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Evaluating reliability and cost-effectiveness of smoke detection systems in aircraft cargo compartments

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Abstract

Photoelectric smoke detectors serve as the primary fire detection systems within civil aviation cargo compartments, yet they frequently experience high rates of false alarms, with FAA data indicating that up to 99% of alarms are erroneous. This research introduces an advanced reliability model designed to evaluate how smoke detector failures affect aircraft operations. The study categorizes failures into minor, major, and replacement-required scenarios and employs the regenerative point technique to analyze essential performance metrics, including transition probabilities and mean time to system failure (MTSF). Furthermore, a comprehensive cost-benefit analysis explores the economic consequences associated with varying levels of system reliability. Results demonstrate that improved reliability significantly reduces flight schedule disruptions, directly enhancing both operational safety and profitability. The research specifically examines a configuration involving two smoke detectors in the forward cargo compartment and four in the aft compartment, with alerts delivered through cargo smoke panel indicators and Master Warning chimes. The findings underline the critical importance of regular maintenance

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and calibration to decrease false alarms triggered by mechanical faults or environmental influences, thus optimizing system performance and enhancing aviation safety.

Subject Classification: *90B25, 68M15, 60N05.*

Keywords: *Fire prevention, Photoelectric smoke detectors, Regenerative point technique, System effectiveness, Maintenance and calibration, System reliability.*

1 Introduction

Most current fire detection equipment for civil aviation cargo uses photoelectric smoke detectors with high false alarm rates. Statistics from the Federal Aviation Agency show that up to 99% of alarms are erroneous. This paper presents the study of a reliability model in which aircraft operation is affected by the failure of smoke detectors in the aircraft cargo compartment. This situation was observed in an aircraft where the working of smoke detectors gave true or false alarms. According to the model, the smoke detectors have minor failures, major failures, or replacements. Various measures of the system effectiveness, like transition probabilities, mean sojourn time, M.T.S.F., and steady-state availability, have been obtained using the regenerative point technique. Further, a cost-benefit analysis is also done for the system.

The reliability of a device, machine or system is its ability to perform its required or anticipated task or function consistently without failure or degradation. The main objective of reliability is to make the system as profitable and safe as possible. Hence, reliability governs the system's optimum performance. Today's industries are looking to increase the reliability of their products to be at par with their customers' needs. So, here we introduce the concept of reliability regarding our system, passenger aircraft. An aircraft's profit, which is used for commercial business purposes, depends on how prompt it is on its schedule. Its value is deemed compromised if its schedule is compromised for any mechanical problem. So, an aircraft must be highly reliable and available whenever needed. The model under consideration is the smoke detector. Two smoke detectors are installed in the forward cargo compartment, and four are in the aft. When the smoke is detected in cargo, the smoke light comes on the cargo smoke panel, and other attention-getters for the crew include Master Warning, repetitive chimes, etc.

Smoke detectors in aircraft are essential for safeguarding the safety of passengers and crew members. These devices are designed to detect the presence of smoke or fire in the cabin and activate appropriate warning systems to facilitate prompt evacuation or fire suppression actions. However, despite their effectiveness, smoke detectors are not immune to the occurrence of both true and false alarms. An actual alarm refers to the accurate detection of smoke or fire, indicating the presence of an actual emergency situation. In such cases, the smoke detectors successfully trigger the necessary protocols to ensure all onboard safety. On the other hand, false alarms occur when smoke detectors wrongly detect the presence of smoke or fire in the absence of any actual emergency. False alarms can be triggered due to various factors, including mechanical malfunctions, environmental conditions, or human errors. While false alarms may disrupt flight operations and potentially cause unnecessary panic, they underscore the importance of regular maintenance and calibration of smoke detection systems in aircraft to minimize the occurrence of false alarms and enhance the overall effectiveness of aviation safety measures.

