Journal of Engineering Research and Education
Volume 17, 2025 [110-124]

Development of an Electrical Fire Risk Assessment Framework for Residential Buildings in Sultanate of Oman

Dawoud Hamed AL-Rashdi[1*], Muhamad S[2], and IM Rusni[3]

[1,2&3]Department of Electrical Engineering, Faculty of Engineering and Life Sciences, University of Selangor, Bestari Jaya Campus, Selangor Darul Ehsan

ABSTRACT

This study developed a comprehensive electrical fire risk assessment framework tailored for residential buildings in the Sultanate of Oman, aiming to identify and calculate fire risks while addressing gaps in existing fire safety legislation. The framework systematically moves through six stages: fire event identification, scenario development, quantitative risk analysis, evaluation, response, and monitoring. It integrates statistical fire data and forensic laboratory findings, applying engineering methods for estimating initiating event frequencies and scenario risk calculations. Based on engineering principles of risk assessment, the framework employs Layer of Protection Analysis (LOPA), encompassing the identification of hazards, calculation of initiating event frequencies, evaluation of protection layers, and risk categorization. A practical application was conducted using a sample of lighting systems, where the most frequent failure causes such as overheating, arcing, and overload were analyzed. The probability of fire occurrence was then calculated and found to fall within a medium-risk range. Accordingly, the framework was applied to formulate appropriate control strategies for this specific fire type, supporting the creation of new fire safety regulations and improving residential fire risk management in Oman.

Keywords: Electrical Fire Framework, Fire Awareness, Fire Safety, Fire Risks

1. INTRODUCTION

Effective fire risk assessment relies on the accurate development of plausible accident scenarios that represent real world conditions and potential failure modes. In residential environments, electrical fires frequently originate from system degradation, misuse, or failure of protective devices (Mi et al., 2020; Xin & Huang, 2014). Scenario development plays a crucial role in identifying initiating events, evaluating the likelihood of fire occurrences, and determining the impact of different hazard pathways. This step builds the foundation for conducting LOPA and supports quantitative risk estimation across various electrical components (Willey, 2014). In this study, three representative accident scenarios were formulated based on statistical fire data and forensic inspection reports. These scenarios reflect the most recurrent causes of electrical fires in Oman's residential sector, including wiring degradation, electrical overload, and internal equipment malfunctions. Each scenario includes a clearly defined initiating event, associated enabling conditions, and possible escalation paths if not mitigated by protective layers. By simulating these scenarios, the framework enables structured analysis of risk frequency and severity. This method ensures a consistent approach to estimating the overall fire risk profile and highlights priority areas for safety improvement (Pawolocki, 2021). The following subsections detail the development of each scenario and its relevance to electrical fire prevention in residential settings.

2. LITERATURE REVIEW

Electrical fires in residential buildings pose a significant safety challenge in the Sultanate of Oman, primarily due to gaps in fire safety regulations tailored to residential facilities (Wallington, 2016). These incidents often originate from factors such as faulty wiring, inadequate fire prevention

D_carlos1988@hotmail.com

systems, and a lack of awareness regarding safety measures (Shokouhi et al., 2019; Omar et al., 2023). Given the increasing risks and the devastating consequences of such fires, there is an urgent need for a structured and effective approach to assess and mitigate these hazards.

This study aims to develop a comprehensive electrical fire risk assessment framework specifically tailored for residential settings in Oman. By integrating historical fire incident data (2018–2020) from the Public Authority for Civil Defense and Ambulance (PACDA), forensic laboratory findings, and expert insights, the framework adopts risk assessment methodologies, including LOPA, to systematically identify, evaluate, and prioritize electrical fire risks (NCSI, 2022; Bougie & Sekaran, 2019). The research addresses key deficiencies in current safety practices and presents a scientifically grounded tool for proactive fire risk management in residential environments. Ultimately, it contributes to strengthening fire safety infrastructure and supporting the formulation of evidence-based regulatory policies in the Sultanate of Oman.

2.1 Electrical Fire Hazards in Residential Buildings

Recent studies highlight that electrical faults remain a leading ignition source in residential fires, both globally and in the Middle East. In the Gulf region, a high proportion of fire incidents occur in homes; for instance, reports from Saudi Arabia indicate that approximately 65% of building fires involve residential structures (Al-Qahtani et al., 2021). According to the National Centre for Statistics and Information (NCSI), the total number of fire incidents increased steadily from (3,409) in 2020 to (4,186) in 2022. Notably, about one third (32.1%) of the fires in 2022 occurred in residential facilities, emphasizing the growing prevalence of domestic fire risks. Electrical malfunctions and overloads were consistently identified as primary ignition causes. In 2022, Oman recorded 234 fire incidents involving electrical equipment, power lines, or utility poles accounting for 5.6% of all fire cases and many more were suspected to originate from indoor wiring faults or appliance failures. By 2023, the number of home fire cases rose to 1,539, marking a 14.4% increase from the previous year.

The civil defence and ambulance authority (PACDA, 2022) has warned that many homes in Oman face serious electrical hazards, ranging from overloaded outlets to aging wiring. Common issues were identified includes plugging multiple appliances into a single socket, leaving devices operating unattended, and allowing unqualified individuals to perform electrical work all of which may result in short circuits or overheating, increasing the likelihood of fires. A recent regional survey (Yousef et al., 2022) of high-rise buildings in developing countries revealed similar patterns, with electrical faults cited as the most frequent cause of residential fires. These findings collectively underscore the urgent need to address electrical fire risks through targeted mitigation strategies, improved public awareness, and the enforcement of safety regulations. Ensuring that homes are equipped with reliable protective devices is a critical component of fire risk reduction.

2.2 Fire Risk Assessment Methodologies

Fire risk assessment methodologies provide structured approaches to identify fire hazards, estimate their likelihood, and evaluate potential consequences. These methods are essential for prioritizing risk reduction measures and ensuring safety compliance. Depending on data availability and required precision, assessments can be qualitative, semi-quantitative, or quantitative each offering varying levels of detail in hazard analysis and decision-making support. Semi-quantitative fire risk assessment methods integrate qualitative expert judgment with numerical techniques to improve decision-making in fire safety evaluations. One commonly used tool is the Risk Matrix, which categorizes likelihood and severity into a visual grid (e.g., low, medium, high). While risk matrices are simple and widely used in practice, they often suffer from subjective inputs, limited resolution, and a lack of consistency in how risk levels are interpreted.

