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Risk Analysis of Electrical Fires in Residential Buildings in Oman Using Layer of Protection Analysis (LOPA)

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ABSTRACT

Electrical fires are a significant global issue, resulting in injuries, fatalities, and extensive property damage. In Oman, the risk of electrical fires is particularly high due to overcrowded urban areas, which increase the likelihood of such incidents. This study uses the Fire Protection System-Layer of Protection Analysis (FPS-LOPA) to assess fire hazards and risks, focusing on the effectiveness of current safety measures in preventing electrical fires. LOPA is a risk assessment tool that systematically evaluates various protective layers, such as circuit breakers and smoke alarms, to understand their role in mitigating electrical fire risks. The study highlights the methodical examination of these protective measures and recommends improvements for enhanced fire prevention in residential settings. The findings demonstrate that LOPA provides accurate risk calculations and reliable results, proving its efficacy in reducing electrical fire risks. Implementing the suggested safety measures can significantly improve resident safety and mitigate fire hazards. The study proves that LOPA is a good way to manage fire risks because it offers a balanced plan that includes cutting-edge options while also reducing risks and making things safer.

Keywords: Electrical Fires, Layer of Protection Analysis (LOPA), & Risk Analysis.

1. INTRODUCTION

Life safety in buildings has been recognised to be a high priority for many organisations, such as the government and the private sector, to protect human life, property, the surrounding environment, and business operation. Reviews on the fire risk assessment of residential buildings have been conducted in China (Mi et al., 2020; Xin & Huang, 2014), Iran (Shokouhi et al., 2020), Jordan (Tawalbeh & El-Khazali, 2020), Poland (Chmielewski & Bak, 2021), and Malaysia (Manan et al., 2020; Zakaria et al., 2019).

In Oman, the electrical fires originating from residential buildings are constantly growing during the period of 2014 to 2017 and decrease onwards but are still high. The increment in these electrical fire cases tend to be alarming to the government. Therefore, this research is focusing on the electrical fire risk assessment in the residential building in the Sultanate of Oman, specifically in the different governorates of Oman. The reason for considering different governorates is to identify the differences in the root causes of electrical fires and how the government's fire safety protection program influences the scenario of fires. It includes the root causes of fires, risk mitigation, risk response and control activities, and monitoring and reviewing the regulating laws as well.

Several fire risk analysis methods have emerged, such as FiRECAM™ (Fire Risk Evaluation and Cost Assessment Model) (Wang et al., 2021), the FIERA system (Fire Evaluation and Risk Assessment system) (Benichou et al., 2005), CESARE-RISK (Centre for Environment Safety and

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Risk Engineering, RISK) (Ishola et al., 2020), and the analytical hierarchy method (AHP) (Lee et al., 2020). However, these models should depend on some strict constraints, such as a large number of input data, specific fire scenarios, and a large number of calculations. This study is concentrating on developing a fire risk analysis tool based on the layer of protection analysis (LOPA). For example, recently Amini et al. (2022) presented a fire risk method based on the LOPA for a central insurance building in Iran. According to Fang et al. (2019), LOPA is a useful technique for prioritising hazards when they correspond to the most economical solutions to satisfy risk tolerance requirements.

2. METHODOLOGY -LOPA: DEVELOPMENT OF RESEARCH MODEL

Once the fire risk is analysed, the layer of protection analysis (LOPA) is conducted. The LOPA process entails identifying the initiating events, evaluating the layers of safety-related controls that are already in place or that are being proposed, and establishing tolerable frequency targets for exposure to people, property, or business interruption (Pawolocki, 2021). Figure 1 summarises the LOPA steps conducted in this study. Focusing on the evaluation of fire protection systems, fire protection system-layer of protection analysis (FPS-LOPA) is utilised. The FPS-LOPA offers a logical, objective, and straightforward method for figuring out the fire protection layers necessary for particular scenarios based on defined risk tolerance criteria (AIChE, 2001).

