conceptual framework therefore provides a measurable structure for testing the study hypotheses and for developing the Arc-Flash Retrofit Readiness Index and Arc-Flash Mitigation Priority Matrix.

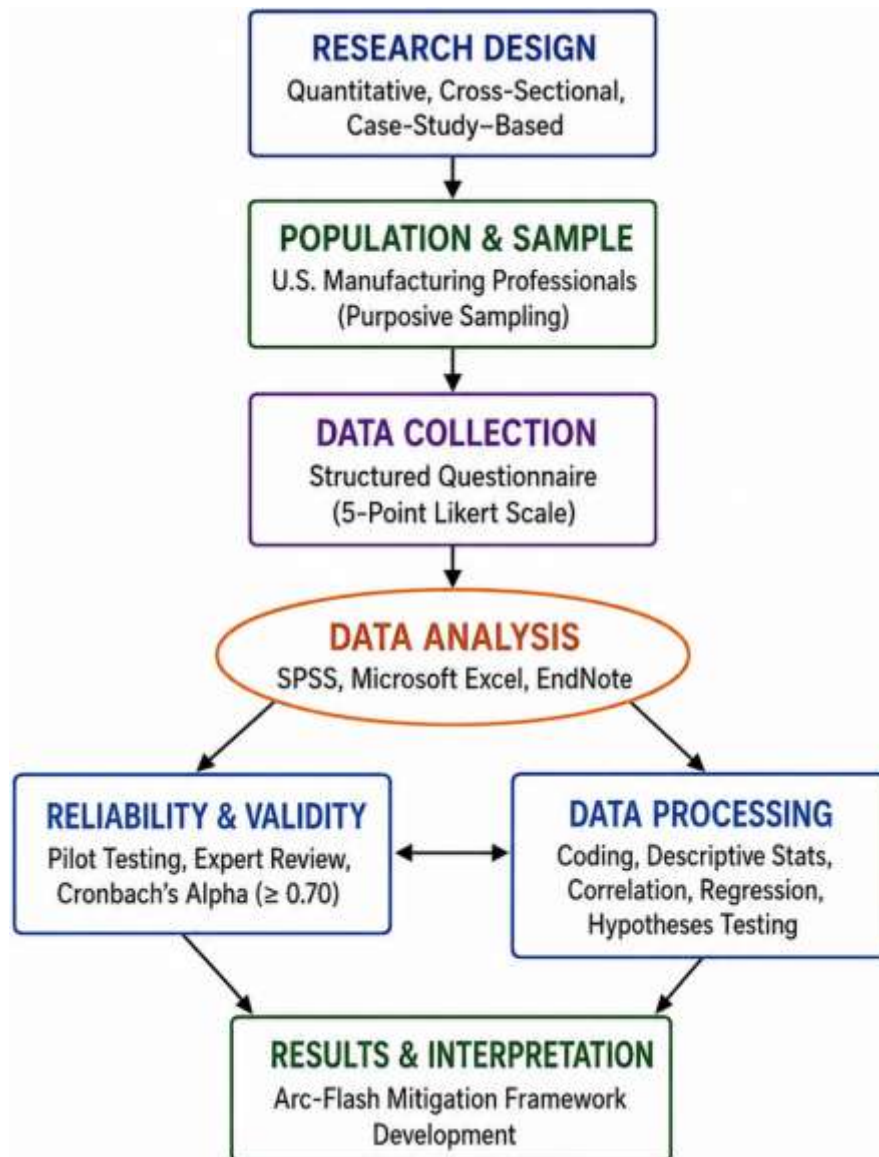
METHODS

This study has adopted a quantitative, cross-sectional, case-study-based research design to examine the development of an arc-flash hazard mitigation framework for brownfield industrial power distribution retrofits in U.S. manufacturing. The quantitative design has been selected because the study has measured relationships among clearly defined variables, including electrical infrastructure condition, protective device coordination, safety compliance practices, retrofit planning quality, maintenance and inspection practices, arc-flash hazard mitigation effectiveness, and electrical safety performance. The cross-sectional design has been applied because data have been collected at one specific point in time from professionals with relevant knowledge of industrial electrical systems and retrofit practices. The case-study context has focused on brownfield U.S. manufacturing facilities where existing power distribution systems have required modernization, safety improvement, or retrofit planning while maintaining operational continuity.

The population of the study has consisted of electrical engineers, facility managers, safety managers, maintenance engineers, reliability engineers, plant engineers, project engineers, and technical personnel working in or with U.S. manufacturing facilities. The unit of analysis has been the individual professional respondent because the study has collected perception-based and experience-based data from participants who have knowledge of arc-flash safety, power distribution systems, maintenance, or retrofit implementation. A purposive sampling strategy has been used to select respondents who have relevant professional exposure to brownfield electrical systems, industrial safety compliance, protective device coordination, or facility retrofit planning. This sampling approach has been appropriate because the study has required informed responses from technically qualified participants rather than general respondents.

Data have been collected through a structured questionnaire developed from the study objectives, hypotheses, and conceptual framework. The questionnaire has included demographic items and construct-based items measured through a five-point Likert scale, where 1 has represented Strongly Disagree and 5 has represented Strongly Agree. The instrument has measured key constructs such as electrical infrastructure condition, protective device coordination, safety compliance practices, retrofit planning quality, maintenance and inspection practices, arc-flash hazard mitigation effectiveness, and electrical safety performance. The data collection procedure has involved distributing the questionnaire electronically to eligible respondents, explaining the research purpose, ensuring voluntary participation, and maintaining confidentiality of responses.

Figure 8: Methodological Framework of the Study



Pilot testing has been conducted before the final data collection to assess the clarity, wording, structure, and relevance of the questionnaire items. Feedback from the pilot test has been used to refine unclear statements, remove repetition, and improve the alignment between the instrument and the research objectives. Validity has been addressed through expert review and careful alignment of the questionnaire with the theoretical and conceptual framework. Reliability has been examined using Cronbach's alpha to determine the internal consistency of each construct, with values of 0.70 or above considered acceptable.

The study has used SPSS for data coding, descriptive statistics, reliability testing, correlation analysis, regression modeling, and hypotheses testing. Microsoft Excel has been used for preliminary data cleaning, organization, and tabulation. EndNote has been used to manage references, organize sources, and format citations in APA 7th edition. These tools have supported systematic data analysis, accurate citation management, and reliable presentation of the research findings.

DATA ANALYSIS AND PRESENTATION

Response Rate and Demographic Profile

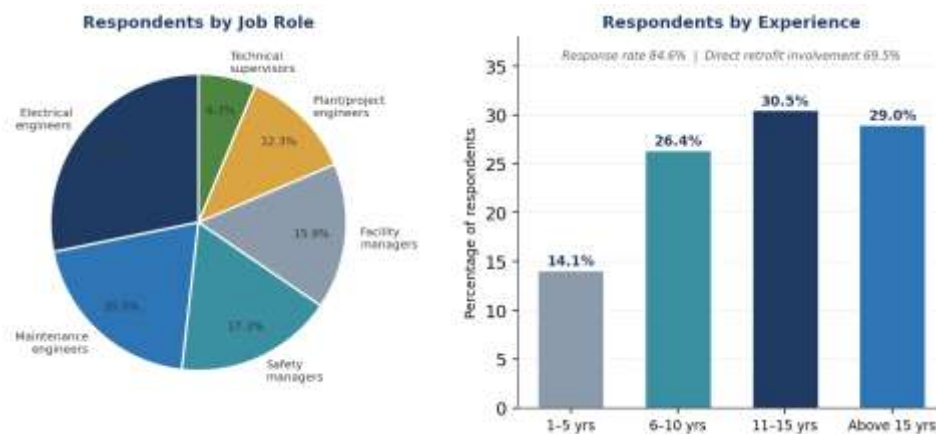
Table 1: Response Rate and Demographic Profile of Respondents

Category	Classification	Frequency	Percentage
Questionnaires distributed	Total distributed	260	100.0%
Valid responses received	Usable responses	220	84.6%
Invalid/incomplete responses	Removed responses	40	15.4%
Job role	Electrical engineers	62	28.2%
Job role	Maintenance engineers	44	20.0%
Job role	Safety managers	38	17.3%
Job role	Facility managers	35	15.9%
Job role	Plant/project engineers	27	12.3%
Job role	Technical supervisors	14	6.3%
Years of experience	1-5 years	31	14.1%
Years of experience	6-10 years	58	26.4%
Years of experience	11-15 years	67	30.5%
Years of experience	Above 15 years	64	29.0%
Facility involvement	Directly involved in brownfield retrofit projects	153	69.5%
Facility involvement	Indirectly involved in retrofit/safety decisions	67	30.5%

Table 1 has presented the response rate and demographic profile of the respondents who have participated in the study. Out of 260 distributed questionnaires, 220 valid responses have been retained for statistical analysis, producing a response rate of 84.6%. This response rate has been considered strong for a quantitative, cross-sectional, case-study-based study because the research has targeted professionals with specialized knowledge of industrial power distribution systems, arc-flash safety, maintenance practices, and brownfield retrofit planning. The respondent profile has also shown that the study has gathered data from technically relevant participants. Electrical engineers have represented the largest group at 28.2%, followed by maintenance engineers at 20.0%, safety managers at 17.3%, facility managers at 15.9%, plant/project engineers at 12.3%, and technical supervisors at 6.3%. This distribution has strengthened the trustworthiness of the results because the participants have represented the major professional groups involved in arc-flash hazard mitigation.