For complex fire scenarios, especially in residential buildings with variable loads and aging infrastructure risk matrices may oversimplify the actual hazard (Ajith et al., 2022). Another tool is the Analytic Hierarchy Process (AHP), which helps prioritize fire risk factors through weighted scores. Alfalah et al. (2023) applied AHP to assess fire safety in Saudi buildings by developing a structured scoring system. Although it offers a more systematic approach than basic matrices, AHP still relies heavily on expert weighting and pairwise comparisons, which can introduce bias and reduce reproducibility (Babrauskas, 2016).

To address these limitations, this study adopts LOPA, a semi-quantitative method that bridges qualitative screening and fully probabilistic models. Originally designed for process safety, LOPA identifies initiating fire events and evaluates the probability of failure for independent protection layers (IPLs), such as breakers, detectors, and alarms. A recent study in Iran applied LOPA to a high-rise building, assessing 26 electrical hazard conditions and successfully prioritizing risks based on residual fire probability (Babrauskas, 2016). LOPA is preferred in this research due to its transparent structure, numerical outputs, and engineering rigor. It enables systematic risk ranking and supports decision-making grounded in measurable protection performance. Unlike matrices or AHP, LOPA minimizes subjective influence and is better suited for developing reliable and actionable fire risk frameworks in residential environments.

2.3 Effectiveness and Reliability of Fire Protection Systems in Residences

Fire detection and alarm systems represent a vital layer of protection in residential fire safety, as supported by contemporary research. Smoke alarms and heat detectors offer early warnings that are essential for occupant evacuation and timely emergency response. Although most comprehensive data on the effectiveness of such systems originates from developed countries, the global consensus confirms that operational smoke alarms significantly reduce fire-related fatalities (Pawolocki, 2021). In the Sultanate of Oman, increasing attention has been directed toward the role of detection systems in mitigating residential fire risks. The PACD has formally recommended that homeowners install smoke detectors and gas leak alarms to enhance early hazard identification. This initiative forms part of broader public awareness campaigns launched in response to incidents in which the absence of alarms nearly resulted in severe consequences. Omani fire officials have consistently cited delayed detection as a key factor that exacerbates fire damage in homes.

To enhance reliability, some international jurisdictions such as Scotland now mandate interlinked smoke alarms in all residential units, ensuring that activation of one unit triggers all alarms in the dwelling. Oman is pursuing a similar strategy by tightening its building safety codes. National regulations require that all commercial properties be fitted with certified fire protection systems, including smoke alarms, fire extinguishers, emergency lighting, and, where applicable, sprinklers or suppression systems (Xing & Huang, 2013). Occupancy is contingent upon obtaining a Civil Defence certificate issued by the Royal Oman Police, confirming compliance with these safety standards (Zhang, 2023). However, installation alone is insufficient. Ongoing maintenance is equally critical to ensure operational effectiveness. Recent guidance emphasizes the need for routine inspections and upkeep of fire detection and suppression systems. Without consistent maintenance such as battery replacement or addressing corrosion these systems may fail at critical moments, negating their intended protective function (Mi et al., 2020).

Emerging empirical studies are shedding light on the reliability of fire protection systems. Surveys evaluating the functionality of smoke alarms have identified common issues in residential settings, such as dead batteries and disconnected units. In response, advancements in technology ranging from sealed long-life smoke alarms to smart Internet of Things based monitoring systems have been introduced to enhance the operational reliability of these preventive fire technologies (Idris et al., 2020). Recent evidence from 2021 to 2025 underscores that well-maintained and functioning fire protection systems significantly reduce the risk of fatalities. Across the middle east and north africa countries, fire safety practices are being progressively updated to mandate the wider adoption of such systems in residential dwellings. Integrating automatic suppression systems (e.g., sprinklers), detection devices (e.g., smoke and heat alarms), and firefighting tools (e.g., portable extinguishers and hose reels) establishes a multilayered defense against electrical fires. Sustaining the effectiveness of these systems through rigorous standards enforcement and regular maintenance remains a central priority within the fire safety community (IAAI, 2019).

2.4 Oman's Fire Safety Trends and Regulatory Developments

The Sultanate of Oman has experienced a significant increase in fire incidents in recent years, drawing heightened regulatory attention and prompting the implementation of proactive safety initiatives. Reported fire emergencies rose from approximately 3,400 cases in 2020 to over 4,000 annually, with residential fires constituting an increasing proportion 1,345 cases in 2022 and more than 1,500 in 2023. This upward case may be attributed to both population expansion and improvements in incident reporting methods. However, it also underscores the urgent need to strengthen domestic fire prevention strategies to address growing risks within residential environments. Investigations conducted by the PACDA consistently identify key ignition sources such as electrical arcing, circuit overloads, and poor electrical connection. In response to these recurrent findings, public awareness campaigns initiated in 2021 have emphasized the importance of preventive practices. These include avoiding the overloading of electrical outlets, closely monitoring household appliances, and ensuring that ignition sources are kept out of children's reach. This reflects a broader shift in Oman's fire safety strategy from reactive response to proactive risk mitigation (Tawalbeh & El-Khazali, 2020).

Due to increased number of fire incidents, regulatory efforts have also intensified. Since 2021, the Royal Oman Police and the PACD have optional that buildings obtain fire safety clearance prior to occupancy. These regulations require the installation of fire alarms, smoke detectors, and extinguishers as essential life safety systems. In parallel, authorities have begun inspecting older buildings and encouraging retrofitting, particularly where outdated wiring and the absence of detection systems present significant risks. In 2022, the Civil Defense and Ambulance Authority recommended the voluntary installation of interlinked smoke alarms in older residences and proposed a regulation requiring at least one smoke detector per floor. Furthermore, Oman is actively modernizing its fire safety codes through collaboration with international standards organizations. This commitment was underscored during the 2023 Civil Defense and Ambulance Conference, which emphasized the adoption of technology-driven risk assessment tools, reflecting a national shift toward smart regulation and data-informed enforcement.