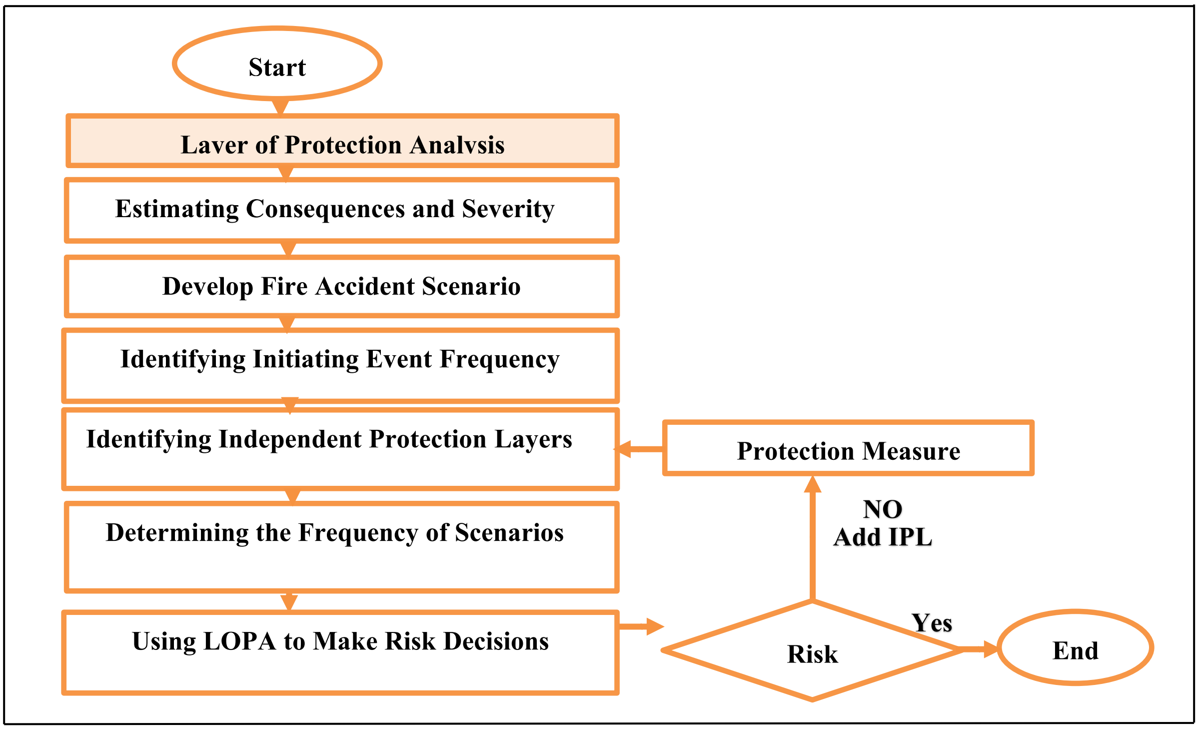

Figure 1. Summary of FPS-LOPA Steps

Step 1: Estimating Consequences and Severity

In the context of risk assessment, the outcome of an accident scenario, known as its consequence, is a critical element. In LOPA, this study gauges these consequences by categorizing them into levels of severity. This step is dedicated to exploring the different methods of analysing consequences within LOPA, and this step represents the initial stage in the LOPA methodology. Consequences encompass the adverse results arising from accident scenarios, with a primary focus in LOPA being the loss of containment involving hazardous materials or energy. Such losses can occur due to various mechanisms, ranging from electrical fires caused by arcs, overheating, and overloads to fires in residential houses and buildings.

Step 2: Develop Accident Scenario

In the context of risk assessment, the outcome of an accident scenario, known as its consequence, is a critical element. In LOPA, this study gauges these consequences by categorising them into levels of severity. This step is dedicated to exploring the different methods of analysing consequences within LOPA, and this step represents the initial stage in the LOPA methodology. Consequences encompass the adverse results arising from accident scenarios, with a primary focus in LOPA being the loss of containment involving hazardous materials or energy. Such losses can occur due to various mechanisms, ranging from electrical fires caused by arcs, overheating, and overloads to fires in residential houses and buildings.

In the developing accident scenario, the high-risk scenario will be used as the accident scenario of the LOPA analysis. When an accident scenario is identified as a candidate for a fire risk evaluation, it must be developed more thoroughly and recorded so that the initiating events, enabling events, and independent fire protection layers (IFPLs) are all understood well. Events that serve as catalysts, enablers, and IFPLs are among the crucial elements for creating FPS-LOPA scenarios. The event tree calculation approach is typically used to determine the possibility of a certain cause-and-effect situation. FPS-LOPA cause-consequence scenarios can be chosen and created based on information retrieved from hazard evaluations.

When constructing a scenario, it is imperative to identify and thoroughly document each crucial step that paves the way from the initiating event to the ultimate consequence. Every factor that could have an impact on the numerical calculation of consequence frequency or size, as well as its type, must find its place in documentation.

Step 3: Identifying Initiating Fire Event Frequency

The objective of these steps encompasses two primary facets. First, it provides guidance on identifying true initiating causes (called initiating events) of incident scenarios within the framework of LOPA. Second, it provides guidance on estimating the frequency of initiating events. The formula for calculating initiating fire likelihood (fire/year) can be expressed as Eq. (1) AIChE. (2014).

$$\text{Initiating Fire Event Likelihood } (F_{annual}) = F/T \tag{1}$$

Where:
F_{annual} is the initiating fire event likelihood within the one-year time frame;
F is the estimated frequency (in this case, historical data); and
T is the time frame (in this case, 3 year).

Step 4: Identifying Independent Protection Layers

Fire protection systems (FPS) are often assessed based on their likelihood of working as planned (such as meeting their functional performance requirements), and it can be either a probability of success or failure. The probability of failure (Pfod) of a fire prevention system refers to the chance that a protective measure will fail to reduce the impact of a fire. Eq. (2) shows the formula of probability of success (Psod) AIChE. (2001).

$$P_{sod} = 1 - \text{Likelihood of Failure} \tag{2}$$

Based on the likelihood that the FPS will achieve its functional performance goals in FPS-LOPA, this study assesses the performance reliability of that FPS. This is accomplished in the following ways: first, to meet the functional performance goals for the particular FPS-LOPA scenario, historical operational reliability data (statistical data from fire investigation team records, lab data, generic databases, and published equipment or component failure rate data) will be used, along with an analysis of the design effectiveness or by employing qualitative event tree analysis (ETA), the elements that contribute to the success or failure of the IFPL are determined.