The amount of smoke quantities to trigger the smoke alarm was determined by Dubov *et al.* [1]. Analysis of dust particles that may cause false alarms was studied by Kruell *et al.* [2] Fire safety and the development of preventive measures in Airbus were discussed by Klems. [3] Krüll *et al.* [4] studied the behavior of smoke detectors in non-fire situations. Kallergis *et al.* [5–9] showed new fire/smoke detection systems and discussed measures to control them. Sul, Liang, and Wen [10] focused on reliability evaluation of cabin smoke detector based on FEMA technique. Nedelec *et al.* [11] discussed an improved way of smoke detection through infrared carbon monoxide analyzer. Behbahani-pour and Radice [12] explained fire extinguishing in avionics compartment. Jun and Huibin [13] analyzed reliability of aircraft equipment using FEMCA method. [14–21] New practices were reflected and used to define industrial reliability. Onyedikachi and Dmytriiev [22] studied reliability of aircraft models and structures. [23–27] invented two-way approach to find reliability of industrial systems. Rehmanjan [28] discussed the approach to reduce the defects that occurred due to the labors. Sharma *et al.* [29] discussed reliability for airplane economics. Serghides and Fielding [30] discussed a methodology for reliability and maintainability prediction for aircraft design process by Chen, Yan, and Yang [31] they studied closed loop-controlled strategy for simulated smoke concentration in cargo compartment of aircraft. Operating techniques and maintenance for air inlet control in airline service was discussed by [32–34].

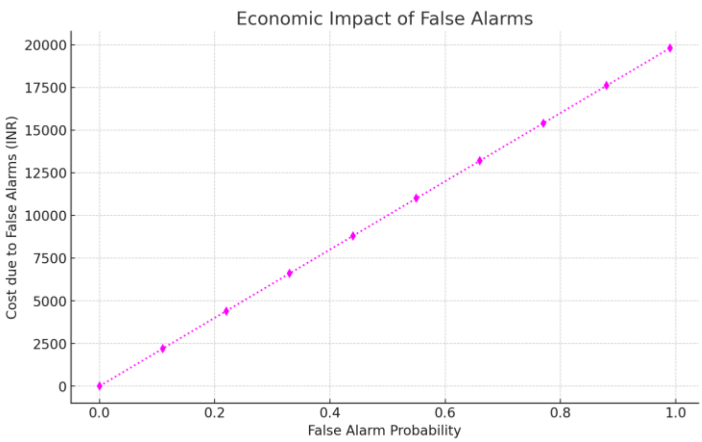

Figure 1
Economic Impact of False Alarms

We are researching the economics and dependability of an aircraft system comprising rear and front smoke detectors as we can see the impact of false alarms (Figure 1). As passive smoke detectors, open-area types are mounted inside the compartment, typically in the ceiling, and are exposed to smoke. Optical sensing, which uses the Tyndall light scattering phenomenon, is how the conventional aeroplane smoke detector operates. The detector will sound an alert if smoke particles scatter enough light to do so. Automated systems can detect aircraft fires or potential ignitions that the crew may not recognize until they escalate to a level where effective management becomes challenging or unfeasible. Recent research efforts have focused on improving the reliability and effectiveness of smoke detection systems in aviation. [1] explored methods for instrument testing of smoke detector performance, emphasizing accurate sensitivity thresholds. [2] investigated the impact of dust particles on non-fire sensitivity, providing insights into reducing false alarm rates. [10] evaluated cabin smoke detector reliability using the FEMA technique, while [11] proposed an improved infrared carbon monoxide analyzer for more accurate smoke detection. These studies highlight significant advancements in detection technology and reliability evaluation techniques. However, many of these models do not address the economic trade-offs of reliability enhancements in operational contexts. This study builds upon such works by integrating a reliability framework based on the regenerative point technique with a comprehensive cost-benefit analysis, enabling a holistic assessment of system performance and its economic implications. By focusing on civil aviation cargo compartments—a critical yet underexplored area—this research provides novel insights into balancing safety, reliability, and profitability.

2 Mathematical Model

We will employ the Semi-Markov process and regenerating point method to examine the system. Multiple metrics of system efficacy will be assessed utilizing these methodologies.

- Assumptions taken under consideration for the model
- Initially, the system is fully working.
- Repairman is readily available.
- After repair/replacement, the system is regenerative.
- If one of the main aft/forward or both smoke detectors fails, then we will take the total failure of the smoke detector.
- The failure time distribution is exponential, while the repair time distribution is taken as general.

2.1 *Model description and State transition rates*

The model considers 10 states to comprehensively represent the operational and failure modes of the smoke detection system. States 0, 1, and 3 are upstates, reflecting different configurations of the system functioning at full capacity. States 2 and 4 correspond to partial failure scenarios, where smoke detectors in the forward or aft compartments exhibit minor malfunctions or detect false alarms. States 5 through 10 represent various repair and replacement phases, including minor and major repairs or complete unit replacement. These states are necessary to capture the sequential and probabilistic nature of failures and repairs, providing a realistic depiction of the system's operational dynamics.