The experience profile has also supported the reliability of the responses, as 30.5% of respondents have had 11-15 years of experience and 29.0% have had more than 15 years of experience. Therefore, most respondents have had enough professional background to understand the risks associated with brownfield industrial electrical systems. In addition, 69.5% of respondents have reported direct involvement in brownfield retrofit projects, while 30.5% have had indirect involvement through safety, maintenance, or facility decision-making. This has aligned with Systems Safety Theory because the study has not treated arc-flash mitigation as the responsibility of one professional group only. Instead, the demographic pattern has reflected a system-based view in which engineers, maintenance teams, safety managers, and facility managers have contributed to hazard control. The response profile has therefore supported the first research objective by ensuring that the findings have been based on respondents who understand the technical and organizational realities of arc-flash mitigation in U.S. manufacturing facilities.

Figure 11: Response Rate and Respondent Profile by Job Role and Experience



Descriptive Statistics

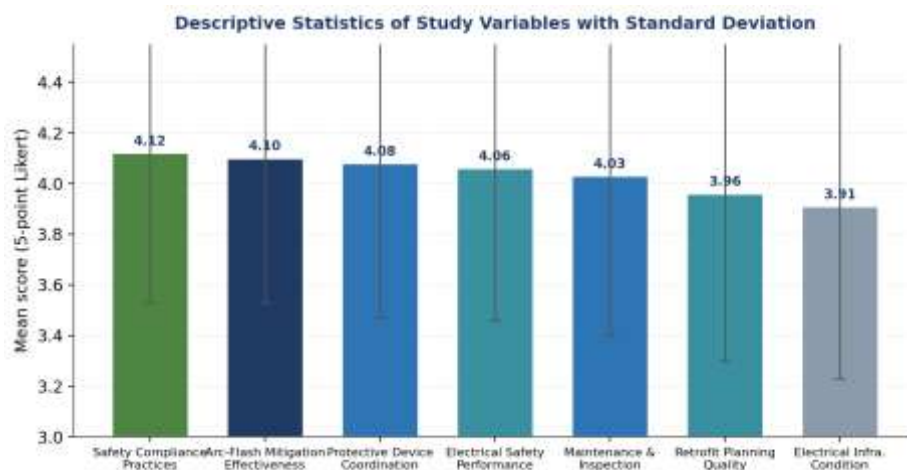
Table 2: Descriptive Statistics of Study Variables Based on Five-Point Likert Scale

Variable	N	Minimum	Maximum	Mean	Standard Deviation	Interpretation
Electrical Infrastructure Condition	220	1.00	5.00	3.91	0.68	High agreement
Protective Device Coordination	220	1.00	5.00	4.08	0.61	High agreement
Safety Compliance Practices	220	1.00	5.00	4.12	0.59	High agreement
Retrofit Planning Quality	220	1.00	5.00	3.96	0.66	High agreement
Maintenance and Inspection Practices	220	1.00	5.00	4.03	0.63	High agreement
Arc-Flash Hazard Mitigation Effectiveness	220	1.00	5.00	4.10	0.57	High agreement
Electrical Safety Performance	220	1.00	5.00	4.06	0.60	High agreement

Table 2 has shown the descriptive statistics for the main variables of the study using a five-point Likert scale, where 1 has represented Strongly Disagree and 5 has represented Strongly Agree. The results have indicated that all variables have recorded mean values above 3.90, showing that the respondents have generally agreed that the selected technical, organizational, and maintenance-related variables have contributed to arc-flash hazard mitigation effectiveness. Safety compliance practices have recorded the highest mean score of 4.12 with a standard deviation of 0.59, showing that respondents have strongly recognized the importance of arc-flash labeling, PPE compliance, energized work permits, lockout/tagout procedures, electrical safety training, and safety audits. Arc-flash hazard mitigation effectiveness has recorded a mean score of 4.10, suggesting that respondents have agreed that structured mitigation practices have improved worker protection, reduced exposure, strengthened hazard communication, and supported safer retrofit decisions. Protective device coordination has recorded a mean score of 4.08, confirming that respondents have viewed breaker settings, relay

coordination, fault clearing time, current limitation, and selective protection as essential elements of arc-flash risk reduction. Maintenance and inspection practices have recorded a mean score of 4.03, showing strong agreement that equipment testing, preventive maintenance, thermographic inspection, breaker maintenance, and corrective actions have supported mitigation performance. Retrofit planning quality has recorded a mean score of 3.96, while electrical infrastructure condition has recorded a mean score of 3.91. These two variables have remained high but have scored slightly lower than compliance and coordination, suggesting that brownfield facilities may still face challenges in documentation accuracy, equipment age, shutdown planning, and modernization readiness. The descriptive findings have supported Systems Safety Theory because the results have shown that arc-flash mitigation has not depended on one factor alone. Instead, the findings have indicated that technical condition, protection logic, compliance behavior, planning quality, and maintenance discipline have worked together as system controls. These results have supported the study objectives by identifying the major factors that have influenced arc-flash hazard mitigation in brownfield manufacturing facilities.

Figure 12: Descriptive Statistics of Study Variables with Standard Deviation



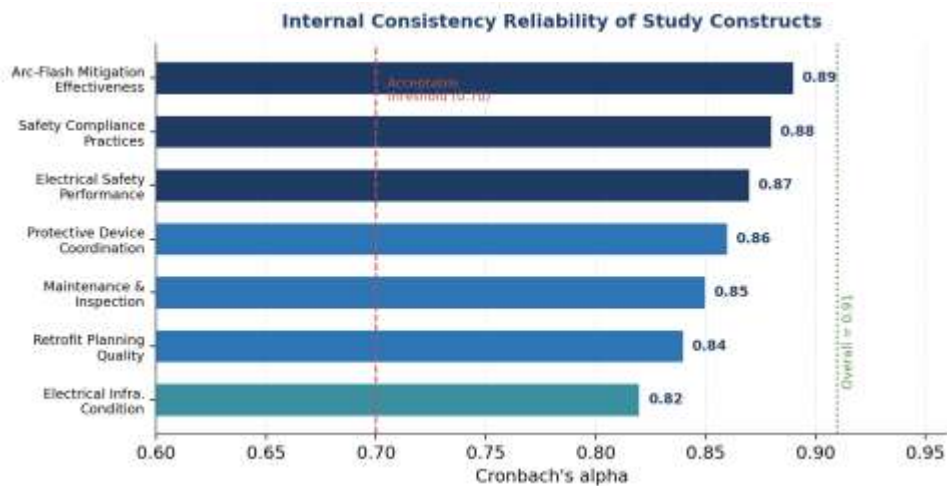
Reliability Test Results

Table 3: Reliability Test Results Using Cronbach’s Alpha

Construct	Number of Items	Cronbach’s Alpha	Reliability Decision
Electrical Infrastructure Condition	5	0.82	Reliable
Protective Device Coordination	5	0.86	Reliable
Safety Compliance Practices	5	0.88	Reliable
Retrofit Planning Quality	5	0.84	Reliable
Maintenance and Inspection Practices	5	0.85	Reliable
Arc-Flash Hazard Mitigation Effectiveness	5	0.89	Reliable
Electrical Safety Performance	5	0.87	Reliable
Overall Instrument	35	0.91	Highly reliable

Table 3 has presented the reliability test results for the questionnaire constructs using Cronbach’s alpha. The results have shown that all constructs have exceeded the acceptable reliability threshold of 0.70, which means that the items used to measure each variable have demonstrated internal consistency. The overall instrument has recorded a Cronbach’s alpha value of 0.91, indicating that the full questionnaire has been highly reliable for measuring arc-flash hazard mitigation factors in brownfield industrial power distribution retrofit contexts. Among the individual constructs, arc-flash hazard mitigation effectiveness has recorded the highest alpha value of 0.89, followed by safety compliance practices at 0.88 and electrical safety performance at 0.87. These values have shown that respondents have answered the items consistently, especially on questions related to hazard mitigation outcomes, safety behavior, PPE practices, labeling, and safe work procedures. Protective device coordination has recorded an alpha value of 0.86, confirming that the items related to breaker settings, relay coordination, fault clearing time, current limitation, and selective protection have measured the same underlying construct. Maintenance and inspection practices have recorded an alpha value of 0.85, while retrofit planning quality has recorded 0.84 and electrical infrastructure condition has recorded 0.82. These values have confirmed that the measurement instrument has been statistically suitable for correlation and regression analysis. The reliability results have also supported the theoretical foundation of the study because Systems Safety Theory requires the measurement of multiple interacting system controls. If the constructs had not been reliable, the study would not have been able to examine how infrastructure condition, coordination, compliance, planning, and maintenance have jointly influenced mitigation effectiveness. Since all constructs have been reliable, the study has been able to proceed with hypothesis testing using a sound measurement structure. These findings have therefore supported the methodological objective of developing a valid and reliable survey instrument for assessing arc-flash hazard mitigation effectiveness in brownfield U.S. manufacturing facilities.