Therefore, a device, system, or course of action is considered to be an independent fire protection layer (IFPL) if it can stop a fire accident scenario from progressing to the level of unintended consequences regardless of how frequently initiating events occur or how any other associated fire protection layers respond to the scenario. An IFPL must be auditable for efficiency and impartiality. It has been determined through the audit process that the IFPL design, installation, functional testing, and maintenance system are sufficient to meet the desired performance reliability for the IFPL.

Calculating the IFPL in a residential house involves assessing its reliability and effectiveness in preventing or mitigating fire-related consequences by using equation Eq. (3) AIChE. (2014).

$$IFPL = R \times E \tag{3}$$

Where R represents reliability and E refers to effectiveness.

Stage 1: Determine Reliability (R)

Reliability measures the probability that an IPL will function as intended when needed. It accounts for factors like failure rates, testing, and maintenance. It is a critical factor because even a highly effective layer is of little value if it's not reliable. It is often assessed through testing and historical data. Eq. (4) can be used to calculate reliability (AIChE, 1993).

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

Where, λ represents the failure rate per unit of time and t refers to the time period of interest (e.g., one year).

Stage 2: Determine Effectiveness (E)

Effectiveness measures how well the IPL mitigates fire-related consequences. This involves evaluating factors like response time and success rate in preventing fires. Effectiveness is typically expressed as a probability, ranging from 0 to 1.

Stage 3: Calculate IFPL

The probability of failure on demand (Pfod) is calculated as the complement of the probability of success. Since the Independent Fire Protection Layer (IFPL) represents the probability of success (the combined reliability and effectiveness of the system), the Pfod is can be calculated simply as in Eq. (5), AIChE. (2001).

$$\text{Probability of Success} = 1 - P_{\text{fod}} = 1 - IFPL_{\text{fod}} \tag{5}$$

Step 5: Determining the Frequency of Scenarios

ETA assesses the possible results based on sequences of success and failure events triggered by initiating events, which are usually incidents. In an event tree, when the fire incident starts, the fire is initially low and non-toxic but quickly becomes denser and poisonous, leading to three potential types of incidents, namely, small low-exposure fire, controlled fires (toxic release), or uncontrolled high-exposure fires. Risk assessment involves determining the likelihood of each scenario, usually by considering the initial event's frequency (ignite fire) and then factoring in the chances of subsequent events.

Once the reliability and effectiveness results have been obtained, then it can sum these values using Eq. (7) to calculate the independent fire protection layer (IFPL). In this scenario, this study calculates the frequency by multiplying the initiating event frequency by the combined product of the IFPL and PFD values. Willey, R. J. (2014)

$$f_i^c = f_i^1 x \prod_{j=1}^{J} P_{fod_{ij}} \quad (6)$$

$$= f_i^1 x \, P_{fod_{i1}} x \, P_{fod_{i2}} \; x \ldots x \, P_{fod_{ij}} \quad (7)$$

Where,
f_i^c is the frequency for consequence C for initiating event i;
f_i^1 is the initiating event frequency for initiating event i; and
$P_{fod_{ij}}$ is the probability of failure on demand of the IFPL that protects against consequence C for initiating event *i*.

Calculating the Frequency of Additional Outcomes

There are two primary approaches to frequency calculation. The first involves focusing solely on quantifying the release frequency. The second approach encompasses establishing risk tolerance criteria for various potential outcomes. Consequently, organisations may opt to integrate the frequencies of these additional outcomes into their calculations of flammable effects such as fire or explosion, toxic effects where applicable, exposure to flammable or toxic effects, and injury or fatality.

To calculate the frequency of such outcomes, Eq. (8) is modified by multiplying the frequency of the release scenario by the appropriate probabilities for the outcome of interest. This includes Eq. (10), which determines the frequency of a fire for a single scenario for a single system. (Willey, R. J. (2014)).

$$f_i^{fire} = f_i^1 x \prod_{j=1}^{J} P_{fod_{ij}} \; x \, P^{\,ignition} \quad (8)$$

Eq. (9) can be used to determine the frequency of a person exposed to a fire in a residential building (Willey, R. J. (2014)).

$$f_i^{fire\ exposure} = f_i^1 x \prod_{j=1}^{J} P_{fod_{ij}} \; x \, P^{\,ignition} \; x \, P^{\text{ person exposed}} \quad (9)$$

Calculating Risk

If a risk index is the desired outcome, the frequency of the outcome of interest is multiplied by a factor related to the magnitude of the consequence. Eq. (10) can be used to calculate risk (Willey, R. J. (2014))

$$R_K^C = f_K^C \; x \; C_K \quad (10)$$

Where,
R_K^C is the risk index of incident outcome of interest k, expressed as a magnitude of consequences per unit time. Specific units will vary depending on the risk being estimated. Some examples might include risk of fatality per year, number of fatalities per year, dollars of economic loss per month, pounds of pollutant released per day;

f_K^C is the frequency of the incident outcome of interest k, in inverse time units, e.g., year-1, hour ‘, etc.; and

C_K is a specific measurement of the consequences of the incident outcome of interest k. Some measures of the consequences might be an individual fatality, number of fatalities, dollars of economic loss, pounds of release of a pollutant, and number of people exposed to a specific concentration of an air pollutant.

