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RESEARCH ARTICLE - ENGINEERING (MISCELLANEOUS)

Integrating Swiss Cheese and STAMP Model: A Systemic Analysis of the Boeing 737 MAX MCAS and Redesign Response

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Abstract

The initial design of the Maneuvering Characteristics Augmentation System (MCAS) on the Boeing 737 MAX relied on a single Angle of Attack (AOA) sensor and inadequate pilot training, contributing to two fatal accidents, the Lion Air Flight 610 and the Ethiopian Airlines Flight 302, within five months, resulting in the loss of 346 lives. While prior studies have addressed technical or organizational factors in isolation, this paper presents a systemic analysis aimed at linking the causes of failures and how they led to changes in system design. The methodology employs an integrated approach using two accident causation models, the Swiss Cheese Model for mapping out the alignment of latent failures and the Systems-Theoretic Accident Model and Process (STAMP) for analyzing the hierarchical deficiencies in the control structure of the system. The analysis ascertains that systemic breakdown across engineering, regulation, and training created the pathway to the accidents. Following the accidents, fault tolerance is successfully implemented in the redesigned system, furthermore, a verified record of zero critical failures across millions of flight hours has been achieved, strengthening the system. Quantitatively, simulations utilizing Root Mean Square Error (RMSE) are carried out to examine the system's control logics in comparison, providing numerical evidence of improved system stability from 1.68° to 0.79°. The study concludes that while the redesigned system is a necessary corrective safety response, the safety of systems depends on robust structural redundancy and mandatory fault tolerance, which must be incorporated at the design stage in line with regulatory requirements for all future flight control systems.

Publisher: Middle Technical University

Keywords: Boeing 737 MAX; MCAS; Systemic Failure; Accident Causation Model; STAMP.

1. Introduction

Automation has become an increasingly important role in the aviation industry, especially in managing pilot workload and improving overall system efficiency. However, when not properly integrated into the existing system, additional complexity is created, as experienced in the Boeing 737 MAX. The Maneuvering Characteristics Augmentation System was designed to preserve the handling characteristics of earlier 737 models after being equipped with larger CFM LEAP-1B engines, altering the aircraft's pitch-up tendencies resulting from the additional lift generated by the reconfigured engine nacelles. This approach was intended to avoid costly pilot retraining.

The originally designed MCAS contained critical vulnerabilities. It relied on a single Angle of Attack (AOA) sensor, was programmed to repeatedly command a nose-down trim of up to 2.5 degrees in ten-second intervals and was omitted from pilot training and documentation. When the system was triggered by erroneous AOA data, these design weaknesses resulted in the catastrophic crashes of Lion Air Flight 610 and Ethiopian Airlines Flight 302 within five months, resulting in the loss of 346 lives and the global grounding of the aircraft fleet [1, 2].

Although the faulty AOA sensor data was an immediate trigger, the accidents resulted from a build-up of deeper systemic factors were addressed in the current study. The technical malfunction represents the active failure that initiated a sequence of latent organizational and regulatory shortcomings. These underlying factors included aggressive business conditions, such as the accelerated production of the 737 MAX driven by the release of Airbus A320 neo [3], a compromised evaluation process of the system and inadequate regulatory oversight. The FAA's Joint Authorities Technical Review (JATR) [4] concluded that the 737 MAX's development occurred under intense commercial pressure, which compromised the design integrity and the evaluation of the human–automation interface. Recognizing and identifying these latent failures systematically is a fundamental objective of this paper.

This article aims to evaluate the failures and redesigned MCAS through established accident causation frameworks, exploring the interaction of organizational pressures, design flaws, and oversight in undermining the system's safety. Also, it provides an effectiveness assessment through comparison of the initial and redesigned system and their implication for safety in aviation systems.

Nomenclature & Symbols

MCAS	Maneuvering Characteristics Augmentation System	AOA	Angle of Attack
STAMP	Systems-Theoretic Accident Model and Process	RMSE	Root Mean Square Error
JATR	Joint Authorities Technical Review	FCC	Flight Control Computer
ADMs	Air Data Modules	ADIRUs	Air Data and Inertial Reference Units
KNKT	Komite National Keselamatan Transportasi	FAA	Federal Aviation Administration
ODA	Organizational Designation Authorization	HMI	Human-Machine Interface