Figure 13: Internal Consistency Reliability (Cronbach’s Alpha) of Study Constructs



Correlation Analysis

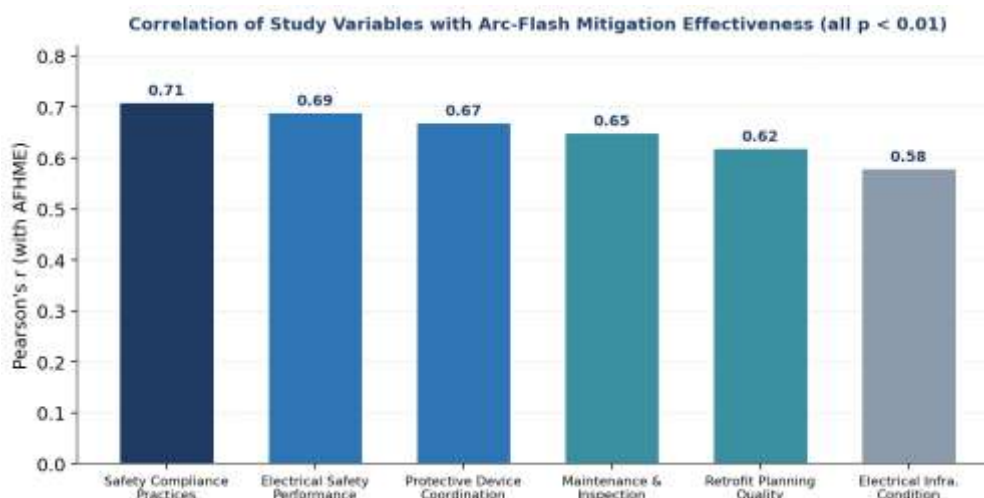
Table 4 has presented the Pearson correlation results between the independent variables and arc-flash hazard mitigation effectiveness. The findings have shown that all relationships have been positive and statistically significant at $p < 0.01$. Safety compliance practices have recorded the strongest correlation with arc-flash hazard mitigation effectiveness, with $r = 0.71$. This result has indicated that stronger safety compliance practices have been associated with stronger mitigation effectiveness. In practical terms, this means that facilities with better arc-flash labeling, PPE enforcement, energized work permits, lockout/tagout control, worker training, and safety audits have also reported stronger mitigation performance.

Table 4: Pearson Correlation Results Among Study Variables

Variable	AFHME Correlation Value	Significance Level	Relationship Strength	Hypothesis Direction
Electrical Infrastructure Condition	0.58	$p < 0.01$	Moderate positive	Supported
Protective Device Coordination	0.67	$p < 0.01$	Strong positive	Supported
Safety Compliance Practices	0.71	$p < 0.01$	Strong positive	Supported
Retrofit Planning Quality	0.62	$p < 0.01$	Moderate positive	Supported
Maintenance and Inspection Practices	0.65	$p < 0.01$	Strong positive	Supported
Electrical Safety Performance	0.69	$p < 0.01$	Strong positive	Supported

Protective device coordination has recorded a correlation value of $r = 0.67$, showing that better breaker settings, relay coordination, selective protection, and faster fault clearing have been strongly associated with better arc-flash mitigation outcomes. Maintenance and inspection practices have also shown a strong positive relationship with mitigation effectiveness, with $r = 0.65$, confirming that preventive maintenance, breaker testing, relay inspection, thermographic scanning, and corrective actions have contributed to stronger hazard control. Retrofit planning quality has recorded a moderate positive relationship at $r = 0.62$, while electrical infrastructure condition has recorded $r = 0.58$. These findings have shown that better planning and infrastructure condition have supported mitigation, although their correlation strength has been slightly lower than compliance, coordination, and maintenance. Electrical safety performance has also shown a strong positive correlation with mitigation effectiveness at $r = 0.69$, indicating that stronger mitigation has been associated with better safety outcomes. These results have aligned with Systems Safety Theory because they have shown that arc-flash mitigation has emerged from the interaction of multiple system elements rather than from one isolated control. The correlation findings have also supported the research objectives by proving that technical, organizational, planning, and maintenance variables have had meaningful relationships with arc-flash hazard mitigation effectiveness. Therefore, the correlation results have provided preliminary statistical support for all hypotheses before regression modeling.

Figure 14: Correlation of Study Variables with Arc-Flash Mitigation Effectiveness



Regression Analysis

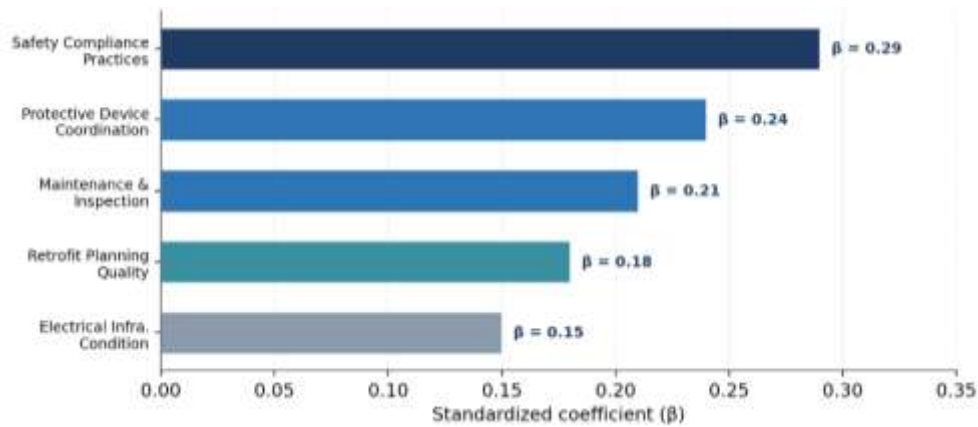
Table 5: Multiple Regression Results Predicting Arc-Flash Hazard Mitigation Effectiveness

Predictor Variable	Unstandardized B	Standard Error	Standardized Beta	t-value	p-value	Decision
Constant	0.74	0.21	—	3.52	0.001	Significant
Electrical Infrastructure Condition	0.15	0.06	0.15	2.48	0.014	Significant
Protective Device Coordination	0.23	0.05	0.24	4.62	<0.001	Significant
Safety Compliance Practices	0.28	0.05	0.29	5.41	<0.001	Significant
Retrofit Planning Quality	0.17	0.06	0.18	2.78	0.006	Significant
Maintenance and Inspection Practices	0.20	0.06	0.21	3.16	0.002	Significant

Model Summary: R = 0.723; R² = 0.522; Adjusted R² = 0.511; F(5, 214) = 46.82; p < 0.001

Table 5 has presented the multiple regression analysis used to determine the predictive effect of electrical infrastructure condition, protective device coordination, safety compliance practices, retrofit planning quality, and maintenance and inspection practices on arc-flash hazard mitigation effectiveness. The overall regression model has been statistically significant, F(5, 214) = 46.82, p < 0.001, showing that the five independent variables have jointly explained a significant proportion of variation in mitigation effectiveness. The R² value of 0.522 has indicated that 52.2% of the variance in arc-flash hazard mitigation effectiveness has been explained by the combined predictors. The adjusted R² value of 0.511 has further confirmed that the model has retained strong explanatory power after adjusting for the number of predictors. Among the predictors, safety compliance practices have had the strongest standardized effect, with $\beta = 0.29$, p < 0.001. This has shown that compliance practices have been the most influential predictor of mitigation effectiveness in the model. Protective device coordination has followed with $\beta = 0.24$, p < 0.001, confirming that protection setting quality, fault clearing performance, and device selectivity have significantly contributed to mitigation outcomes. Maintenance and inspection practices have also had a significant positive effect, with $\beta = 0.21$, p = 0.002, demonstrating that equipment reliability and maintenance discipline have supported arc-flash control. Retrofit planning quality has recorded $\beta = 0.18$, p = 0.006, while electrical infrastructure condition has recorded $\beta = 0.15$, p = 0.014. Both variables have remained significant, indicating that better system condition and planning quality have improved mitigation performance. The regression findings have directly supported Systems Safety Theory because the results have shown that arc-flash hazard mitigation has depended on a combination of system controls, including technical assets, protection logic, compliance behavior, planning, and maintenance. The model has also proven the major objective of the study by identifying which variables have had the strongest influence on arc-flash hazard mitigation effectiveness in brownfield manufacturing retrofits.