Overall, Oman's fire safety strategy since 2021 demonstrates a clear transition toward prevention, regulatory enforcement, and modernization. The PACD, now operating as an independent entity, has established a dedicated fire risk prevention division and adopted internationally recognized standards, including those of the NFPA and IEC. Although the total number of fire incidents has not yet shown a decline, improvements in early detection systems and heightened public awareness indicate enhanced community preparedness. Collectively, these measures establish a robust foundation as an input to propose electrical fire risk assessment framework, ensuring its alignment with Oman's evolving safety regulations and infrastructure development priorities (NFPA, 2023).

3. METHODOLOGY

The research process follows a structured sequence, starting with a comprehensive review of fire safety regulations and relevant literature on residential fire risk assessment. This review focuses on electrical fire incidents and the development of a safety framework. Data is collected through statistical reports (2018–2020) and laboratory inspections to investigate the causes and public awareness of electrical fires. Risk assessment includes hazard identification, consequence analysis, and the use of LOPA to evaluate and mitigate fire risks. Based on the LOPA results, a risk management framework is developed and making recommendations to enhance residential fire safety. Figure 1 illustrates the research process that is carried out in this research.

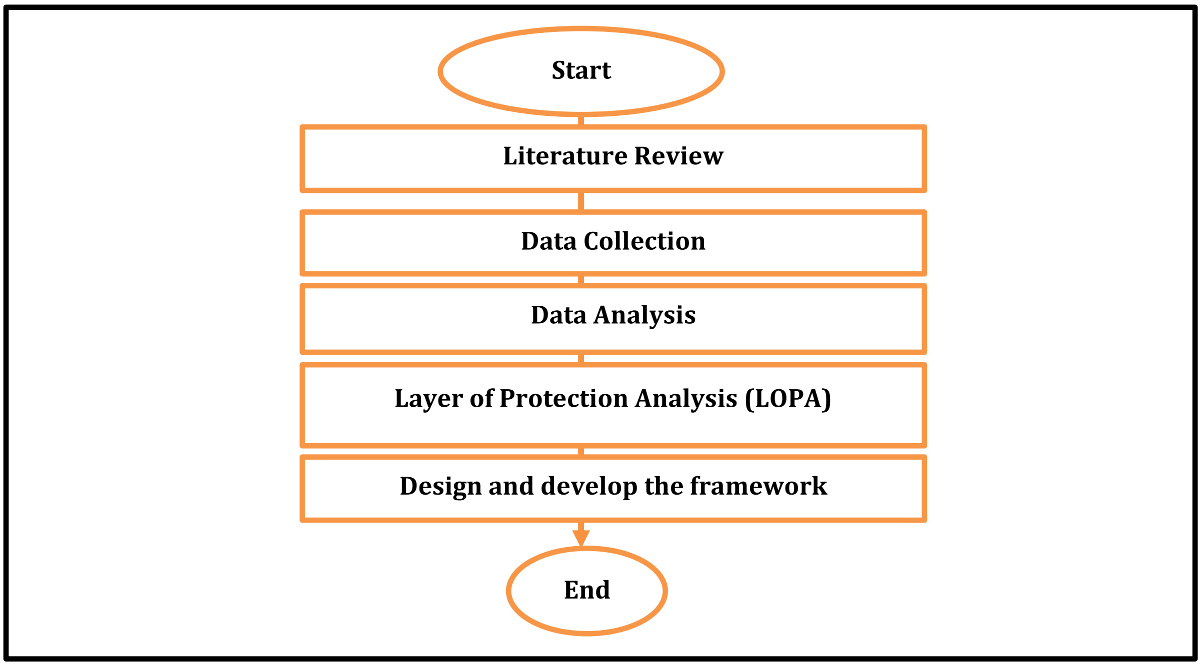

Figure 1. Flowchart of the study

3.1 Layer of Protection Analysis (LOPA)

FPS-LOPA involves a systematic approach for risk evaluation through six structured steps as in Figure 2. Key steps are summarized below:

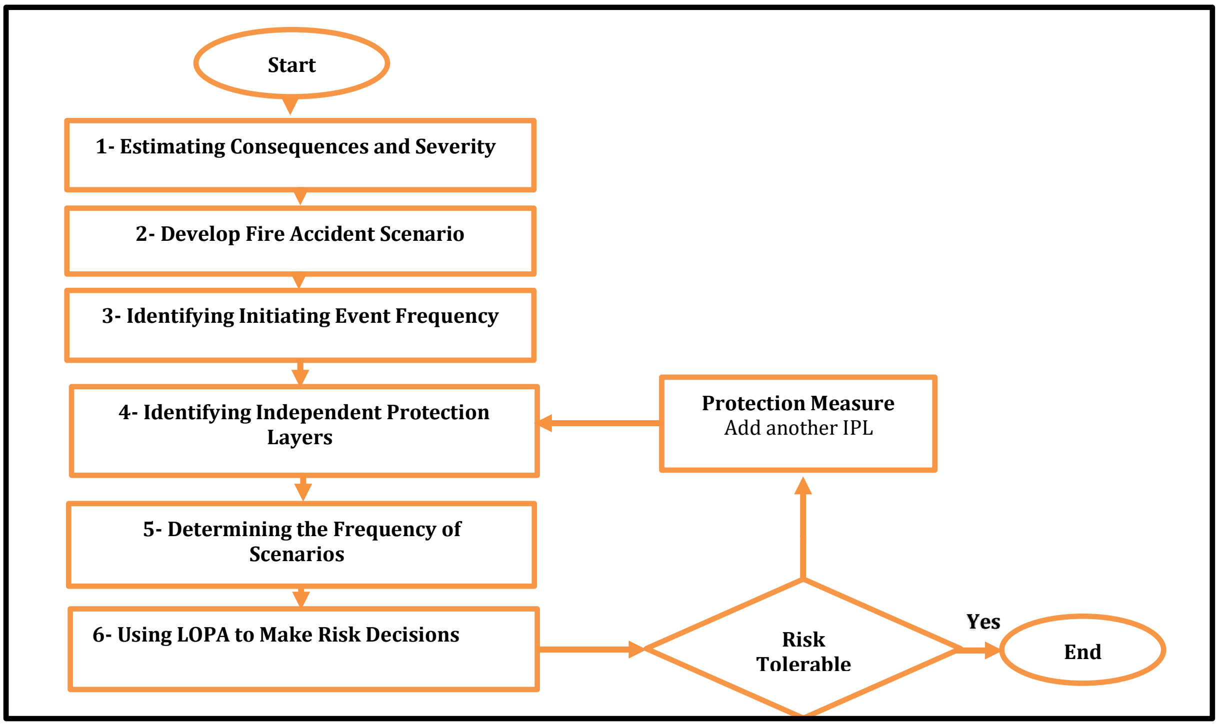

Figure 2. Summary of FPS-LOPA Steps

Step 1: Estimating Consequences and Severity

As outlined in the Center for Chemical Process Safety (CCPS, 2014), potential fire consequences such as those resulting from electrical faults like arcing, overheating or overloads are assessed using qualitative metrics. These metrics categorize severity into five levels: minimal, low, medium, high, and very high. This classification reflects the potential degree of harm to personnel, the surrounding community, the environment, and facility infrastructure. The inputs used in Table 1 are directly adapted from the CCPS guidelines to ensure consistency with internationally recognized risk assessment practices.