Summing Up Frequencies for Multiple Scenarios

When multiple risk criteria are in play, it becomes imperative to aggregate the frequencies from various scenarios that impact the resulting consequences. This involves individual evaluations of each scenario using Eq. (11), as different Independent Protection Layers (IPLs) may be applicable to distinct scenarios, even if the ultimate consequences are the same (Willey, R. J. (2014)).

$$f^c = \sum_{i=1}^{I} f_i^C \tag{11}$$

Whereby, $f_i^C = f_1^C + f_2^C + \cdots + f_I^C$

Where, f_i^C is the frequency of the C[th] consequence for the initiating event.

Step 6: Using LOPA to Make Risk Decisions

This step outlines methods for incorporating the results obtained in the previous steps into the decision-making process regarding risk. Various methodologies can be employed to achieve risk levels that are considered 'as low as reasonably practicable,' which is synonymous with acceptable risk level. The following section delves into several numerical criteria-based approaches as well as a method relying on expert judgement provided by an analyst.

Once the scenarios are thoroughly developed and the existing risk is quantified as outlined in preceding steps, the decision-making phase ensues. Decisions pertaining to risk typically align with one of three overarching categories:

a) Residual Risk Management: Maintain existing risk levels through established management systems, assuming they are within tolerable limits.
b) Risk Mitigation: Implement modifications or measures to bring risk to a tolerable level.
c) Risk Abandonment: Consider discontinuing a specific business or process due to excessive risk levels.

LOPA is typically employed to ascertain whether a scenario aligns with predefined risk tolerance criteria or if risk reduction is warranted. There are three fundamental approaches to assessing risk within the LOPA framework, which are as follows:

a) Quantitative Comparison: The primary approach involves comparing the calculated risk against established risk tolerance criteria.
b) Expert Judgement: A secondary method involves the expert judgement of a qualified risk analyst.
c) Relative Evaluation: The third method involves comparing the relative risks of competing alternatives for risk reduction, utilising one of the aforementioned quantitative or expert judgement methods.

Comparing Calculated Risk to Scenario Risk Tolerance Criteria

For this particular approach to risk decision-making, the risk calculated in step 6 is evaluated against specific risk criteria that pertain to the maximum acceptable risk per scenario. These criteria can manifest in various forms, such as a risk matrix, maximum permissible risk per scenario, or stipulated requirements regarding the number of Independent Protection Layers (IPLs), factoring in the frequency of initiating events and the severity of potential consequences.

When the calculated risk falls below the risk criteria, it is deemed to have reached a sufficiently low level or to possess ample mitigation measures (or IPLs), obviating the need for further risk reduction. Conversely, if the calculated risk surpasses the stipulated risk criteria, it necessitates additional or more robust risk mitigation measures (IPLs) or a redesign of the process to enhance inherent safety. This redesign aims to reduce the frequency or severity of the scenario or, ideally, eliminate it altogether. In scenarios where the risk criteria are unclear or where the suggested mitigation or design changes are intricate or cost-intensive, further analysis.

Risk matrices are favoured in a specific type of risk assessment because they provide a visual representation of acceptable scenario frequencies based on consequence severity and frequency of occurrence. They offer clear delineation of scenario risk, both visually and numerically, accommodating an organisation's specific risk tolerance values. Risk matrices are precise, making them well-suited for use with the LOPA method, which simplifies assumptions. They streamline decision-making as they assess one scenario at a time.

Make Decisions on Risk Reduction

The next consideration is whether additional protective measures should be in place. If risk reduction is needed, consideration can be given to reducing the frequency of the human failure initiating event by providing additional protective measures. FPS-LOPA can offer a fire protection layer that has to be upgraded to reach a tolerable risk level based on the absolute worst-case risk (assuming all fire protection layers fail) and mitigated risk as-is (with existing or proposed fire protection layers in place). If the risk tolerance thresholds are not met, it is suggested that there is a need to improve the current (or proposed) IFPLs (for example, increased performance reliability), add additional independent levels of fire protection, or it could be necessary to use both at once.

3. RESULTS

This section adapts the Layer of Protection Analysis (LOPA) to evaluate and improve fire safety in residential buildings in Oman. LOPA, a risk assessment tool, is applied here to systematically assess electrical fire hazards by analysing protective layers, such as circuit breakers and smoke alarms, to evaluate their effectiveness and recommend improvements. By focusing on electrical fire risks, this study aims to identify and address potential hazards within homes. Table 1 presents data on the causes of residential electrical fires in Oman from 2018 to 2020, primarily involving lighting, air conditioners, and faulty wiring. This data is derived from forensic laboratory analyses.