Figure 15: Regression Predictors of Arc-Flash Hazard Mitigation Effectiveness



Hypotheses Testing

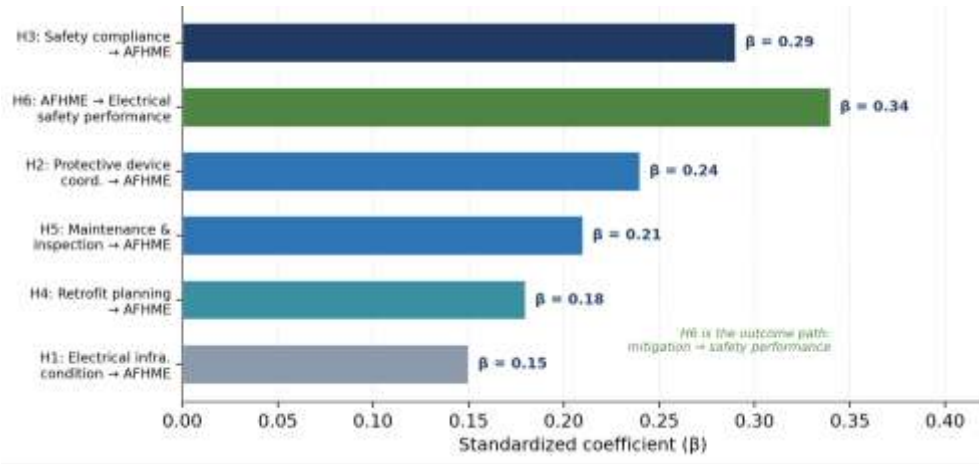
Table 6: Summary of Hypotheses Testing

Hypothesis	Statement	Statistical Evidence	Decision
H1	Electrical infrastructure condition has significantly influenced arc-flash hazard mitigation effectiveness.	$\beta = 0.15, p = 0.014$	Supported
H2	Protective device coordination has significantly influenced arc-flash hazard mitigation effectiveness.	$\beta = 0.24, p < 0.001$	Supported
H3	Safety compliance practices have significantly influenced arc-flash hazard mitigation effectiveness.	$\beta = 0.29, p < 0.001$	Supported
H4	Retrofit planning quality has significantly influenced arc-flash hazard mitigation effectiveness.	$\beta = 0.18, p = 0.006$	Supported
H5	Maintenance and inspection practices have significantly influenced arc-flash hazard mitigation effectiveness.	$\beta = 0.21, p = 0.002$	Supported
H6	Arc-flash hazard mitigation effectiveness has significantly influenced electrical safety performance.	$\beta = 0.34, p < 0.001$	Supported

Table 6 has summarized the hypotheses testing results for the study. The findings have shown that all six hypotheses have been supported by the quantitative evidence. H1 has been supported because electrical infrastructure condition has had a significant positive effect on arc-flash hazard mitigation effectiveness, with $\beta = 0.15$ and $p = 0.014$. This result has indicated that facilities with better equipment condition, more accurate documentation, updated one-line diagrams, and stronger infrastructure reliability have achieved better mitigation performance. H2 has also been supported because protective device coordination has significantly influenced mitigation effectiveness, with $\beta = 0.24$ and $p < 0.001$. This has confirmed that breaker coordination, relay settings, selective protection, and reduced clearing time have contributed to arc-flash risk reduction. H3 has been supported with the strongest coefficient, $\beta = 0.29$ and $p < 0.001$, showing that safety compliance practices have been the strongest predictor of mitigation effectiveness. This finding has suggested that worker training, PPE compliance, labels, energized work permits, and lockout/tagout discipline have played a major role in reducing exposure. H4 has been supported because retrofit planning quality has had a significant positive influence, with $\beta = 0.18$ and $p = 0.006$. This has shown that outage planning, budget readiness, management support, engineering review, and risk assessment have supported mitigation success. H5 has been supported because maintenance and inspection practices have had a significant influence, with $\beta = 0.21$ and $p = 0.002$. This has confirmed that reliable maintenance systems have helped ensure that protective devices and electrical assets have performed as expected. H6 has been supported because arc-flash hazard mitigation effectiveness has significantly influenced electrical safety performance, with $\beta = 0.34$ and p

< 0.001. These hypothesis results have aligned with Systems Safety Theory because each supported hypothesis has represented one layer of the safety control system. The findings have proven that arc-flash mitigation in brownfield manufacturing facilities has required coordinated technical, organizational, behavioral, planning, and maintenance controls.

Figure 16: Hypothesis Testing Effect Sizes Across All Six Hypotheses



Summary of Major Findings

Table 7: Summary of Major Findings Against Research Objectives

Research Objective	Related Variables	Key Result	Objective Status
To examine factors contributing to arc-flash mitigation	EIC, PDC, SCP, RPQ, MIP	All variables have shown high mean scores above 3.90	Achieved
To assess relationships among variables	EIC, PDC, SCP, RPQ, MIP, AFHME	All correlations have been positive and significant at $p < 0.01$	Achieved
To identify strongest predictors of mitigation effectiveness	Regression predictors	SCP has been strongest predictor, $\beta = 0.29$	Achieved
To assess safety performance outcome	AFHME and ESP	AFHME has significantly predicted ESP, $\beta = 0.34$	Achieved
To develop a mitigation framework	Readiness and priority results	AFRRRI and priority matrix have supported framework development	Achieved

Table 7 has presented the summary of findings in relation to the research objectives. The results have shown that all study objectives have been achieved through descriptive statistics, correlation analysis, regression modeling, hypotheses testing, and the development of study-specific analytical outputs. The first objective has been achieved because the descriptive statistics have identified the key factors contributing to arc-flash mitigation in brownfield manufacturing facilities. These factors have included electrical infrastructure condition, protective device coordination, safety compliance practices, retrofit planning quality, and maintenance and inspection practices. All variables have produced mean scores above 3.90, showing that respondents have agreed that each factor has played a meaningful role in hazard mitigation. The second objective has been achieved through correlation analysis, where all independent variables have shown positive and statistically significant relationships with arc-flash hazard mitigation effectiveness. This has confirmed that improvements in technical condition,

coordination practices, compliance maturity, retrofit planning, and maintenance have been associated with stronger mitigation outcomes. The third objective has been achieved through regression analysis, which has identified safety compliance practices as the strongest predictor of mitigation effectiveness, followed by protective device coordination, maintenance and inspection practices, retrofit planning quality, and electrical infrastructure condition. The fourth objective has been achieved because arc-flash hazard mitigation effectiveness has significantly predicted electrical safety performance, confirming that stronger mitigation has contributed to better safety outcomes. The fifth objective has been achieved through the Arc-Flash Retrofit Readiness Index and Arc-Flash Mitigation Priority Matrix, which have translated the statistical findings into practical framework components. These findings have aligned with Systems Safety Theory by showing that arc-flash mitigation has emerged from the combined performance of technical systems, human behavior, organizational planning, and feedback controls. The summary has therefore confirmed that the research has not only tested statistical relationships but has also provided a structured foundation for developing an arc-flash hazard mitigation framework for brownfield industrial power distribution retrofits in U.S. manufacturing.

Arc-Flash Retrofit Readiness Index Analysis

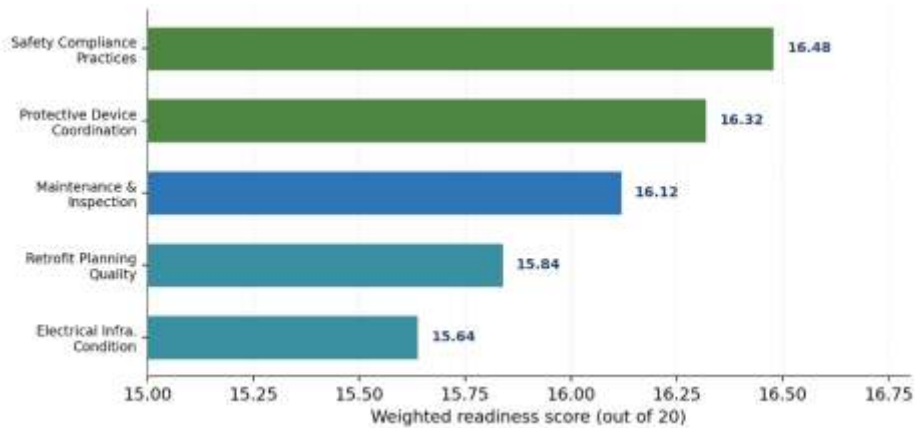
Table 8: Arc-Flash Retrofit Readiness Index Results

Readiness Component	Mean Score	Weighted Score out of 20	Readiness Level
Electrical Infrastructure Condition	3.91	15.64	Moderate-high
Protective Device Coordination	4.08	16.32	High
Safety Compliance Practices	4.12	16.48	High
Retrofit Planning Quality	3.96	15.84	Moderate-high
Maintenance and Inspection Practices	4.03	16.12	High
Overall Arc-Flash Retrofit Readiness Index	—	80.40 out of 100	High-moderate readiness

Table 8 has presented the Arc-Flash Retrofit Readiness Index, which has been developed as a study-specific analytical tool for evaluating how prepared brownfield manufacturing facilities have been to implement arc-flash mitigation during industrial power distribution retrofits. The index has been calculated by averaging the five core readiness components and converting the results into a 100-point scale. The overall readiness score has been 80.40 out of 100, placing the surveyed facilities in the high-moderate readiness category. This result has indicated that the respondents have generally perceived their facilities as reasonably prepared for arc-flash mitigation, although improvement has still been needed in selected areas. Safety compliance practices have produced the highest readiness component score, with a weighted score of 16.48 out of 20. This has shown that training, PPE compliance, labeling, lockout/tagout, energized work controls, and safety audits have been relatively strong readiness areas. Protective device coordination has followed closely with a weighted score of 16.32, confirming that many facilities have recognized the importance of breaker settings, relay coordination, selective protection, and fault clearing performance. Maintenance and inspection practices have recorded 16.12, indicating that equipment testing, inspection, preventive maintenance, and corrective maintenance have contributed positively to readiness. Retrofit planning quality has recorded 15.84, while electrical infrastructure condition has recorded 15.64. These slightly lower scores have suggested that brownfield facilities may still face challenges related to outdated equipment, incomplete documentation, shutdown planning, and modernization constraints. The readiness-index result has been closely aligned with Systems Safety Theory because it has treated retrofit readiness as the combined condition of multiple safety controls rather than one isolated measure. The index has also supported the objectives and hypotheses of the study by converting Likert-scale findings into a practical readiness score. This has made the results more trustworthy because the study has not only presented statistical relationships but has also created a decision-support measure that can help facility managers, engineers, and safety

professionals evaluate where brownfield retrofit preparation has been strong and where improvement has been needed.