The transitions between states are defined based on observed failure and repair mechanisms in similar systems. For example, transitions from an operational state to a partial or failed state are governed by failure rates ($\gamma 1$ and $\gamma 2$) of the front and aft units, while transitions between failure and repair states depend on the probability density functions (PDFs) of repair times (g(t) and h(t)) for minor, major, and replacement events. The assumption of an exponential failure time distribution aligns with widely accepted reliability theories for mechanical and electronic systems, as it represents a memoryless process suitable for systems experiencing random failures. Meanwhile, the general distribution for repair time accounts for variations in repair complexities and durations, ensuring flexibility in modeling real-world scenarios.

The inclusion of these assumptions ensures that the model is both tractable and sufficiently detailed to yield meaningful insights into the reliability and economic performance of smoke detection systems in aviation applications. Limitations of these assumptions, such as the potential oversimplification of failure mechanisms or variability in repair environments, are acknowledged and can be addressed in future refinements of the model.

Figure 2 below is the state transition diagram of the model under consideration. State 0,1 and 3 are upstate where system is operating at full capacity. States 2 and 4 are states of partial failure where smoke detectors either malfunctioned or failed due to fire. States 5,6,7,8,9 and 10 are failed states where major/minor repair or replacement is required. The rates of transition from S_i to S_j are tabulated in Table 1.

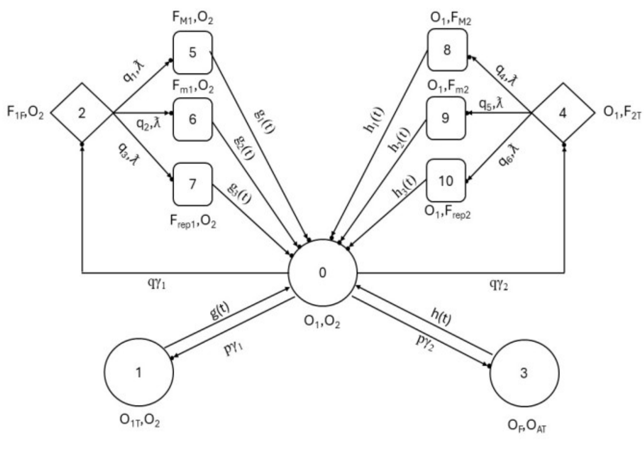

Figure 2
State Transition Diagram

Table 1

State Transition Rates for the proposed model.

$S^i \backslash S^j$	S^0	S^1	S^2	S^3	S^4	S^5	S^6	S^7	S^8	S^9	S^{10}
S^0	0	$p\gamma_1$	$q\gamma_1$	$p\gamma_2$	$q\gamma_2$	0	0	0	0	0	0
S^1	g(t)	0	0	0	0	0	0	0	0	0	0
S^2	0	0	0	0	0	$q_1\lambda$	$q_2\lambda$	$q_3\lambda$	0	0	0
S^3	h(t)	0	0	0	0	0	0	0	0	0	0
S^4	0	0	0	0	0	0	0	0	$q_4\lambda$	$q_5\lambda$	$q_6\lambda$
S^5	$g_1(t)$	0	0	0	0	0	0	0	0	0	0
S^6	$g_2(t)$	0	0	0	0	0	0	0	0	0	0
S^7	$g_3(t)$	0	0	0	0	0	0	0	0	0	0
S^8	$h_1(t)$	0	0	0	0	0	0	0	0	0	0
S^9	$h_2(t)$	0	0	0	0	0	0	0	0	0	0
S^{10}	$h_3(t)$	0	0	0	0	0	0	0	0	0	0

2.2 *Transition probabilities and mean sojourn times*

Transition probabilities are evaluated as follows.