Table 1. Qualitative Categorization (Combined Loss Categories)

	Minima Consequences	Low Consequences	Medium Consequences
Personnel	Negligible	Minor or no injury.	Single injury, not severe.
Community	Negligible	No injury, hazard, or annoyance to public	Odor or noise complaint from the public
Environment	Negligible	Recordable event with no agency notification or permit violation	Release that results in agency notification or permit violation
Facility	Negligible	Minimal equipment damage.	Some equipment damage
		High Consequences	**Very High Consequences**
Personnel		One or more severe injuries	Fatality or permanently disabling injury
Community		One or more minor injuries	One or more severe injuries
Environment		Significant release with serious offsite impact	Significant release with serious offsite impact and more likely than not to cause immediate or long-term health effects
Facility		Major damage to process area(s)	Major or total destruction of process area(s)

Source: Adapted from Center for Chemical Process Safety (CCPS, 2014). Guidelines for Initiating Events and Independent Protection Layers in Layer of Protection Analysis. American Institute of Chemical Engineers.

Step 2: Developing Fire Accident Scenarios

Fire accident scenarios are methodically constructed using hazard identification, historical event analysis, and event tree methods. Each scenario includes initiating along with Independent Protection Layers (IPLs), providing clarity for scenario assessment and documentation.

Step 3: Identifying Initiating Event Frequency

The annual frequency (F_annual) of fire initiating events is calculated using historical data:

$$F_{annual} = F/T \quad (1)$$

Where: F: Number of historical initiating events and T: Time period analyzed (years)
Event frequency adjusted for operational risk period:

$$F(event/year) = (\lambda)\ x\ (time\ at\ risk\ in\ hr\ /\ 8760\ hr) \quad (2)$$

Where λ is the failure rate.

Step 4: Identifying Independent Protection Layers (IPLs)

Reliability of each IPL is quantified using probability of failure on demand (P_{fod}) and probability of success (P_{sod}):

$$P_{sod} = 1 - P_{fod} \quad (3)$$

Reliability (R) of IPL systems over operational time (t) is expressed as:

$$R = e^{\wedge} (-\lambda t) \tag{4}$$

Where (R) is reliability, λ is the failure rate, and (t) is the period of operation.
Reliability assessments rely on historical operation data, fire statistics, and failure rate from databases sheet.

Step 5: Determining Scenario Frequency

The Independent Fire Protection Layer $(IFPL)$ frequency is determined by multiplying the initiating event frequency with the probability of Independent Protection Layer (IPL) success and failure on demand (P_{fod}) as per Equation (5) and (6).

$$f_i^c = f_i^1 x \prod_{j=1}^{J} P_{fod_{ij}} \tag{5}$$

$$= f_i^1 x\, P_{fod_{i1}} x\, P_{fod_{i2}}\ x \ldots x\, P_{fod_{ij}} \tag{6}$$

Where f_i^c is the final scenario frequency, f_i^1 is the initiating event frequency, and $\prod_{j=1}^{J} P_{fod_{ij}}$ is the product of IPL failure probabilities.
This includes Eq. (7) that determines the frequency of a fire for a single scenario for a single system

$$f_i^{fire} = f_i^1 x \prod_{j=1}^{J} P_{fod_{ij}}\ x\, P^{\,ignition} \tag{7}$$

Eq. (8) can be used to determine the frequency of a person exposed to a fire in a residential building.

$$f_i^{fire\ exposure} = f_i^1 x \prod_{j=1}^{J} P_{fod_{ij}}\ x\, P^{\,ignition}\ x\, P^{\text{ person exposed}} \tag{8}$$

Where each probability represents ignition likelihood and human presence probability.
The final risk index is determined as:

$$R_K^C = f_K^C\ x\ C_K \tag{9}$$

Where R_K^C is the risk index for an outcome, is the frequency of the outcome, and represents consequence severity (e.g., fatalities, financial losses).

Step 6: using LOPA to make risk decisions

If calculated risks exceed acceptable criteria Table 1, measures such as increasing IPL reliability, introducing new IPLs, or system design modifications are implemented. Risk matrices visually facilitate decision-making and prioritization. This refined FPS-LOPA methodology integrates robust historical analysis, quantitative reliability assessments, and structured decision-making frameworks. It provides a clear, objective, and regulatory-aligned approach to managing residential electrical fire risks effectively.

3.2 Designing and Develop the Framework

The final stage of the data analysis in this study is to propose the electrical fire risk assessment framework for the residential buildings in the Sultanate of Oman. This electrical fire risk assessment framework is designed to enhance the safety and compliance practices so that it is consistent with the relevant legislation. The proposed framework will consider the identified hazards and risks, as well as existing legislation and policy guidelines. The framework will also include recommendations for mitigating identified risks through the implementation of appropriate engineering and administrative controls. The framework prescribes a thorough identification of potential electrical fire scenarios specific to residential settings. This includes systematic listing of possible ignition sources (e.g. faulty wiring, overloaded circuits, appliance failures) and contributing factors (such as lack of maintenance, high ambient temperatures, or improper installations common in Oman's context). The identified hazards then inform the risk analysis stage. For risk analysis, the framework integrates the (LOPA) concept advocated by the Center for Chemical Process Safety (CCPS) to evaluate scenario risk in a semi-quantitative manner. (LOPA) offers a middle ground between purely qualitative and fully quantitative analyses by examining each credible fire scenario with its initiating event frequency, potential consequences, and existing independent protective layers (e.g. circuit breakers, smoke alarms, fire extinguishers)