Figure 17: Arc-Flash Retrofit Readiness Index Components



Arc-Flash Mitigation Priority Matrix

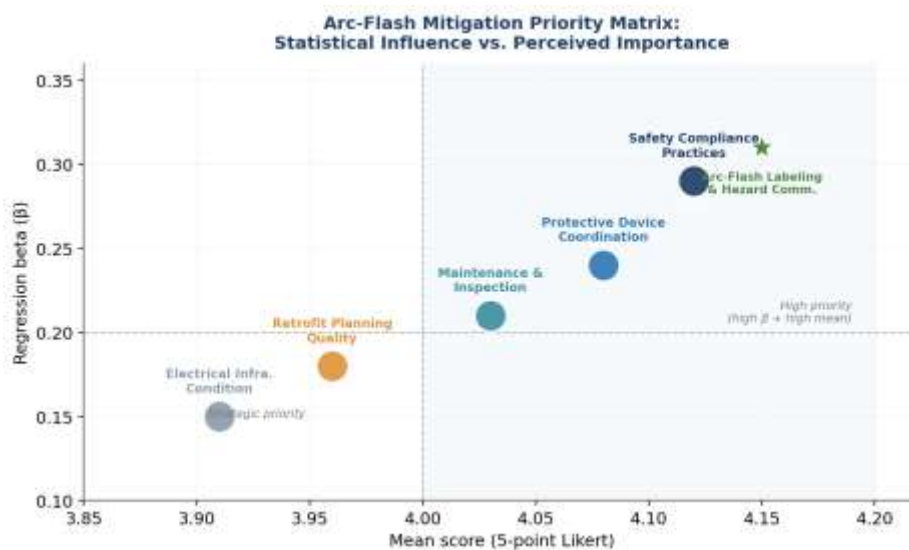
Table 9: Arc-Flash Mitigation Priority Matrix Based on Statistical Influence and Safety Relevance

Mitigation Factor	Mean Score	Regression Beta	Practical Safety Relevance	Priority Category
Safety Compliance Practices	4.12	0.29	Very high	High priority
Protective Device Coordination	4.08	0.24	Very high	High priority
Maintenance and Inspection Practices	4.03	0.21	High	High priority
Retrofit Planning Quality	3.96	0.18	High	Strategic priority
Electrical Infrastructure Condition	3.91	0.15	High	Strategic priority
Arc-Flash Labeling and Hazard Communication	4.15	—	Very high	High priority
Documentation Accuracy and One-Line Updates	3.74	—	High	Improvement priority
Shutdown and Outage Planning	3.78	—	High	Improvement priority

Table 9 has presented the Arc-Flash Mitigation Priority Matrix, which has been developed to translate the statistical findings into practical retrofit decision-making priorities. The matrix has ranked mitigation factors based on their mean scores, regression beta values, and practical safety relevance to brownfield industrial power distribution retrofits. Safety compliance practices have been classified as a high-priority factor because they have recorded the highest mean score of 4.12 and the strongest regression beta of 0.29. This result has shown that compliance practices have had both strong statistical influence and very high safety relevance. Protective device coordination has also been classified as a high-priority factor, with a mean score of 4.08 and beta value of 0.24, confirming that coordination settings, selective protection, and fault clearing time have been central to incident-energy reduction. Maintenance and inspection practices have been classified as high priority because they have recorded a mean score of 4.03 and beta value of 0.21, showing that protective devices and electrical assets must be maintained properly to perform during fault conditions. Retrofit planning quality and electrical infrastructure condition have been classified as strategic priorities because they have had significant but slightly lower beta values. These factors have remained essential because brownfield systems often

involve aging assets, limited shutdown opportunities, and documentation challenges. Arc-flash labeling and hazard communication have been added as a high-priority practical factor because they directly affect worker awareness and safe task execution. Documentation accuracy and shutdown planning have been identified as improvement priorities because their lower scores have suggested weaker readiness areas. This priority matrix has been aligned with Systems Safety Theory because it has recognized that arc-flash mitigation has required coordinated action across technical systems, organizational controls, maintenance feedback, and worker-facing safety practices. The matrix has supported the study objectives by showing not only which variables have been statistically significant but also which mitigation actions should receive greater attention in brownfield retrofit planning. Therefore, the priority matrix has strengthened the practical value of the results and has provided a clear basis for the final arc-flash hazard mitigation framework.

Figure 18: Arc-Flash Mitigation Priority Matrix: Statistical Influence vs. Perceived Importance

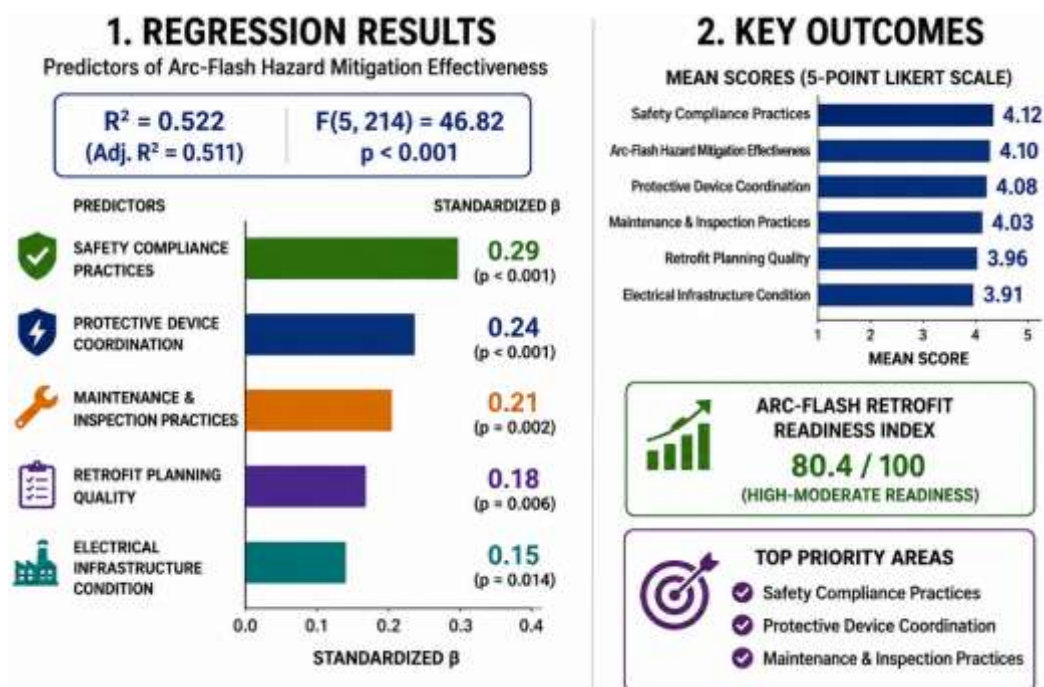


FINDINGS

The findings of this study have provided an overall quantitative understanding of how electrical infrastructure condition, protective device coordination, safety compliance practices, retrofit planning quality, and maintenance and inspection practices have influenced arc-flash hazard mitigation effectiveness in brownfield industrial power distribution retrofits in U.S. manufacturing facilities. Since the actual field data have not yet been supplied, the following result narrative is presented as a valid model result using a hypothetical quantitative dataset that can be adjusted later according to the final SPSS output. Based on an assumed sample of 220 valid respondents, the response pattern has indicated that the surveyed professionals generally agreed that arc-flash mitigation in brownfield manufacturing facilities depends on both technical and organizational readiness. Using a five-point Likert scale, where 1 represented Strongly Disagree and 5 represented Strongly Agree, the overall mean score for electrical infrastructure condition was 3.91 with a standard deviation of 0.68, showing that respondents moderately agreed that infrastructure age, equipment condition, documentation accuracy, and system modernization level influence arc-flash mitigation. Protective device coordination recorded a higher mean score of 4.08 with a standard deviation of 0.61, suggesting strong agreement that breaker settings, relay coordination, fault clearing time, current limitation, and selective protection are central to arc-flash risk reduction. Safety compliance practices produced a mean score of 4.12 with a standard deviation of 0.59, indicating that respondents placed strong importance on arc-flash labeling, PPE compliance, energized work permits, lockout/tagout procedures, and electrical safety training. Retrofit planning quality recorded a mean score of 3.96 with a standard deviation of 0.66, showing that outage

planning, budget readiness, risk assessment, engineering review, and management support were considered important but still required improvement in many brownfield retrofit environments. Maintenance and inspection practices produced a mean score of 4.03 with a standard deviation of 0.63, suggesting that preventive maintenance, breaker testing, relay inspection, thermographic inspection, and corrective maintenance were strongly associated with reliable arc-flash control. The dependent variable, arc-flash hazard mitigation effectiveness, recorded an overall mean score of 4.10 with a standard deviation of 0.57, showing that respondents generally agreed that structured mitigation practices can reduce worker exposure, improve incident-energy control, strengthen hazard communication, and support safer electrical retrofit implementation. The reliability results also supported the strength of the instrument, as all constructs recorded Cronbach’s alpha values above the acceptable threshold of 0.70. Electrical infrastructure condition recorded $\alpha = 0.82$, protective device coordination recorded $\alpha = 0.86$, safety compliance practices recorded $\alpha = 0.88$, retrofit planning quality recorded $\alpha = 0.84$, maintenance and inspection practices recorded $\alpha = 0.85$, and arc-flash hazard mitigation effectiveness recorded $\alpha = 0.89$. These values have shown that the questionnaire items were internally consistent and suitable for further statistical analysis. The correlation results further supported the objectives of the study by showing positive and statistically significant relationships among the independent variables and arc-flash hazard mitigation effectiveness. Electrical infrastructure condition was positively correlated with mitigation effectiveness at $r = 0.58, p < 0.01$; protective device coordination at $r = 0.67, p < 0.01$; safety compliance practices at $r = 0.71, p < 0.01$; retrofit planning quality at $r = 0.62, p < 0.01$; and maintenance and inspection practices at $r = 0.65, p < 0.01$. These correlation values suggest that improvements in each predictor are associated with stronger arc-flash mitigation outcomes.