Table 1 Distribution of Electrical Fires Causes by Types of Electrical Appliances

Years	2018	2019	2020	Total
Light	40	12	15	67
Air Conditioner	23	23	19	65
Wires	24	15	21	60

Table 1 categorises fire origins from wiring faults investigated between 2018 and 2020, which were examined by the forensic laboratory, highlighting defects, deterioration, insulation damage, and faulty connections. It aids in understanding wiring-related fire causes. The next sub-sections discuss the application of LOPA for each of these electrical devices, which are wires, air conditioners, and lights. Referring to Table 1, the reduction in fire incidents from 2018 to 2019, and the relative stability in 2020, could be partially attributed to the COVID-19 pandemic. During lockdowns, increased home occupancy likely led to earlier detection and resolution of electrical faults, preventing minor issues from escalating into major fires. The greater presence of individuals at home may have also contributed to more timely maintenance, reducing the risk of undetected hazards. Despite a rise in electricity usage due to remote work and online learning, prompt intervention appears to have limited the severity of fire incidents. This trend highlights the significance of fire awareness and rapid response in mitigating residential fire disasters.

The LOPA analysis pinpoints an electrical wire failure as the initial event that leads to overheating and potential ignition. Consequences of such an event could include extensive damage, injuries, or fatalities. This safeguard will be thoroughly evaluated in the LOPA process's sixth step to confirm its reliability and capacity as an IPL. In this particular case, the LOPA scenario is characterised by a singular initiating event, typically quantified in terms of occurrences per year. Eq. (1) is used to calculate the initiating fire event likelihood per year. Relevant data for this metric can be sourced from Table 2.

Table 2 Distribution of Fire Origins from Wiring Faults of Wires, Air Conditioner-related Faults and Lighting-related Faults

Wire's Fire Causes	**2018**	**2019**	**2020**	**Total**
Overload	2	7	9	**18**
Arc	8	5	5	**18**
Overheat	8	2	7	**17**
Total	**18**	**14**	**21**	**53**
Air Conditioner's Fire Causes	**2018**	**2019**	**2020**	**Total**
Overload	0	4	5	**9**
Arc	6	7	2	**15**
Overheat	8	8	8	**24**
Total	**14**	**19**	**15**	**48**
Lights	**2018**	**2019**	**2020**	**Total**
Overload	0	1	1	**2**
Arc	10	3	2	**15**
Overheat	11	5	7	**23**
Total	**22**	**9**	**10**	**40**

Step 1: Estimating Consequences and Severity

The study uses historical data to quantify fire incident consequences, with a qualitative classification for "very high consequences". Referring to Table 3, it shows the distribution of injuries due to electrical fires in residential buildings (Crime Scene Report, 2020). Table 4 displays the qualitative categorization (AIChE, 2001).

Table 3 Distribution of Injuries and Fatalities due to Electrical Fires in Residential Building

Types of Faults	Fatalities	Injuries
Arc	8	17
Overload	11	14
Overheat	0	9
Others	4	20

Table 4 Qualitative Categorization (Combined Loss Categories)

Very High Consequences	
Personnel	Fatality or permanently disabling injury
Community	One or more severe injuries
Environment	Significant release with serious offsite impact and more likely than not to cause immediate or long-term health effects
Facility	Major or total destruction of process area(s) at an estimated cost greater than $10,000,000 or a significant loss of production

Step 2: Develop Accident Scenarios

By analysing the data and fire origins as determined by forensic laboratory investigations, it can consolidate the understanding of the fire's causes, its outcomes, and the measures that can mitigate such incidents. Table 5 distils these findings into a clear and comprehensive report of the results.

Table 5 Findings of an Accident Scenarios.

Scenario	Initiating Event	Potential Consequences	Mitigation Measures
Overload	Electrical arcing from loose or corroded connections	Arcing causes overheating, leading to potential fire hazards, property damage, and safety risks	- Arc Fault Circuit - Interrupters (AFCI) - Regular inspections - Thermal imaging
Arc	Excessive current drawn by devices or circuits	Circuit overheating, leading to equipment failure, wire insulation melting, and fire ignition	- Circuit breaker - Overcurrent protection devices (OCPD) - Load management
Overheat	Prolonged exposure to high temperatures in wires	Overheating of wires or components leads to insulation degradation, system failure, and potential fire	- Thermal cut-offs - Proper ventilation - Routine maintenance and inspections

These issues commonly occur in electrical wiring in homes and are further validated through laboratory testing.

Step 3: Identifying Initiating Fire Event Frequency

This step identifies initiating events for fire scenarios within the LOPA framework and estimates their frequency.

Initiating Events

The initiating event is measured annually using Equation 1 and data from Table 2. Table 6 presents the frequency of fire events caused by wiring faults in Omani residential buildings, highlighting the top three initiating events from past incidents.