Several studies have independently explored the technical, organizational, and regulatory approaches of MCAS. For instance, Cannon-Patron et al., 2019 [5] highlighted organizational pressures such as the expedited certification, concealment of design shortcomings, and inadequate disclosure by Boeing identified as the root cause of the accidents. Furthermore, Wendel [6] expanded on this from an ethical perspective, calling for accidents in which such technicality should be viewed from a systems-based approach to legal accountability to avoid the blame being placed solely on individuals[7]. Similarly, Donald Thompson, 2019 [8] and Johnston, et al. [9] emphasized that organizational culture must exceed the obligation of fulfilling regulatory requirements but have a great sense in promoting transparency, strong engineering processes and better human-automation integration. More studies focused on the main technical failures of the Maneuvering Characteristics Augmentation System (MCAS) including the system's dependence on a single AOA sensor and its ability to command a severe nose-down stabilizer defection of up to 2.5 degrees during low-speed events [10], operation without pilot awareness creating a single point of failure. The lack of transparency further connects to the human factor aspects. Where Jaime Paul [11] applied the SCHELL model in analyzing the impact of automation on pilots, the study noted that the complexity of automated systems can lead to disorientation and delay in recognizing system malfunctions. An insight that directly relates to the unannounced activations of MCAS. Paul also found that inaccurate sensor data, especially airspeed information, has been a major contributing factor in accidents relating to automated systems for decades. To address this, the authors proposed a novel cognitive training framework aimed at improving manual flying skills and reducing automation complacency. Consistent with this study's systems-based perspective, Seref Demirci [12] analyzed improving automation requirements in aviation using the Swiss Cheese Model to evaluate the MCAS accidents. His work supports this study by contextualizing MCAS not only as a technical failure but as a socio-technical imbalance. However, these studies often neglect the use of accident frameworks in analyzing accidents, which is usually a result of several factors not just a single malfunction in the technical, organizational, regulatory, or human-factor, but from interacting weaknesses across multiple socio-technical layers [13].

The current study addresses that gap by utilizing a model-driven analysis linking these dimensions, by integrating two accident-established frameworks, James Reason's Swiss Cheese Model and Leveson's Systems-Theoretic Accident Model and Process (STAMP) in evaluating the contributors to the MCAS failures. By systematically identifying the interdependencies in design, training and regulatory oversight, this paper provides a holistic assessment of the MCAS redesign. The analysis incorporates both qualitative evaluations such as: improvements in redundancy, activation logic and pilot override capability and quantitative assessments: including a simulation-based comparison of the control performance between MCAS-1(the original MCAS) and MCAS-2 (the redesigned MCAS) using RSME evaluation. These results demonstrate measurable safety improvement and reinforce the importance of fault tolerance and transparency in future flight control system design.

1.1. Technicality of the MCAS system (Pre-Redesign)

To understand the accidents involving MCAS its technicality has to be studied. MCAS was designed to automatically control the 737 MAX aircraft's pitch-up tendencies during flight. The commands are embedded within the speed trim, through the Flight Control Computer (FCC). The system was designed to command the nose-down stabilizer movement without pilot input when AOA becomes excessively high, indicating a potential stall condition.

MCAS was designed to activate under the following specific conditions:

- The aircraft must be airborne.
- The flaps must be fully retracted.
- The AOA must exceed a calculated threshold based on airspeed and altitude.

Once the preset conditions are met, the system is activated. The system relied on a single AOA sensor with no cross-validation and applied repeated nose-down trim inputs every ten-second intervals. Unknown to the pilots, MCAS could be deactivated manually using the stabilizer Trim CUTOUT switches when the measured AOA reached the activation threshold. The system is engaged via key components illustrated in Fig. 1.

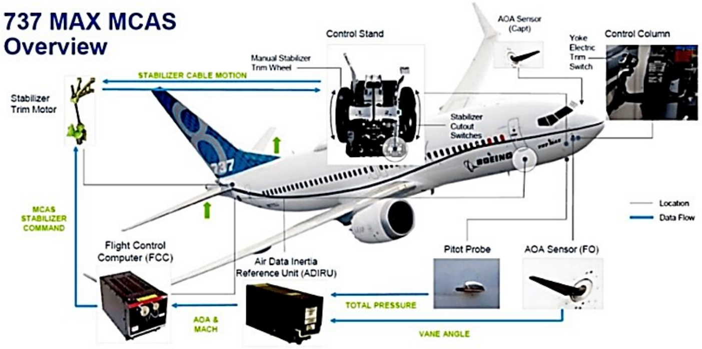

Fig. 1. Diagram showing components of MCAS [14]

Each of the component elements contributes to the system's overall function and stability. The 737 MAX is equipped with dual Flight Control Computers (FCCs) responsible for executing the MCAS logic using input signals from the air-data system. The MCAS control law engages based on specific flight parameters such as Angle of Attack (AOA), air or ground status, pitch rate, flap position, and Mach number. Ensuring a consistent stick-force gradient at high AOA by commanding stabilizer movement, thereby supporting the aircraft's longitudinal stability.