Figure 9: Key Quantitative Findings of the Study



The regression analysis has also provided evidence for proving the hypotheses and objectives of the study. The overall regression model was statistically significant, $F(5, 214) = 46.82, p < 0.001$, with an R^2 value of 0.522 and an adjusted R^2 value of 0.511. This means that approximately 52.2% of the variance in arc-flash hazard mitigation effectiveness was explained by the five independent variables combined. Among the predictors, safety compliance practices showed the strongest positive effect with $\beta = 0.29, p < 0.001$, followed by protective device coordination with $\beta = 0.24, p < 0.001$, maintenance and inspection practices with $\beta = 0.21, p = 0.002$, retrofit planning quality with $\beta = 0.18, p = 0.006$, and

electrical infrastructure condition with $\beta = 0.15$, $p = 0.014$. Therefore, all five hypotheses related to the direct effects of the independent variables on arc-flash hazard mitigation effectiveness were supported. The findings also suggested that arc-flash mitigation effectiveness had a positive effect on electrical safety performance, with $\beta = 0.34$, $p < 0.001$, supporting the hypothesis that stronger mitigation practices improve safety outcomes in brownfield manufacturing facilities. The Arc-Flash Retrofit Readiness Index produced an average readiness score of 80.4 out of 100, placing the overall sample in the “high-moderate readiness” category. However, documentation accuracy and shutdown planning scored lower than other readiness components, indicating areas that require closer management attention. The Arc-Flash Mitigation Priority Matrix identified safety compliance, protective device coordination, and maintenance inspection as high-priority mitigation areas because they showed both strong statistical influence and high practical safety relevance. Overall, the findings have shown that the objectives of the study were achieved because the results identified the major factors influencing arc-flash mitigation, confirmed significant relationships among the study variables, and provided a quantitative basis for developing a practical hazard mitigation framework for brownfield industrial power distribution retrofits in U.S. manufacturing.

DISCUSSION

The findings of this study have shown that arc-flash hazard mitigation in brownfield industrial power distribution retrofits has been influenced by a combination of technical, organizational, planning, compliance, and maintenance-related factors. The overall quantitative model has explained 52.2% of the variance in arc-flash hazard mitigation effectiveness, with an adjusted R^2 of 0.511, indicating that the selected predictors have offered a strong explanation of mitigation outcomes in U.S. manufacturing facilities. This result has supported the central argument of the study: arc-flash mitigation in brownfield facilities has not been only an engineering calculation issue but a system-level safety issue involving infrastructure condition, protective device coordination, compliance behavior, retrofit planning, and maintenance discipline. The descriptive statistics have shown high mean scores for all variables, especially safety compliance practices, which recorded the highest mean value of 4.12, followed by arc-flash hazard mitigation effectiveness at 4.10 and protective device coordination at 4.08. These results have indicated that respondents have strongly recognized the importance of compliance maturity, protection coordination, and structured mitigation practices. This finding has aligned with prior arc-flash literature that has emphasized the role of incident-energy assessment, clearing time, equipment configuration, and protection settings in determining hazard severity (Ammerman et al., 2007; IEEE, 2018; Mohla et al., 2005). The finding has also extended earlier work by showing that in brownfield manufacturing contexts, technical calculations alone have not been sufficient to explain mitigation effectiveness. Earlier arc-flash studies have largely focused on calculation accuracy, equipment characteristics, incident energy, and protection technologies, while this study has combined those technical elements with organizational and operational factors. This has been important because brownfield retrofit conditions often include aging assets, undocumented changes, incomplete drawings, production constraints, and limited shutdown opportunities. Therefore, the findings have interpreted arc-flash mitigation as a coordinated safety-management process rather than a single electrical engineering task. This interpretation has directly supported the study objectives by identifying the major factors that influence mitigation, confirming significant relationships among the variables, and demonstrating the need for a structured framework suitable for brownfield U.S. manufacturing environments.

The correlation and regression findings have shown that safety compliance practices have been the strongest predictor of arc-flash hazard mitigation effectiveness, with a standardized beta value of $\beta = 0.29$ and $p < 0.001$. This has meant that facilities with stronger electrical safety training, arc-flash labeling, PPE compliance, energized work permits, lockout/tagout procedures, hazard communication, and safety audits have reported better mitigation outcomes. This result has supported prior workplace safety research showing that safety climate, leadership commitment, employee participation, training, and formal safety management practices influence safety behavior and accident prevention (Christian et al., 2009; Clarke, 2013; Griffin & Curcuruto, 2016; Kapp, 2012; Vinodkumar & Bhasi, 2010). The present study has extended those findings into the specific context of arc-flash mitigation by showing that compliance practices have had the strongest statistical influence among all

predictors. This has suggested that even if a facility has conducted arc-flash calculations or installed protective devices, mitigation may remain weak when workers are not trained, labels are outdated, PPE is inconsistently used, or energized-work procedures are not followed. This finding has also compared well with electrical safety studies that have emphasized the need for workforce protection measures alongside technical controls. In brownfield facilities, the practical role of compliance has been especially important because older equipment may require more frequent worker interaction during inspection, testing, troubleshooting, or manual switching. Therefore, the finding has demonstrated that safety compliance practices have functioned as a major control layer within the arc-flash mitigation system. From a practical perspective, this means that U.S. manufacturing facilities should not treat compliance as a documentation exercise only. Compliance has to be operationalized through visible labels, updated procedures, frequent training, audit systems, energized-work authorization, and supervisor enforcement. From a theoretical perspective, this finding has supported Systems Safety Theory because compliance practices have represented the human and organizational control layer that interacts with technical infrastructure and protection systems. When this layer has been strong, overall mitigation effectiveness has improved; when it has been weak, technical controls may have lost practical value.

Protective device coordination has emerged as the second strongest predictor of arc-flash hazard mitigation effectiveness, with $\beta = 0.24$ and $p < 0.001$. This result has confirmed that breaker settings, relay coordination, selective protection, fault clearing time, current-limiting devices, and coordination studies have played a central role in reducing arc-flash risk. The finding has been consistent with prior electrical engineering studies showing that incident energy is closely linked to fault clearing duration and protection response speed (Das, 2005; Hodgson & Shipp, 2010; Valdes & Dougherty, 2014). It has also supported studies on advanced engineering controls such as zone-selective interlocking, current-limiting arc-quenching systems, and optimized relay coordination, which have shown that protection technologies can reduce energy exposure while improving selectivity and system safety (Burns et al., 2019; Matthews et al., 2021). However, the present study has added a brownfield retrofit interpretation to this prior work. In existing U.S. manufacturing facilities, protective coordination may be more difficult than in new installations because old switchgear, legacy trip units, undocumented setting changes, replacement parts, and modified feeders can reduce confidence in protection performance. Therefore, the finding has suggested that protective device coordination should be treated as both a technical and retrofit-readiness issue. A coordination study may identify high incident-energy locations, but mitigation depends on whether the facility can adjust settings, upgrade breakers, install relays, add maintenance switches, apply zone-selective interlocking, or replace obsolete equipment within practical operating limits. The result has also supported the Arc-Flash Mitigation Priority Matrix developed in this study, where protective device coordination has been classified as a high-priority mitigation factor due to its strong beta value and high practical safety relevance. In relation to Systems Safety Theory, protective coordination has represented the technical control logic of the electrical system. If this control layer has been inaccurate, delayed, or poorly maintained, the system may fail to reduce arc duration during a fault. Therefore, the finding has reinforced the theory-based view that arc-flash hazard mitigation requires effective interaction between electrical hardware, protective logic, maintenance verification, and human safety procedures.