Table 6 Annual Frequency of Event by Year (Wires)

Initiating Event	Frequency Range in Decimal	Frequency Range in Scientific Notation
Overload	6 events / year	60×10^{-1} event / year
Arc	6 events / year	60×10^{-1} event / year
Overheat	5.67 events / year	50×10^{-1} event / year
Total	**17. 6 events / year**	

Step 4: Identifying Independent Protection Layers

The study first evaluates the Independent Fire Protection Layer (IFPL) of a residential circuit breaker, assessing its reliability in preventing or mitigating fire risks. Circuit breakers, which interrupt excessive current, are crucial for fire prevention. The Schneider formula is used as a safety benchmark. The reliability calculation involves three factors: time (1 year), failure proportion (10%), and average failures (National Fire Protection Association. (2023) & DeDad (2006))

Calculation of Reliability R(t)

Reliability is calculated using the exponential decay formula as equation 4, which results in 90.48%.

$$R = e^{-0.1x1} = 0.9048$$

Determine of Effectiveness (E)

Effectiveness (E) is calculated based on the average number of successful operations. Since this study does not have the total number of demands or operations, therefore there is a need to use the average number of failures to infer it based on equation 12 and data extracted from the Schneider circuit breaker data sheet (DeDad (2006)). Total operation is 100, failure is 9 within 1 year (Smith, D. J. (2011) and DeDad (2006).

$$E = \frac{Total\ Operations - Average\ Number\ of\ Failures}{Total\ Operations} \qquad (12)$$

$$E = \frac{100-9}{100} = 0.91 = 91\%$$

Calculation of IFPL

IFPL is calculated as 0.819 using equation 3 by taking the reliability and effectiveness of 0.9 and 0.91, respectively. To determine the PFD, the IFPL is subtracted from 1, as PFD is the complement of the probability of success. By using equation 5, the PFD is yielded to 0.181. This means there is an 18% chance that the circuit breaker will fail to operate when needed based on the calculated IFPL value.

$IFPL = R \times E = 0.90 \times 0.91 = 0.819$

In the second calculation step, the study evaluates the (IFPL) for a surge protection device (SPD) against overload. SPDs prevent electrical fires by redirecting excess voltage, protecting circuits from overheating. Failures often result from incorrect use or prolonged overvoltage, rather than direct surges, as reported by EC&M. The IFPL effectiveness of SPDs is 95%, indicating high reliability in preventing surge-related damage and fires. The Probability of Failure on Demand (PFD) is calculated as 0.05. This means there is a 5% chance the SPD will fail to perform its protective function when needed (DeDad, J. (2006)).

Lastly, the study also assesses the Independent Fire Protection Layer (IFPL) for smoke alarms in residential settings. Smoke alarms are evaluated based on their sensitivity, operational reliability, and effectiveness in alerting occupants. Australian fire engineers estimate a 65% probability of success for smoke alarms, resulting in an IFPL value of 0.65, which plays a key role in preventing fire-related incidents. The Probability of Failure on Demand (PFD) is calculated as 0.35. This means there is a 35% chance that the smoke alarm will fail to perform its protective function when needed. Table 7 shows the Independent Fire Protection Layers (IFPL) and Probability of Failure on Demand (PFD).

Table 7 Independent Fire Protection Layers and Probability of Failure on Demand

Independent Fire Protection Layers (IFPLs)	Probability of FPS Performance Success based on Functional Requirements	P_{fod} of IFPL (Probability of Failure on Demand)
Circuit Breaker (CB)	0.82	0.18
Surge Protection Device (SPD)	0.95	0.05
Smoke Alarm	0.65	0.35

Figure 2 illustrates an Event Tree Analysis (ETA) for an electrical fire in a residential building caused by faulty wiring, showing three Independent Protection Layers (IPLs).