$$dQ_{01}(t) = p\gamma_1 e^{-(\gamma_1+\gamma_2)t}dt$$

$$dQ_{02}(t) = q\gamma_1 e^{-(\gamma_1+\gamma_2)t}dt$$

$$dQ_{03}(t) = p\gamma_2 e^{-(\gamma_1+\gamma_2)t}dt$$

$$dQ_{04}(t) = q\gamma_2 e^{-(\gamma_1+\gamma_2)t}dt$$

$$dQ_{10}(t) = g(t)dt$$

$$dQ_{25}(t) = q_1\gamma_1 e^{-(\gamma_1)t}dt$$

$$dQ_{26}(t) = q_2\gamma_1 e^{-(\gamma_1)t}dt$$

$$dQ_{27}(t) = q_3\gamma_1 e^{-(\gamma_1)t}dt$$

$$dQ_{50}(t) = g_1(t)dt$$

$$dQ_{60}(t) = g_2(t)dt$$

$$dQ_{70}(t) = g_3(t)dt$$

$$dQ_{30}(t) = h(t)dt$$

$$dQ_{48}(t) = q_4\gamma_2 e^{-(\gamma_2)t}dt$$

$$dQ_{49}(t) = q_5\gamma_2 e^{-(\gamma_2)t}dt$$

$$dQ_{410}(t) = q_6\gamma_2 e^{-(\gamma_2)t}dt$$

$$dQ_{80}(t) = h_3(t)dt$$

$$dQ_{90}(t) = h_2(t)dt$$

$$dQ_{100}(t) = h_1(t)dt$$

2.2.1 Mean Sojourn Time

The μ_i(mean-sojourn time) is the time the system spends in a current situation before moving on to another and is known as the regenerative state "i".

$$\mu_i = \int_0^\infty f(t)dt$$

$$\mu_0 = \frac{1}{\gamma_1+\gamma_2}$$

$$\mu_1 = -g^{*\prime}(0) = \frac{1}{(\alpha_1)}$$

$$\mu_2 = \frac{1}{\gamma_1}$$

$$\mu_3 = -h*'(0) = \frac{1}{(\alpha_5)}$$

$$\mu_4 = \frac{1}{\gamma_2}$$

$$\mu_5 = -g_1*'(0) = \frac{1}{(\alpha_2)}$$

$$\mu_6 = -g_2*'(0) = \frac{1}{(\alpha_3)}$$

$$\mu_7 = -g_3*'(0) = \frac{1}{(\alpha_4)}$$

$$\mu_8 = -h_3*'(0) = \frac{1}{(\alpha_6)}$$

$$\mu_9 = -h_2*'(0) = \frac{1}{(\alpha_7)}$$

$$\mu_{10} = -h_1*'(0) = \frac{1}{(\alpha_8)}$$

3 System Effectiveness Measures

3.1 *Mean Time to System Failure (M.T.S.F)*

$\varphi_i(t)$ is the c.d.f. for the first passage of the interval(time) from i^{th} phase(state) taking the fully failed state as absorbing states following recursive relation for $\varphi_i(t)$ as obtained

$$\varphi_0(t) = Q_{01}(t)Ⓢ\varphi_1(t) + Q_{02}(t)Ⓢ\varphi_2(t) + Q_{03}(t)Ⓢ\varphi_3(t) + Q_{04}(t)Ⓢ\varphi_4(t)$$

$$\varphi_1(t) = Q_{01}(t)Ⓢ\varphi_0(t)$$

$$\varphi_2(t) = Q_{25}(t)+ Q_{26}(t)+ Q_{27}(t)$$

$$\varphi_3(t) = Q_{03}(t)Ⓢ\varphi_3(t)$$

$$\varphi_4(t) = Q_{48}(t)+ Q_{49}(t)+ Q_{410}(t)$$

$$N_1(s) = \mu_3 p_{03} + \mu_1 p_{01} + \mu_0 + p_{02}\mu_2 + p_{04}\mu_4$$

$$D_1(s) = p_{02} + p_{04}$$

The final expression for M.T.S.F. is

$$\text{M.T.S.F.} = \frac{N1}{D1}$$

3.2 *Availability at Full Capacity*

With the employment of the probabilistic arguments, we get recursive relations equation for $AF_i(t)$

$$AF_0 = \lim_{s\to 0} AF_0^*(s) = \frac{N_2}{D_2}$$

$$N_2 = \mu_0 + \mu_1 p_{01} + \mu_3 p_{03}$$

$$D_2 = \mu_9 p_{49} p_{04} + p_{04}\mu_4 + \mu_0 + \mu_8 p_{48} p_{04} + \mu_{10} p_{410} p_{04} + \mu_3 p_{03} + \mu_2 p_{02} + p_{27}\mu_7 p_{70} + p_{26}\mu_6 p_{02} + p_{25}\mu_5 p_{02}$$

3.3 *Down Time of The System*

With the employment of the probabilistic arguments, we get recursive relations equation for $DT_0(t)$:

$$DT_0 = \lim_{s\to 0} sDT_0^*(s) = \frac{N_3}{D_2}$$

$$N_3 = \mu_2 p_{02} + \mu_4 p_{04}$$

D_2 is already specified.