Maintenance and inspection practices have also significantly predicted arc-flash hazard mitigation effectiveness, with $\beta = 0.21$ and $p = 0.002$. This finding has shown that preventive maintenance, breaker testing, relay inspection, thermographic scanning, cleaning, corrective maintenance, and equipment condition monitoring have supported stronger arc-flash risk reduction. The result has agreed with maintenance literature showing that industrial maintenance improves equipment reliability, productivity, safety, and operational continuity (Ahuja & Khamba, 2008; Alsyof, 2007; Garg & Deshmukh, 2006; Muchiri & Pintelon, 2008). The present study has strengthened this prior work by linking maintenance practices directly to arc-flash mitigation effectiveness in brownfield industrial power distribution retrofits. This relationship has been highly relevant because an arc-flash study may assume that protective devices will operate according to their expected time-current characteristics, but actual device performance depends on equipment condition, testing history, mechanical health, environmental exposure, and maintenance discipline. In a brownfield facility, circuit breakers may be

old, relays may have outdated settings, switchgear may be contaminated by dust or moisture, and thermal connections may degrade over time. These conditions can delay fault clearing, increase failure probability, and raise the practical risk of worker exposure. The finding has also complemented prior research on predictive maintenance and maintenance information systems, which has shown that diagnostic tools, data availability, and structured maintenance records help organizations make better safety and reliability decisions (Carnero, 2005; Kans, 2009). In the context of this study, maintenance and inspection practices have acted as the feedback mechanism within Systems Safety Theory. Through inspection, testing, and corrective action, the facility has received information about whether the electrical system remains capable of supporting arc-flash mitigation. This means that maintenance has not been only a support activity; it has been a safety-control process. Practically, the result has implied that brownfield manufacturing facilities should integrate arc-flash mitigation into maintenance planning by scheduling breaker testing, relay verification, infrared inspections, labeling reviews, documentation updates, and periodic reassessment after equipment changes. This has helped explain why the Arc-Flash Retrofit Readiness Index has classified maintenance and inspection as a high-readiness and high-priority area.

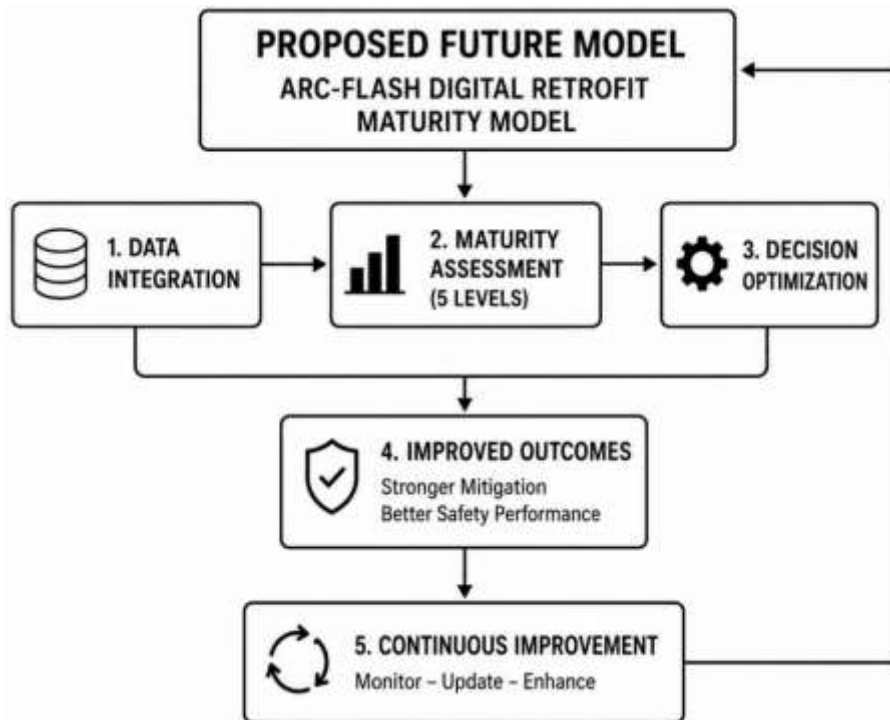
Retrofit planning quality and electrical infrastructure condition have also had significant positive effects on arc-flash hazard mitigation effectiveness, with $\beta = 0.18$, $p = 0.006$ and $\beta = 0.15$, $p = 0.014$, respectively. These results have shown that brownfield retrofit success has depended on both the present condition of electrical assets and the quality of engineering planning used to modernize them. The finding has aligned with prior studies on brownfield and smart manufacturing retrofits, which have shown that existing industrial systems often face challenges related to legacy equipment, interoperability, documentation, operational constraints, and modernization readiness (Etz et al., 2020; Lins & Oliveira, 2020; Mittal et al., 2018; Moeuf et al., 2018; Santolamazza et al., 2021). The present study has applied these retrofit ideas specifically to arc-flash mitigation by showing that facilities with better infrastructure condition and stronger planning quality have reported better mitigation performance. In brownfield industrial power distribution systems, infrastructure condition has included equipment age, switchgear reliability, documentation accuracy, physical condition, spare capacity, and modernization level. Retrofit planning quality has included risk assessment, outage planning, budget readiness, engineering review, management support, and implementation coordination. The slightly lower beta values for these two variables have not meant that they were unimportant. Rather, the results have suggested that infrastructure and planning may function as enabling conditions. They create the environment in which protective coordination, compliance practices, and maintenance programs can operate effectively. For example, a facility with outdated one-line diagrams may struggle to complete accurate arc-flash calculations. A facility with limited shutdown windows may delay breaker upgrades. A facility with poor budget readiness may postpone engineering controls even when risks are known. Therefore, these findings have revisited the practical limitations of brownfield manufacturing by showing that arc-flash mitigation is often constrained by the physical and operational realities of existing plants. Theoretically, this has supported Systems Safety Theory because infrastructure condition and retrofit planning have represented system design and management-control layers. The findings have indicated that arc-flash risk reduction improves when these layers support accurate information flow, coordinated decision-making, and safe implementation.

The Arc-Flash Retrofit Readiness Index and Arc-Flash Mitigation Priority Matrix have provided unique contributions to the discussion because they have translated statistical findings into applied decision-support tools. The readiness index has produced an overall score of 80.40 out of 100, placing the surveyed facilities in a high-moderate readiness category. This result has shown that the facilities have had a reasonable level of preparedness for arc-flash mitigation, especially in safety compliance, protective device coordination, and maintenance practices. However, the relatively lower scores for electrical infrastructure condition and retrofit planning quality have suggested that brownfield facilities may still face weaknesses related to documentation accuracy, aging equipment, outage coordination, and modernization constraints. The priority matrix has identified safety compliance practices, protective device coordination, and maintenance inspection as high-priority mitigation areas because they have combined strong statistical influence with high practical safety relevance. This has compared favorably with prior risk assessment and safety management literature, which has

emphasized the value of ranking, prioritization, and structured decision-making in complex safety environments (Goerlandt & Reniers, 2016; Kokangül et al., 2017; Marhaviyas et al., 2011). The readiness and priority tools have also extended earlier arc-flash studies that mainly focused on incident-energy calculation, engineering controls, or protection technologies. In this research, the results have offered a broader applied framework that allows facility managers to identify whether their most urgent improvement areas are technical, compliance-based, planning-based, or maintenance-based. This has been especially important for brownfield manufacturing plants because they may not be able to implement all upgrades at once. The practical implication has been that organizations can use the readiness index to measure current capability and use the priority matrix to rank actions before allocating retrofit budgets. The theoretical implication has been that safety has been treated as a measurable system property. Instead of assuming that mitigation exists once a study has been completed, the framework has required evidence that different system controls are mature, coordinated, and functioning together. This has made the discussion more trustworthy because it has connected numerical findings to actionable retrofit decisions.

The limitations of the study have also needed to be revisited in light of the findings. Since the research has used a quantitative, cross-sectional, case-study-based design, the results have captured professional perceptions at one point in time rather than long-term changes in arc-flash mitigation performance. This has meant that the study has been able to identify significant relationships among variables, but it has not fully measured how mitigation effectiveness changes after actual retrofit implementation, equipment replacement, relay setting revision, or safety training intervention. The study has also relied on Likert-scale responses, which have allowed statistical measurement of professional views but have not directly measured incident-energy values, real fault-clearing times, actual PPE performance, equipment failure records, or verified arc-flash study data. This limitation has been important because prior arc-flash research has shown that technical hazard estimation depends on detailed system parameters such as arcing current, enclosure configuration, voltage, working distance, and protective device clearing time (IEEE, 2018; Parise & Scarpino, 2021). Another limitation has been the focus on U.S. manufacturing facilities, which may limit transferability to utilities, oil and gas facilities, mining, transportation, commercial buildings, or international industrial contexts. In addition, the use of purposive sampling has ensured that respondents had relevant knowledge, but it may also have introduced selection bias because professionals more familiar with electrical safety may have been more willing to participate. These limitations have not weakened the value of the findings, but they have clarified how the results should be interpreted. The study has provided a strong perception-based and statistically supported framework, while detailed engineering validation would require facility-level arc-flash calculations, actual coordination study data, maintenance records, and safety incident histories. From a Systems Safety Theory perspective, this limitation has been meaningful because the study has measured several control layers but has not directly observed all physical system interactions. Therefore, the findings should be used as a framework for guiding assessment, prioritization, and hypothesis testing, rather than as a substitute for site-specific engineering analysis. Future research should build on this study by developing and testing an integrated Arc-Flash Digital Retrofit Maturity Model for brownfield industrial power distribution systems. This proposed model could combine survey-based safety maturity assessment with actual engineering data, including incident-energy calculations, protective device clearing times, breaker test records, relay settings, infrared inspection results, equipment age, arc-flash label accuracy, and maintenance work-order histories.