By using engineering rules to estimate the likelihood of electrical fire incidents and the effectiveness of protection layers, the framework can prioritize risks in an order of magnitude sense. This approach complements risk matrices and aligns with the best international practices for fire risk engineering, where multiple safeguard layers are considered to prevent or mitigate fire outbreaks. The system design of the initial framework was thus both comprehensive and contextualized. It delineated clear steps from hazard identification through risk evaluation. In the risk evaluation step, the framework requires comparing the analyzed risk levels against acceptable risk criteria, drawing on the (LOPA) principle and any applicable local fire safety standards. If a risk was found to exceed acceptable thresholds, the framework outlined risk treatment measures ranging from engineering controls (e.g. upgrading electrical components, adding surge protectors) to administrative controls (e.g. improved inspection regimes, public awareness for safe appliance use). Throughout these steps, feedback incorporation was anticipated as part of the framework's engineering structure. Each step generated documentation and data (such as hazard logs, risk ratings, recommended controls) that would later be reviewed and adjusted based on real-world insights. Thus, the initial framework was not a static scheme; it included provisions for monitoring and review, echoing the continuous improvement ethos of ISO 31000 and NFPA guidelines to "monitor the risk" and update risk assessments as conditions change. By the end, a theoretical framework was in place one that was built on proven risk identification principles, structured methodically, and tailored to address electrical fire risks in Omani homes.

4. RESULTS AND DISCUSSIONS

This section presents the findings and discussion of the proposed electrical fire risk assessment framework, outlined in section (4.1), followed by its develop the framework in section (4.2) in alignment with Omani laws and regulations for residential building safety.

4.1 Fire Risk Analysis Results for Lighting-Related Faults

Lighting systems were identified as critical sources of electrical fires through forensic inspection (2018–2020), mainly due to overloads, arc faults, and overheating failures. figure (3) summarizes the incident distribution:

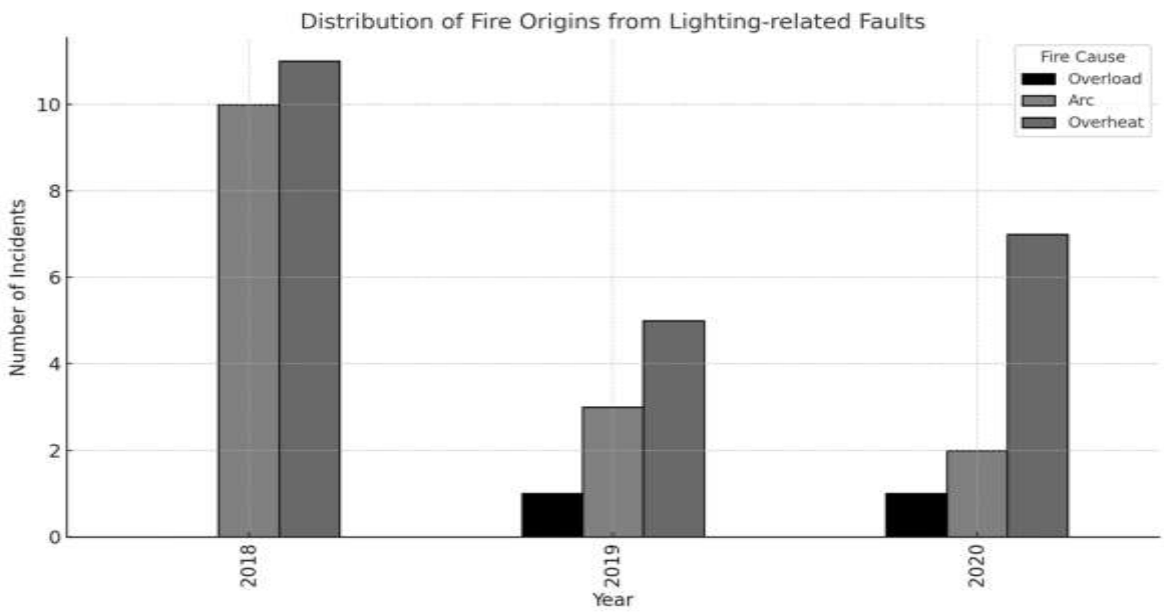

Figure 3. Distribution of Fire Origins from Lighting-related Faults

4.1.1 Scenario Development

Three representative electrical fire scenarios were developed based on common initiating events observed in residential lighting systems. These scenarios reflect frequent failure modes, such as poor wiring, circuit overload, and overheating components, which are critical to fire ignition. Figure (4) shows the types of faults. Each scenario serves as a foundation for the subsequent LOPA-based risk assessment:

- Scenario 1 (Wires Arcing): Initiating event is degradation of wiring causing shorts and ignition.
- Scenario 2 (Overload): Initiating event is excessive current due to substandard connections or circuit breaker failures.
- Scenario 3 (Overheating): Initiating event is failure of internal lamp components generating excessive heat.