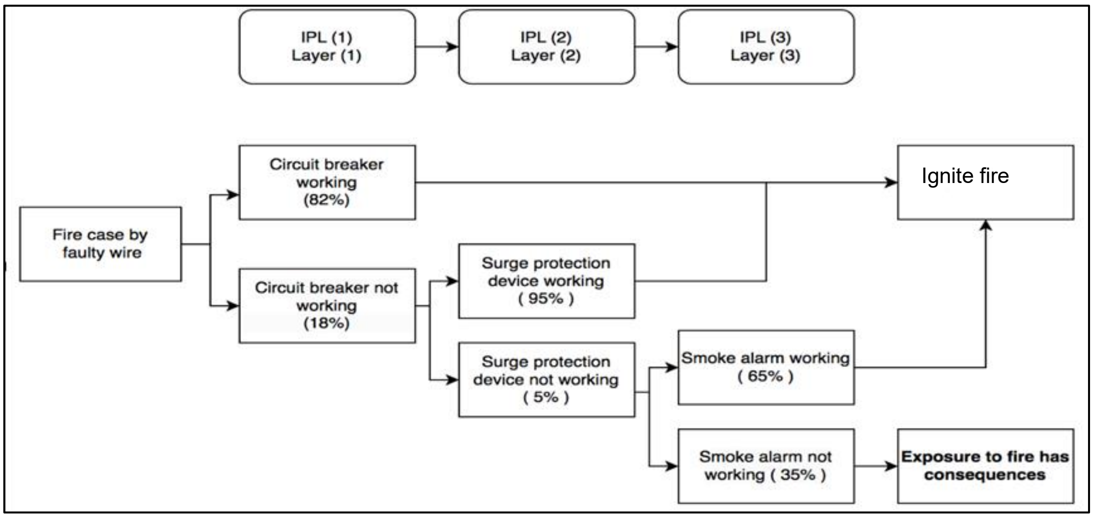

Fig 2. Fire Event Tree Analysis for Wire Ignite Fire

In the case of if any layer operates successfully, the event tree moves to the ignite fire. The calculation gives the overall probability of a fire occurring given failures of all protection layers. It does not directly account for the probability of the fire being contained or extinguished after it starts.

Step 5: Determining the Frequency of Scenarios

The first is to calculate the accident frequency determined by multiplying the frequency of the initiating event with the probability of each subsequent branch event as shown in equation 6. By applying equation 6 to the overheat, arc, and overload scenarios, we provide the frequency results for each consequence. These results quantify the likelihood of each event occurring.

$$f_{\text{Overload}} = \text{IEF}_{\text{overload}} \times (\text{PFD}_{\text{CB}} \times \text{PFD}_{\text{RPD}} \times \text{PFD}_{\text{SD}}) = 6 \times 0.00315 \approx 0.0189\ accidents/year$$

$$f_{\text{Arc}} = \text{IEF}_{\text{arcing}} \times \text{PFD}_{\text{combined}} = 6 \times 0.00315 \approx \frac{0.0189\ accidents}{year}$$

$$f_{\text{Overheat}} = \text{IEF}_{\text{overheat}} \times \text{PFD}_{\text{combined}} = 5.67 \times 0.00315 \approx 0.0179\ accidents/year$$

The outcome derived from equation 6 can serve as input for evaluating the calculated risk against scenario risk tolerance criteria. These criteria are integral to decision-making methods, encompassing matrices, numerical benchmarks, and the allocation of Independent Protection Layer (IPL) credits.

In equation 6, the study deliberately excludes the probability of human-caused fires, focusing solely on electrical sources as the ignition point. This allows for an in-depth analysis of electrical fire dynamics and prevention methods. By depending on electrical factors, the study provides a clear framework for understanding causes, frequencies, and safeguards related to electrical fires. Consequently, P ignition = 1, and the results remain unchanged in equation 6 (Smith, J. (2020)).

$$f_{\text{Overload}} = \text{IEF}_{\text{overload}} \times \text{PFD}_{\text{combined}} \times P^{\,ignition} \approx \frac{0.0189\ accidents}{year}$$

$$f_{\text{Overheat}} = \text{IEF}_{\text{overheat}} \times \text{PFD}_{\text{combined}}\ x\ P^{\,ignition} \approx \frac{0.0179\ accidents}{year}$$

$$f_{\text{Arc}} = \text{IEF}_{\text{arcing}} \times \text{PFD}_{\text{combined}} \times P^{\,ignition} \approx 0.0189\ accidents/year$$

Calculating Risk by Summing Up Frequencies for Multiple Scenarios

The findings for each scenario are then summed up to find one answer that represents the multiple scenarios using the equation 11 (Willey, R. J. (2014)). The calculation is as follows:

$$f^{c} = f_1^{C} + f_2^{C} + \cdots + f_I^{C}$$

$$f^{c} = f_1^{overheat} + f_2^{arc} + f_3^{overload}$$

$$f^{c} = 0.0053 + 0.0056 + 0.0056 = 0.0165\ accidents/year$$

Based on the above calculation, the combined frequency of these fire scenarios occurring within a year would be 0.0165 or 1.65 × 10−2 fires/year.

Step 6: Using LOPA to Make Risk Decisions

In conclusion, the comprehensive assessment of fire-related risk scenarios has yielded a cumulative annual frequency of occurrence at 1.65 × 10−2 fires per year. Coupled with this quantification, a rigorous analysis carried out in Step 2 categorically identifies the outcomes of these fire incidents as carrying 'Very High Consequences' (refer to Table 8). Given their severity and the statistical probability of such events, the current risk profile dictates the necessity for immediate and decisive mitigation actions. This entails the strategic incorporation of additional

Independent Protection Layers (IPLs) or the enhancement of existing ones to effectively reduce the risk to an acceptable level. Based on the results in Table 8, it is evident that the desired step has not been achieved, and the current Independent Protection Layers is inadequate for its intended function. Consequently, an additional IPL is necessary to lower the risk to a tolerable level.

Extra IPL, the Identifying Independent Protection Layers

In residential electrical safety, Independent Protection Layers (IPLs) like Arc Fault Circuit Interrupters (AFCIs) are critical, particularly if circuit breakers fail. AFCIs may detect and interrupt arc faults, which are potential fire hazards, more effectively than standard breakers, thus serving as an essential safeguard against electrical fires. This emphasises the role of AFCIs as an independent layer of protection that activates to prevent electrical fires in cases where traditional circuit breakers may fail to detect dangerous arc faults. Given that the failure rate (λAFCI) = 0.0697 failures per year, and the effectiveness (E) range is between 88% and 95%, next is the calculation of reliability, effectiveness, and IFPL.