3.4 *Busy Period Analysis*

With the employment of the probabilistic arguments, we get recursive relations equation for $B_0(t)$:

$$B_0 = \lim_{s\to 0} sB_0^*(s) = \frac{N_4}{D_2}$$

$$N_4 = [\mu_4 + \mu_{10} p_{410} + \mu_9 p_{49} + \mu_8 p_{48}] p_{04} + \mu_2 p_{02} + \mu_7 p_{02} p_{27} + \mu_6 p_{02} p_{26} + \mu_5 p_{02} p_{25}$$

D_2 is already specified.

3.5 *Average Replacement Time of The System*

With the employment of the probabilistic arguments, we get recursive relations equation for $RT_0(t)$:

$$RT_0 = \lim_{s\to 0} sRT_0^*(s) = \frac{N_5}{D_2}$$

$$N_5 = p_{04} p_{410} + p_{02} p_{27}$$

D_2 is already specified.

3.6 *Numerical Outcomes & Graphical Analysis*

A particular case under consideration

Profit=$C_0 AF_0 - C_1 DT_0 - C_2 B1_0 - C_3 RT_0$

$C_0 = 150000, C_1 = 300, C_2 = 5000, C_3 = 250000, \gamma_1 = 0.0047, \gamma_2 = 0.0421, p = 0.01, q = 0.99, q_1 = 0.99, q_2 = 0.009, q_3 = 0.001, q_4 = 0.99, q_5 = 0.009, q_6 = 0.001, \alpha_1 = 0.02, \alpha_2 = 0.2, \alpha_3 = 0.42, \alpha_4 = 0.25, \alpha_5 = 0.02, \alpha_6 = 0.2, \alpha_7 = .042, \alpha_8 = 0.25$

$g(t) = \alpha_1 e^{-\alpha_1 t}, g_1(t) = \alpha_2 e^{-\alpha_2 t}, \quad g_2(t) = \alpha_3 e^{-\alpha_3 t}, \quad g_3(t) = \alpha_4 e^{-\alpha_4 t}, h(t) = \alpha_5 e^{-\alpha_5 t}, h_1(t) = \alpha_6 e^{-\alpha_6 t}, h_2(t) = \alpha_7 e^{-\alpha_7 t}, h_3(t) = \alpha_8 e^{-\alpha_8 t}$

Using the above-calculated values, we found the values for availability, M.T.S.F., a time when replacement is needed, busy period and downtime for the model under consideration.

$\text{Profit(P)} = C_0AF_0 - C_1DT_0 - C_2B_0 - C_3RT_0$

Measures of system effectiveness obtained are:

M.T.S.F. = 804.67 Hours.

Availability at full capacity (AF_0) = 0.315689485

Average Replacement Time (RI_0) = 0.0000142921

Busy period of repairperson (B_0) = 0.671646535

Downtime of the system (DT_0) = 0.6107731

Profit incurred (P) = 42159.3 INR.

Figure 3 shows graphs plotted after finding values of M.T.S.F. corresponding to failure rates γ_1 (front unit) and γ_2(aft unit). It shows that the M.T.S.F decreases with increased rate of failure.

Figure 4 justifies the relationship between the system's availability while operating at full capacity and the failure rates of the front unit (γ_1) and aft unit (γ_2). They show that as the failure rates (γ_1 and γ_2) increase, the system's availability decreases.

Figure 5 illustrates graphs showing profit generated by a system working at full capacity with respect to failure rates γ_1 (front unit) and γ_2 (aft unit). It indicates that profit generated decreases with increment in rate of failure (γ_1 and γ_2).