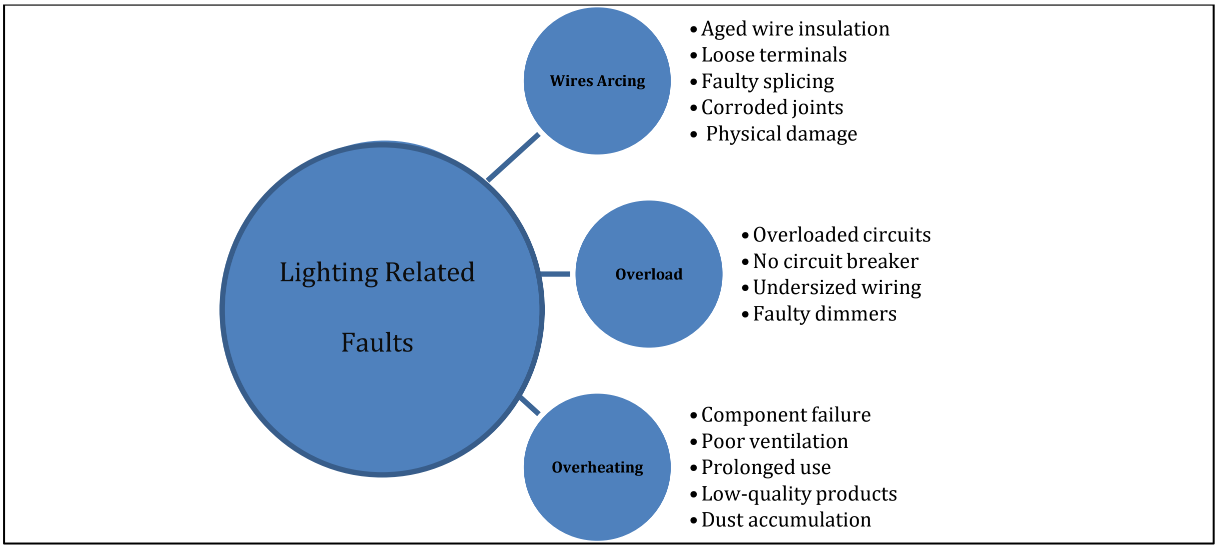

Figure 4. The potential undesired consequences for Lighting-related Faults

4.1.2 Frequency Analysis

Initiating Event Frequencies (F_annual) were calculated by use equation (1) for three years.

Table 2. Initiating Event Frequencies for single scenario

Initiating Event	Annual Frequency (events/year)	Scientific Notation
Overload	0.66 ÷ 3 = 0.22	10×10^{-1} event / year
Arc	15 ÷ 3 = 5.0	50×10^{-1} event / year
Overheat	23 ÷ 3 = 7.6	80×10^{-1} event / year

Accident frequencies (*fc*) were calculated using eqn 5, which considers the annual initiating event frequency and the probability of failure on demand (P_{fod}) for each independent protection layer. The selected protection layers (CB), (SPD), and (SD) have respective failure probabilities of 0.18, 0.05, and 0.35 Figure 5 shows that.

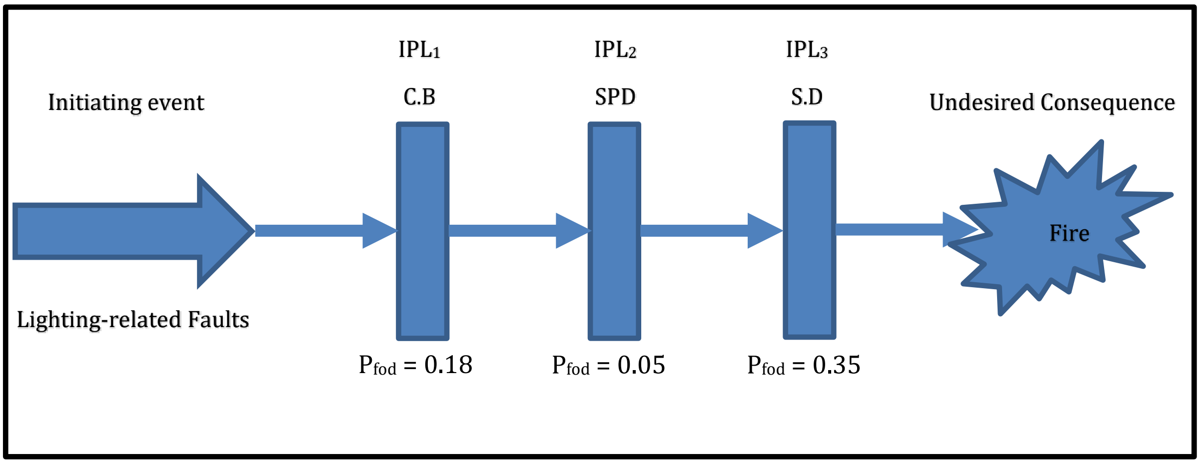

Figure 5. The potential undesired consequences for Lighting-related Faults

The combined P_{fod} value of 0.00315 reflects the cumulative likelihood of failure across all layers.

Where combined ${P_{fod}}_{\text{CB}} = 0.18$, ${P_{fod}}_{\text{C.B}}$ x 0.05, ${P_{fod}}_{\text{SPD}}$ x 0.35 $P_{S.D}$ = 0.00315

Accident frequencies (*fc*) were determined using eq. 5, table 3 shows the results of each accident frequencies scenarios (Smith, J. (2020)).

$$f_c = \text{F}_{\text{annual}} \times {P_{fod}}_{\text{CB}} \times {P_{fod}}_{\text{SPD}} \times {P_{fod}}_{\text{SD}}$$

Table 3. Frequency of a fire for a single scenario

Cause	f_c (accidents/year)	Scientific Notation
Overload	0.66 × 0.00315 = 0.0021	2.1×10^{-3} event / year
Arc	5 × 0.00315 = 0.0157	1.57×10^{-2} event / year
Overheat	7.6 × 0.00315 = 0.0239	2.39×10^{-2} event / year

4.1.3 Person Exposure Risk

To determine the risk index for the desired outcome, this study considers the level of exposure individuals face, previously assessed at 30%. Eq. 8 is employed for this purpose, determining the frequency of person-exposure to fire within a residential setting. Table 4 shows the results of each accident scenario.

$$f_i^{Fire\ Exposure} = f_i^1 \ x \prod_{j=1}^{J} P_{fod_{ij}} \ x \ P^{Ignition} \ x \ P^{Person\ Exposed}$$

Table 4. Person Exposure Risk single scenario

Cause	$f_i^{Fire\ Exposure}$ (accidents/year)	Scientific Notation
Overload	0.0021 × 0.3 = 0.00063	6.3 x 10^{-4} event / year
Arc	0.0157 × 0.3 = 0.00471	4.71 x 10^{-3} event / year
Overheat	0.0239 × 0.3 = 0.00717	7.17 10^{-3} event / year

4.1.4 Summed Frequency

To calculate the overall annual risk of electrical fires, the frequencies of all identified scenarios were aggregated (Willey, R. J. (2014)).:

f_{Total}^{c}= 0.00063 + 0.00471 + 0.00717 = 0.0125 ≈ 1.25×10^{-2} fires/year

4.1.5 Risk Decision Based on LOPA

Based on the LOPA, the combined frequency of potential light fire events is calculated to be (0.0125) or 1.25×10^{-2} fires /year. This frequency aligns with the range of 10^{-1} fires /year to 10^{-2} fires /year, in the risk evaluation framework, which, for a **Medium Consequences** classification by refer to table 5, does not necessitate immediate action. Instead, the prescribed response is to take action at the next available opportunity. This indicates that while the scenario warrants attention, there is sufficient time to evaluate and implement appropriate mitigation measures without urgency.