Calculation the Reliability R(t)

Reliability is calculated using the exponential decay as in Equation 4.

$$R = e^{-\lambda t} = e^{-0.0697\times 1} \approx 0.9327$$

Using the exponential decay formula for reliability in equation 4 and given a failure rate (λ = 0.0697) for a time period of 1 year, the reliability is approximately 0.9327 or 93.27%.

Calculation of Effectiveness (E)

Given the range between 88 and 95%, the effectiveness is calculated using Equation 12 as follows:

$$E_{avg} = \frac{\text{Total Operations} - \text{Average Number of Failures}}{\text{Total Operations}} = \frac{88+95}{2} = 91.5 = 0.915$$

Calculation of average IFPL

Substituting the given values into Eq. (3), this study gets the value of average IFPL of 0.8534.

$$IFPL_{avg} = R \times E_{avg} = 0.9327 \times 0.915 = 0.8534$$

If the average IFPL (Interim Failure Probability Level) value is 0.8534, then the probability of failure on demand (which can be interpreted as the complement of the IFPL) is calculated as follows.

$$PFD = 1 - 0.8534 \approx 0.1466$$

This means that there is approximately a 14.66% chance that the system will fail to perform its protective function upon demand. Inserting this result into Equation 11, the new combined frequency of these fire scenarios occurring within a year would be 0.00231 or 2.31×10−2 fires/year.

$$f^{c} = \sum_{i=1}^{I} f_i^{C} = 0.0165 \frac{accidents}{year} x\, PFD_{AFCI}$$

$$f^{c} = 0.0165x\, 0.14 = 0.00231$$

Table 8 Assessment of Fire-related Risk Scenarios for Wires According to Qualitative Categorization (Very High Consequences)

Consequences Category / Frequency of Consequence per year	Category (1)	Category (2)	Category (3)	Category (4)	Category (5)
10^{-1}	Optional (evaluate alternative)	Optional (evaluate alternative)	Action at next opportunity	Immediate action	Immediate action
10^{-2}	Optional (evaluate alternative)	Optional (evaluate alternative)	Optional (evaluate alternative)	Action at next opportunity	Immediate action
10^{-3}	No further action	Optional (evaluate alternative)	Optional (evaluate alternative)	Optional (evaluate alternative)	Action at next opportunity
10^{-4}	No further action	No further action	Optional (evaluate alternative)	Optional (evaluate alternative)	Optional (evaluate alternative)
10^{-5}	No further action	No further action	No further action	Optional (evaluate alternative)	Optional (evaluate alternative)
10^{-6}	No further action	No further action	No further action	No further action	Optional (evaluate alternative)
10^{-7}	No further action	No further action	No further action	No further action	No further action

By comparing this result to the qualitative categorization as depicted in Table 8, this study finds the new frequency of consequence is acceptable and action at the next opportunity (Centre for Chemical Process Safety (CCPS, 2001)).

4. CONCLUSIONS AND RECOMMENDATIONS

The findings of this study highlight the urgent need for improved fire safety measures in Oman, particularly in residential buildings where electrical fires remain a serious concern. The primary causes overheating, electrical arcs, and circuit overloads are well-documented, but several hidden risk factors also contribute to fire incidents. These include aging electrical infrastructure, high temperatures, humidity, dust accumulation, and substandard electrical components. Additionally, poor installation practices and human error such as overloading circuits or using low quality wiring exacerbate fire risks. Addressing these challenges requires a multifaceted approach that integrates advanced fire detection technologies, regulatory enforcement, and public awareness programs.

Oman's current fire safety regulations and building codes require further strengthening to align with international best practices. The Civil Defense & Ambulance Authority oversee fire safety regulations, while the Oman Electrical Standards (OES) govern electrical installations. However, gaps remain in enforcement and safety requirements. Unlike the United States, where Arc Fault Circuit Interrupters (AFCIs) are mandatory, Oman's regulations do not require these devices, leaving homes vulnerable to arc-induced fires. Regular electrical inspections are also not mandated, allowing fire hazards to go undetected. Additionally, there are no strict penalties for non-compliance, making adherence to fire safety largely voluntary. Another significant limitation is the lack of a national fire risk database, which could help policymakers track trends, identify high-risk areas, and implement targeted safety interventions. To systematically address these hazards, this study proposes the integration of Layer of Protection Analysis (LOPA), whereby the resulting insights can inform the development of evidence-based policy and legislative interventions.

In conclusion, regulatory reforms, improved fire protection technologies, and structured risk. Assessments are essential to mitigating electrical fire hazards in Omani residential buildings. While existing safety measures provide partial protection, they are insufficient to reduce fire risks to a tolerable level. Future research should explore the economic feasibility of AFCI adoption, the impact of public awareness programs, and AI-based fire risk detection. Implementing these strategies will strengthen Oman's fire safety framework and serve as a model for other countries facing similar challenges.

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