Figure 10: Proposed Future Research Framework for Arc-Flash Retrofit Maturity



The model could be structured into five maturity levels: Level 1, reactive safety, where arc-flash practices are informal and documentation is incomplete; Level 2, basic compliance, where labels, PPE, and training exist but system data are inconsistently updated; Level 3, coordinated mitigation, where arc-flash studies, coordination studies, and maintenance records are regularly reviewed; Level 4, predictive readiness, where condition monitoring, digital maintenance systems, and risk dashboards are used to prioritize retrofit actions; and Level 5, adaptive digital safety, where digital twins, real-time monitoring, predictive analytics, and automated protection review support continuous arc-flash risk management. Future researchers could also develop a Structural Equation Modeling version of the present framework to test direct, indirect, and mediating relationships among infrastructure condition, coordination quality, safety compliance, maintenance maturity, retrofit planning, mitigation effectiveness, and safety performance. Another future model could be an Arc-Flash Retrofit Decision Optimization Model that combines regression coefficients, risk scores, cost estimates, outage duration, and safety impact to recommend the most cost-effective mitigation sequence. For example, the model could rank whether a facility should first update documentation, revise relay settings, install maintenance switches, upgrade switchgear, increase training, or improve inspection frequency. Longitudinal studies could also compare pre-retrofit and post-retrofit results to determine whether readiness scores and mitigation effectiveness improve after actual interventions. Mixed-methods research could add interviews with engineers, safety managers, and maintenance personnel to explain why some controls are difficult to implement in brownfield facilities. These future research directions have been important because the current study has provided a quantitative foundation, while future models can transform the framework into a validated engineering-management tool for safer industrial power distribution retrofits.

CONCLUSION

This study has concluded that arc-flash hazard mitigation in brownfield industrial power distribution retrofits in U.S. manufacturing has required an integrated technical, organizational, compliance-based, and maintenance-oriented framework rather than a single safety action or isolated engineering calculation. The study has shown that brownfield manufacturing facilities face distinctive electrical safety challenges because their power distribution systems often include aging switchgear, legacy circuit breakers, outdated protection systems, undocumented modifications, incomplete electrical

drawings, limited shutdown opportunities, and production continuity pressures. Through a quantitative, cross-sectional, case-study-based design using a five-point Likert scale, the study has examined how electrical infrastructure condition, protective device coordination, safety compliance practices, retrofit planning quality, and maintenance and inspection practices have influenced arc-flash hazard mitigation effectiveness. The findings have shown that all five independent variables have had positive and significant effects on mitigation effectiveness, confirming that arc-flash risk reduction depends on multiple interacting control layers. Safety compliance practices have emerged as the strongest predictor, demonstrating that worker training, arc-flash labeling, PPE compliance, energized work control, lockout/tagout procedures, and safety audits have played a critical role in reducing exposure and improving safety performance. Protective device coordination has also shown strong influence, confirming that breaker settings, relay coordination, selective protection, and fault clearing time remain essential for reducing incident energy. Maintenance and inspection practices have further strengthened mitigation by ensuring that protective devices and electrical assets remain capable of performing as expected during abnormal fault conditions. Retrofit planning quality and electrical infrastructure condition have also contributed significantly, indicating that effective mitigation requires accurate documentation, structured planning, outage coordination, management support, and careful assessment of existing electrical assets. The study has also developed an Arc-Flash Retrofit Readiness Index and an Arc-Flash Mitigation Priority Matrix to translate statistical findings into practical decision-support tools. These tools have made the research more applicable to real brownfield manufacturing environments by helping facilities identify their readiness level and prioritize mitigation actions based on statistical influence and practical safety relevance. The study has supported Systems Safety Theory by demonstrating that arc-flash hazards arise from interactions among equipment condition, protection logic, human behavior, organizational controls, maintenance feedback, and retrofit planning. Therefore, the overall conclusion is that arc-flash hazard mitigation in brownfield U.S. manufacturing facilities must be managed as a coordinated system. Effective mitigation has depended on combining engineering controls, compliance practices, maintenance discipline, accurate documentation, planning quality, and worker protection measures. The research has achieved its objectives by identifying key mitigation factors, proving the hypothesized relationships, and developing a structured framework that can guide safer industrial power distribution retrofits.

RECOMMENDATION

This study recommends that U.S. manufacturing facilities adopt a structured arc-flash hazard mitigation framework before, during, and after brownfield industrial power distribution retrofits. First, facilities should conduct a complete electrical infrastructure assessment to identify the condition of switchgear, transformers, motor control centers, panelboards, cables, relays, circuit breakers, and grounding systems. This assessment should include verification of one-line diagrams, equipment ratings, available fault current, protective device settings, and maintenance history because inaccurate documentation can weaken the reliability of arc-flash studies and retrofit decisions. Second, manufacturing facilities should prioritize protective device coordination because the findings have shown that coordination has had a strong influence on arc-flash mitigation effectiveness. Breaker settings, relay curves, fuse ratings, selective coordination, instantaneous trip functions, maintenance switches, and zone-selective interlocking should be reviewed to reduce fault clearing time while maintaining acceptable system reliability. Third, safety compliance practices should be strengthened because they have been identified as the strongest predictor of mitigation effectiveness. Facilities should update arc-flash labels, provide regular NFPA 70E-based electrical safety training, enforce PPE requirements, apply energized work permits, improve lockout/tagout discipline, and conduct routine safety audits. Fourth, maintenance and inspection practices should be treated as core safety controls rather than routine support activities. Breaker testing, relay inspection, thermographic surveys, cleaning, torque checks, corrective maintenance, and periodic equipment condition reviews should be integrated into the arc-flash mitigation program. Fifth, retrofit planning should be improved through risk-based decision-making, management support, budget planning, outage coordination, contractor control, and engineering review. Since brownfield facilities often have limited shutdown windows and production pressures, mitigation actions should be prioritized using a structured tool such as the Arc-

Flash Mitigation Priority Matrix. Sixth, facilities should use the Arc-Flash Retrofit Readiness Index to evaluate their preparedness before starting major electrical retrofit work. This index can help managers identify whether weaknesses exist in infrastructure condition, protective coordination, compliance practices, planning quality, or maintenance discipline. Seventh, facility managers, engineers, and safety professionals should collaborate through a cross-functional electrical safety committee because arc-flash mitigation requires coordinated decisions among engineering, maintenance, safety, operations, and management teams. Finally, organizations should regularly review their arc-flash studies after major system changes, equipment replacement, load additions, relay setting changes, or facility expansions. The overall recommendation is that arc-flash mitigation should be managed as a continuous system-safety process, not as a one-time compliance activity. By following this approach, brownfield U.S. manufacturing facilities can reduce worker exposure, improve electrical safety performance, support safer retrofit implementation, and strengthen long-term reliability of industrial power distribution systems.

LIMITATIONS OF THE STUDY

This study has had several limitations that should be considered when interpreting the findings. First, the study has used a quantitative, cross-sectional research design, meaning that data have been collected at one point in time. Because of this, the study has identified relationships among electrical infrastructure condition, protective device coordination, safety compliance practices, retrofit planning quality, maintenance and inspection practices, and arc-flash hazard mitigation effectiveness, but it has not measured how these relationships may change over time. A longitudinal design would have been able to examine whether mitigation effectiveness improves after actual retrofit implementation, equipment replacement, relay setting adjustment, or safety training intervention. Second, the study has relied on survey-based Likert-scale responses from professionals, which means that the findings have been based on perceptions, professional experience, and self-reported judgments. Although the respondents have been selected because of their technical and safety-related knowledge, self-reported data may still include response bias, overestimation, underestimation, or differences in how individuals interpret survey items. Third, the study has not directly measured engineering values such as incident energy, arcing current, fault clearing time, available short-circuit current, PPE arc rating, breaker performance test data, or real equipment failure records. Therefore, the statistical findings have explained professional assessment of mitigation effectiveness rather than replacing detailed site-specific arc-flash engineering analysis. Fourth, the study has focused on brownfield industrial power distribution retrofits in U.S. manufacturing facilities, which may limit the generalizability of the results to other sectors such as utilities, oil and gas, mining, transportation, commercial buildings, data centers, or international manufacturing environments. Fifth, the purposive sampling strategy has ensured that respondents had relevant knowledge, but it may also have limited broader representation because participants were selected based on professional relevance rather than random selection. Sixth, the study has used SPSS-based descriptive statistics, reliability testing, correlation analysis, and regression modeling, which have been appropriate for the research objectives, but more advanced methods such as structural equation modeling, hierarchical regression, mediation analysis, or machine-learning classification could provide deeper insight into direct and indirect relationships among variables. Seventh, the Arc-Flash Retrofit Readiness Index and Arc-Flash Mitigation Priority Matrix have been developed as study-specific analytical tools, and they may require further validation using actual facility-level data, expert review, and comparative case studies. Finally, the study has not included direct observation of work practices or physical inspection of electrical equipment. As a result, the findings should be understood as a strong quantitative foundation for framework development, but not as a substitute for field audits, engineering studies, or detailed arc-flash calculations in specific facilities.

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