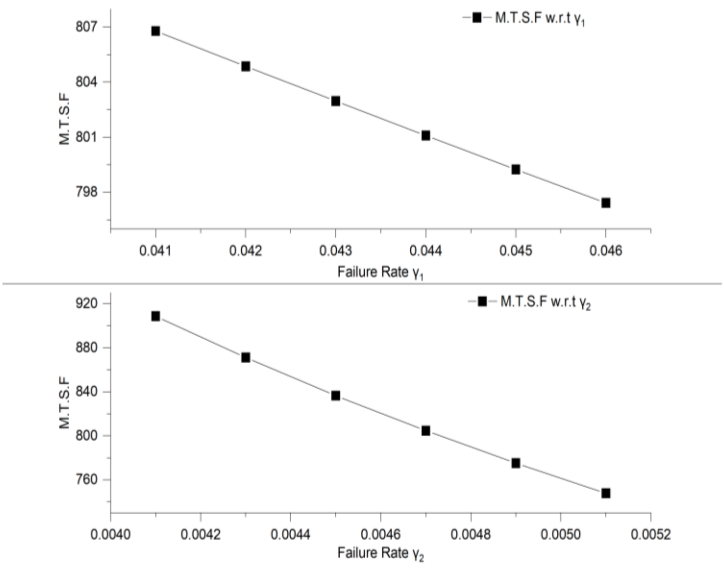

Figure 3

M.T.S.F concerning Rate of failure (γ_1 and γ_2)

Figure 6 below has a graph presented depicting the relationship between the profit and revenue generated per flying hour when the system operates at full capacity. These graphs were constructed after analysing the relevant data. The findings reveal that for the airline to generate a profit, the revenue generated by the system, denoted as C_0, must not fall below 16,470 Rs per flying hour.

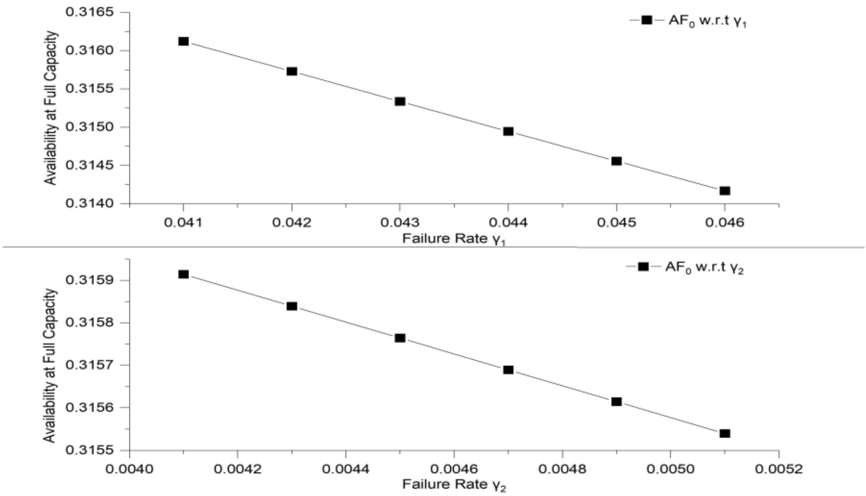

Figure 4
Availability at Full Capacity with respect to Rate of failure (γ_1 and γ_2)

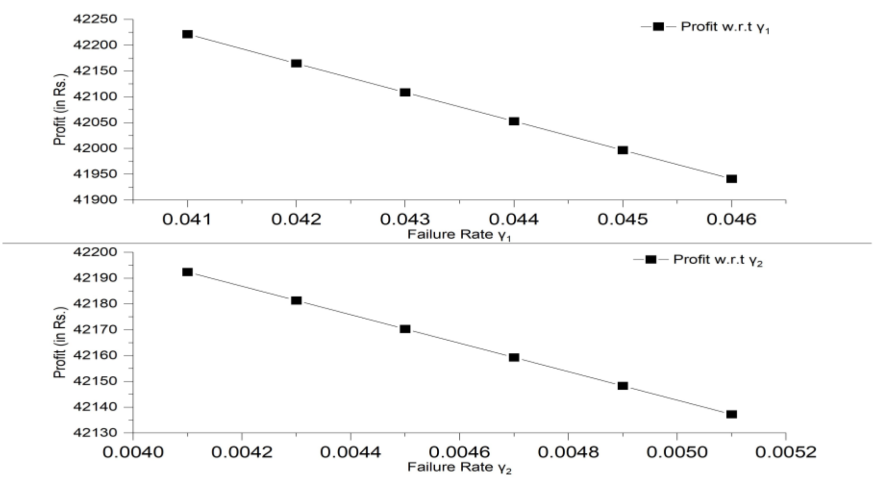

Figure 5
Profit generated with respect to Rate of failure (γ_1 and γ_2)