Table 5. Assessment of Fire-related Risk Scenarios for Wires According to Qualitative Categorization

Consequences Category / **Frequency of Consequence per year**	**Minimal Consequences (1)**	**Low Consequences (2)**	**Medium Consequences (3)**	**High Consequences (4)**	**Very High Consequences (5)**
10^{-1}	Optional	Optional	Action at next opportunity	**Immediate action**	**Immediate action**
10-2	Optional	Optional	Optional	Action at next opportunity	**Immediate action**
10-3	No further action	Optional	Optional	Optional	Action at next opportunity
10-4	No further action	No further action	Optional	Optional	Optional
10-4	No further action	No further action	Optional	Optional	Optional
10-5	No further action	No further action	No further action	Optional	Optional
10-6	No further action	No further action	No further action	No further action	Optional

- A frequency of 1.25 \times 10-2 fires/year lies within 10-2 to 10-1.
- Action is recommended at the next available opportunity, not immediate.
- Risk is moderate and requires monitoring and future review.

4.2 Fire Risk Framework Development for Residential Buildings

This section discusses the results of the development framework, which is to develop the electrical fire risk assessment framework so that the identified risk can be minimized to an acceptable level. Figure 9 illustrates the electrical fire risk assessment framework developed in this study, meticulously devised to address the issue of electrical fires in the residential facilities. The primary objective of this framework is to conduct an in-depth evaluation of hazards possibilities, as well as identifying potential risks and vulnerabilities within the context of residential settings.

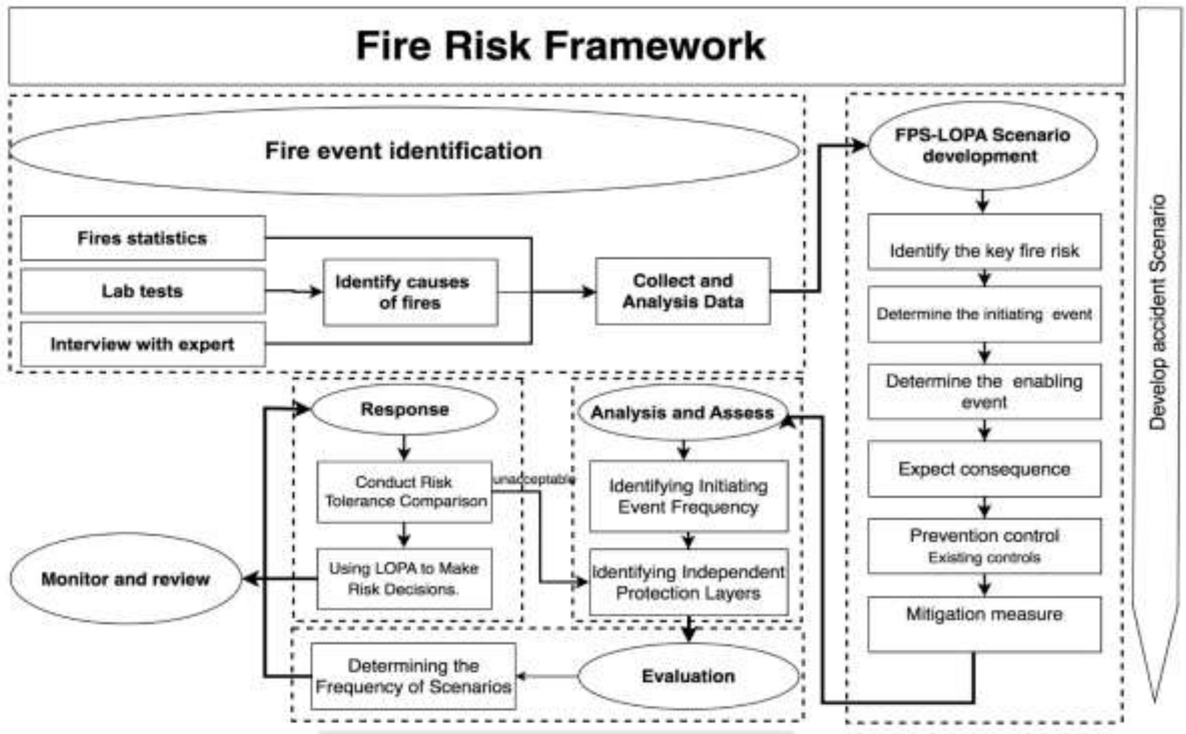

Figure 9. Electrical Fire Risk Assessment Framework

4.2.1 Fire Event Identification

In the first stage, all potential fire initiating events in a residential building are identified and documented. This involves gathering empirical data and expert knowledge on how fires start for example, reviewing fire incident statistics, conducting laboratory fire inspection. By analyzing this information, engineers can identify the causes of fires most relevant to the building and estimate how often each cause might occur. Quantitatively, an initiating event frequency is assigned to each cause based on historical evidence. If an event has been observed F times over a period years, its annual frequency can be estimated as:

$$Initiating\ Fire\ Event\ Likelihood\ (F_{annual}) = F/T$$

4.2.2 FPS-LOPA Scenario Development

Building on the identified causes, detailed fire scenarios were developed using the FPS-LOPA approach. Each scenario was structured by defining the initiating event, enabling conditions, expected consequences, and existing safeguards by using:

$$f_i^c = f_i^1 x \prod_{j=1}^{J} P_{fod_{ij}}$$

leading to the creation of a complete set of accident scenarios that simulate realistic residential fire events based on historical failures and protection gaps.

4.2.3 Analysis and Assessment

A quantitative assessment of each fire scenario was performed, refining risks by factoring ignition probability and human exposure likelihood:

$$f_i^{Fire\ Exposure} = f_i^1 \ x \prod_{j=1}^{J} P_{fod_{ij}} \ x \ P^{Ignition} \ x \ P^{Person\ Exposed}$$

The total fire risk was determined by summing across all scenarios:

$$f^c = \sum_{i=1}^{I} f_i^C$$

4.2.4 Response

For scenarios exceeding acceptable risk thresholds, targeted risk mitigation measures were proposed, such as improving fire detection systems, reinforcing electrical circuits, or installing additional protection layers. FPS-LOPA calculations were reapplied to verify that the proposed improvements effectively reduced the fire scenario frequencies to tolerable levels, demonstrating a systematic engineering-driven risk reduction.