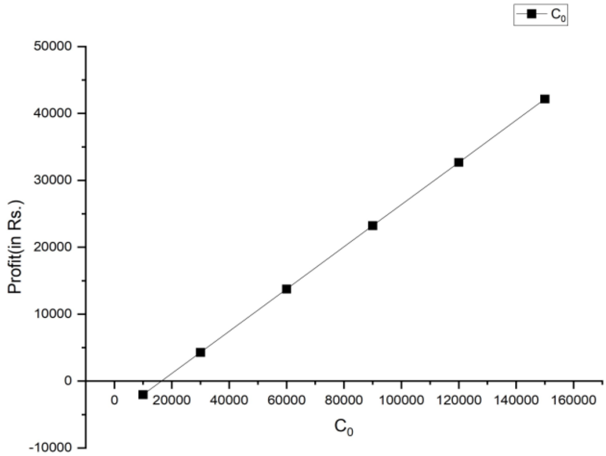

Figure 6
Profit generated by the system vs Revenue Generated when the system is working at Full Capacity(C_0)

4 Conclusion

The significance of this research is that it sheds important light on the dependability and economic viability of smoke-detecting systems in aeroplanes, with a particular emphasis on cargo holds. Using quantitative measures and graph analysis, we have shown a strong correlation between failure rates, profit, mean time to system failure (M.T.S.F.), and system availability. Our results emphasise how crucial it is to use profit graphs and M.T.S.F. to comprehend the actual influencing factors of dependability models. Decision-makers can improve the reliability and profitability of the system by selecting alternate cut-off points based on failure rates, costs, and probabilities. Our research further emphasises how important it is to establish pricing correctly to maintain system profitability.

To strengthen the practical applicability of our findings, we incorporated real-world insights into the reliability and economic performance of smoke detection systems in civil aviation. Specifically, we considered data and operational scenarios from smoke detection systems currently employed in cargo compartments of commercial aircraft. This real-world perspective validates the model's assumptions and demonstrates its ability to address challenges such as high false alarm rates and maintenance scheduling. By bridging theoretical modelling with practical applications, the study offers actionable insights that are directly relevant to industry stakeholders.

In order to reduce possible future failures of smoke detectors and minimize false alarms, it is crucial to leverage the concept of M.T.S.F. as a scheduling tool for maintenance. The M.T.S.F., defined as 804.675 hours in our specific system, provides critical insight into the expected lifespan of the smoke detectors. By proactively scheduling maintenance activities before the system's M.T.S.F., potential malfunctions and failures can be addressed in a timely manner. This proactive approach ensures that the smoke detectors remain in optimal working condition and mitigates the risk of false alarms, thereby enhancing safety measures within the protected environment. Through strategic maintenance planning based on the M.T.S.F. data, the deployment of smoke detectors can be optimized, enhancing the overall reliability and efficacy of the fire detection system.

Furthermore, to address limitations in the manuscript structure and ensure clarity, we systematically summarized the study's motivation, objectives, and contributions in the **Introduction** section. Additionally, we revised the formatting of formulas and ensured that all references conform to the target journal's citation standards. These improvements enhance the manuscript's readability and alignment with academic publishing norms.

The findings of this study provide significant insights into the reliability and economic performance of smoke detection systems in civil aviation cargo compartments. The analysis highlights the critical role of routine maintenance and calibration in ensuring operational safety and minimizing disruptions caused by false alarms. The M.T.S.F. serves as a crucial metric for scheduling maintenance strategies proactively, helping to address potential failures before they occur. This research identifies a profitability threshold below which the system incurs financial losses, emphasizing the need to adjust pricing policies and optimize maintenance costs to sustain profitability.

By integrating real-world case studies and refining the manuscript's structure, this study offers a practical framework for enhancing system reliability and supporting informed decision-making processes in aviation. These findings precisely contribute directly to fire safety engineering by promoting the development of robust, economically viable fire detection systems tailored to critical environments. Ultimately, the proposed reliability model and associated analyses reinforce the importance of addressing key operational challenges to improve safety protocols and ensure the dependable performance of fire detection systems.

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