4.2.5 Evaluation

Following the mitigation phase, all scenarios were re-evaluated against predefined risk acceptance criteria. The evaluation confirmed that after implementing additional controls, the majority of fire scenarios were successfully brought into acceptable.

4.2.6 Monitor and Review

Finally, a monitoring and review system was developed, ensuring continuous updating of initiating event frequencies and protection layer reliability based on real-world data. The framework was designed to adapt dynamically to new incidents, operational changes, or maintenance findings, ensuring sustained and proactive fire safety management over time.

5. CONCLUSIONS AND RECOMMENDATIONS

This study demonstrated the effectiveness of using (LOPA) as a structured, semi-quantitative method to assess and prioritize electrical fire risks in residential buildings in the Sultanate of Oman. By systematically identifying hazards, calculating initiating event frequencies, and evaluating independent protection layers, LOPA enabled a clear, engineering-based risk categorization aligned with Oman's evolving safety needs. The application of LOPA in this research highlighted critical fire scenarios related to lighting systems and quantified the associated risk frequencies, providing a practical basis for informed decision-making.

Building upon these findings, the study successfully developed an adaptable electrical fire risk assessment framework tailored to Oman's residential environment. This framework integrates the structured analysis provided by LOPA with practical mitigation and monitoring strategies, ensuring that identified risks are systematically reduced to acceptable levels while maintaining alignment with local legislation and safety codes. The framework's design supports continuous improvement by incorporating real-world data for ongoing refinement, reflecting a proactive approach in managing electrical fire risks. Ultimately, the integration of LOPA into the development of this framework not only strengthens Oman's domestic fire safety infrastructure but also offers a scalable model that can be applied to other contexts requiring structured electrical fire risk management. Future research can further enhance this framework by incorporating advanced data analytics and IoT-based monitoring to support dynamic risk updates, ensuring sustained residential fire safety and resilience in the Sultanate of Oman.

REFERENCES

[1] Ajith, S., Arumugaprabu, V., Ajith, V., Naresh, K., & Sreekanth, P. R. (2022). Hazard identification and risk assessment in firework industry. Materials Today: Proceedings, 56, 1083–1085.

[2] Al-Qahtani, M., Alshahrani, S., & Alotaibi, A. (2021). Analysis of fire incidents in residential buildings in the Gulf region: Causes and preventive strategies. Journal of Safety Science.

[3] Alfalah, T., Alshammari, M., & Alzahrani, F. (2023). Application of AHP to prioritize fire safety risk factors in Saudi Arabian buildings. International Journal of Fire Science and Safety, 28(2), 150–160.

[4] Babrauskas, V. (2016). Electrical fires. In M. Hurley (Ed.), SFPE Handbook of Fire Protection Engineering (pp. 662–704).

[5] Bougie, R., & Sekaran, U. (2019). Research methods for business: A skill-building approach (8th ed.). Wiley.

[6] CCPS. (2001). Layer of protection analysis: Simplified process risk assessment. Center for Chemical Process Safety of the AIChE.

[7] CCPS. (2001). *Layer of protection analysis: Simplified process risk assessment*. Center for Chemical Process Safety of the AIChE.

[8] IAAI. (2019). Fire investigator: Principles and practice to NFPA 921 and 1033 (5th ed.). Jones & Bartlett Learning.

[9] Idris, A. M., Rusli, R., Burok, N. A., Mohd Nabil, N. H., Ab Hadi, N. S., Abdul Karim, A. H., & Mydin, I. (2020). Human factors influencing the reliability of fire and gas detection system. Process Safety Progress, 39, e12116.

[10] Mi, H., Liu, Y., Wang, W., Xiao, G., & Abdelhameed, E. H. (2020). An integrated method for fire risk assessment in residential buildings. Mathematical Problems in Engineering, 2020, 9392467.

[11] National Centre for Statistics and Information (NCSI). (2022). Statistical yearbook. Government of Oman.

[12] National Fire Protection Association. (2023). NFPA 70: National Electrical Code (NEC). National Fire Protection Association.

[13] Omar, H., Al Rawahi, N., & Al-Harthy, A. (2023). Fire safety practices in Omani residential buildings: Challenges and opportunities. Journal of Fire Protection Engineering, 32(1), 45–60.

[14] Pawolocki, F. J. (2021). Layer of protection analysis as auxiliary technique in process safety incident investigations. Process Safety Progress, 40, S13–S23.

[15] Public Authority for Civil Defence and Ambulance (PACDA). (2022). Annual fire safety report. Muscat, Oman.

[16] Shokouhi, M., Zolfaghari, M., & Moradi, A. (2019). Investigating causes of residential fires and prevention strategies. International Journal of Safety and Security Engineering, 9(3), 210–219.

[17] Smith, J. (2020). Fire safety engineering: Principles and applications. Routledge.
[18] Tawalbeh, N., & El-Khazali, R. (2020). Analysis and evaluation of electrical wiring safety requirements in Jordanian residential buildings. IEEE Jordan Conference on Applied Electrical Engineering and Computing Technologies (AEECT) (pp. 1–5). IEEE.
[19] Wallington, T. J. (2016). Residential fire safety: Global perspectives and lessons for Oman. *Fire Science Review*, 5(2), 87–95.
[20] Willey, R. J. (2014). Layer of protection analysis. *Procedia Engineering*, *84*, 12-22. https://doi.org/10.1016/j.proeng.2014.10.405.
[21] Xing, J., & Huang, C. (2013). Fire risk analysis of residential buildings based on scenario clusters and its application in fire risk management. *Fire Safety Journal*, 62, 72-78.
[22] Xu, W., & Zammit, K. (2020). Applying thematic analysis to education: A hybrid approach to interpreting data in practitioner research. *International Journal of Qualitative Methods*, *19*, 1609406920918810.
[23] Yousef, R., Ahmed, A., & Jassim, H. (2022). Residential fire risks in developing countries: A survey of high-rise buildings. *Fire Technology*, 58(4), 1941–1963. https://doi.org/10.1007/s10694-021-01156-2.
[24] Zhang, C. (2023). Review of structural fire hazards, challenges, and prevention strategies. *Fire*, *6*(4), 137-144.