Located on both the Captain's and First Officer's sides, the Air Data Modules (ADMs) gather essential information from the Pitot tubes, static ports and AOA vanes. These data are then transmitted to the Air Data and Inertial Reference Units (ADIRUs), which process and convert them into flight parameters displayed on the cockpit instruments. The ADIRUs also detect sensor inconsistencies and generate alerts, such as the AOA DISAGREE warnings, when discrepancies occur.

The Pitch Trim System interfaces directly with MCAS to adjust the horizontal stabilizer. It comprises the electrical and manual control yoke-mounted trim switches and trim wheels. Trim indicators provide pilots with visual feedback of the stabilizer position, allowing continuous monitoring during flight. Additionally, the stick shaker serves as an artificial stall warning device, vibrating the control yoke when AOA readings exceed safe limits, alerting pilots of potential stall conditions. Together, these interconnected systems ensure that MCAS responds to aerodynamic conditions while providing pilots with essential feedback [15].

1.2. Contributions of the Study

The present study builds on these insights, using a unified framework: the Swiss Cheese and Systems-Theoretic Accident Model and Process (STAMP) frameworks to reveal how technical, organizational, and regulatory weaknesses interacted with the MCAS system and how the subsequent redesign mitigated these vulnerabilities. In addition, the study presents quantitative analysis, including Root Mean Square Error (RMSE) evaluation and key safety metrics such as redundancy improvements, activation logic refinements, and pilot training reforms. These assessments offer practical insights for future flight control systems.

2. Methodology

This study evaluates the MCAS accident using a systems-based approach that combines James Reason's Swiss Cheese Model and Leveson's Systems-Theoretic Accident and Process (STAMP) in examining failures and the redesign response of the Boeing 737 MAX MCAS. These models were chosen because they complement each other: the Swiss Cheese Model highlights how alignment of defense layers and how they can fail, while STAMP explains how feedback and control breakdowns spread through a system. The flowchart in Fig. 2 outlines the methodology design flowchart.

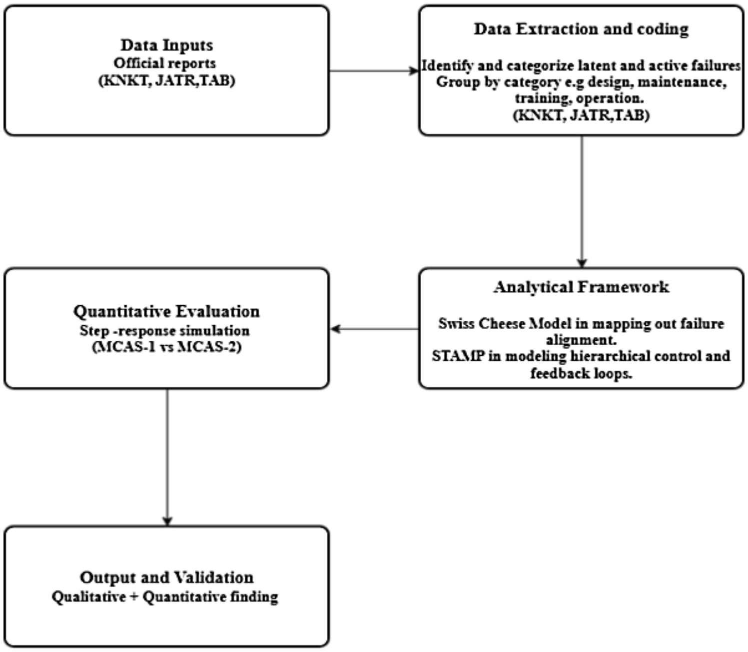

Fig. 2. Methodology design flowchart

The process begins with accessing official reports of the lion AIR flight 610 and Ethiopian Airlines Flight 302 from their aviation bodies, the Komite National Keselamatan Transportasi (KNKT) and the Ethiopian Civil Aviation Authority respectively [1, 2]. The data was extracted manually to categorize failures into latent or active failures using five classifications: design, certification, maintenance, training and operational response. Latent failure was defined as the hidden processes and problems the organization faced while active failure referred to the direct technical/human errors encountered. The Swiss Cheese Model [16] was used to visualize how the failures across the five categories lined up to create multiple weaknesses and pathways for the occurrence of the accidents. The STAMP model [17] was then used to map out control structures between the FAA, Boeing and the flight crew. This revealed where the feedback gaps fell in the system. The control structure diagrams and flowcharts utilized in this study were modeled using Diagrams.net emphasizing how missing constraints contributed to unsafe system behavior and extracted to the current paper. To complement qualitative findings, a comparative evaluation was conducted between Boeing's initial MCAS termed MCAS-1 and its post-crash redesign termed MCAS-2 for this study. This was done to determine whether the corrective measures taken after the crash effectively addressed the weaknesses identified through the Swiss Cheese and STAMP analyses. In addition, a simplified Root Mean Square Error (RMSE) simulation was carried out to compare control response between MCAS-1 and MCAS-2 under a 10-second, 0.5-second interval, instant activation scenario. RMSE was calculated using the following Eq. 1 [18]:

$$\text{RMSE} = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(y_i - \hat{y}_i)^2} \tag{1}$$

y_i is the periodic stabilizer deflection (actual trim angle at each step), $\hat{y}_i$ is the trim reference at the steady position and N is the total number of data points utilized. The RMSE results for the two scenarios were compared to evaluate the redesigned effect on control precision, where lower RMSE values indicate improved response stability. The RMSE parameters used in the analysis are summarized in Table 1. The study presents an evaluation of systemic weaknesses and the effectiveness of redesigned MCAS in mitigating them using system-theoretic models and quantitative performance analysis.

Table 1. Parameters used in RMSE analysis

Parameter	MCAS-1	MCAS-2	Source
Time range	0-10 seconds	0-10 seconds	Sampling choice
Time step	0.5 seconds	0.5 seconds	
Trim rate	0.27 °/s	0.27 °/s	
Maximum stabilizer deflection	2.5 °	0.9 °	MCAS logic
Reference trim position	0.00 °	0.00 °	Assumed Steady trim
Number of samples (N)	21	21	Calculated (10s /0.5s)
Activations	Multiple	One-time	FAA-RTS
Actual trim angle of each step	Trim rate * t	Trim rate * t	Calculated

3. Use of Causation Models

Accident causation models are widely used in identifying the how and why of accidents, revealing the interactions of the systems in theoretical frameworks. This paper utilizes Accident causation models, which are widely used in identifying the how and why of accidents, revealing the interactions of the systems in theoretical frameworks. This paper uses the Swiss cheese model and the STAMP model in evaluating the MCAS accidents.

3.1. Swiss cheese model

The Swiss cheese model, was developed by James Reason. It explains accidents as the result of latent conditions aligning with active failure. Each “slice” of cheese signifies a layer of defense, while the holes signify weaknesses within those defenses. When these weaknesses align across several layers, they create a pathway for hazards to pass through, resulting in failure occurrence.

The model emphasizes the importance of redundancy in critical safety systems, ensuring that even if a layer fails, others can still protect against risks. It is widely used as a tool for identifying, understanding and preventing risks in safety-critical systems. Table 2 provides a comparative analysis of the Lion Air Flight 610 and Ethiopian Airlines Flight 302 accidents using the Swiss Cheese Model framework.

Table 2. Comparative analysis of lion air 610 and Ethiopian airlines 302 using the Swiss cheese model

Defense Layers	Lion Air 610, October 29, 2018	Ethiopian Airlines 302, March 10, 2019
Design and Engineering	MCAS relied on a single AOA sensor. Repeated trim activations.	MCAS relied on a single AOA sensor. Repeated trim activations.
Certification	FAA delegated certification tasks to Boeing. FAA lacked knowledge of MCAS behavior. Boeing underestimated the risk of MCAS in its safety assessment.	Software fix implementation delayed The urgency of the risk model was underestimated.
Maintenance and repairs	The AOA sensor was not properly tested after replacement. Reoccurrence of faults is not fully addressed. The prior flight had experienced the same issue which was not fully reported.	Left AOA sensor failed. Absence of AOA disagree indications.
Pilot training and Manuals	MCAS is omitted in manuals. Pilots are unaware of the MCAS system behavior. No simulator training or MCAS-specific procedures.	Incomplete Emergency AD guidance. Full procedures on the cutout switch were not adhered to. No simulator training or MCAS-specific procedures.
Operational response	In-flight failures triggered activation of multiple alerts. Active stick shaker. Pilots are overwhelmed by work overload.	Aerodynamic forces greatly exceeded manual trim. Multiple alerts and the stick shaker are active. Pilots are overwhelmed by work overload.

The findings in Table 2 show that the two separate accidents shared a similar trajectory and had recurring system-level weaknesses. The Swiss cheese model reveals that the accidents were not isolated but resulted from the alignment of failures across design, certification, maintenance, training and operational response as shown in Fig. 3, which shows the modelled Swiss cheese analysis.

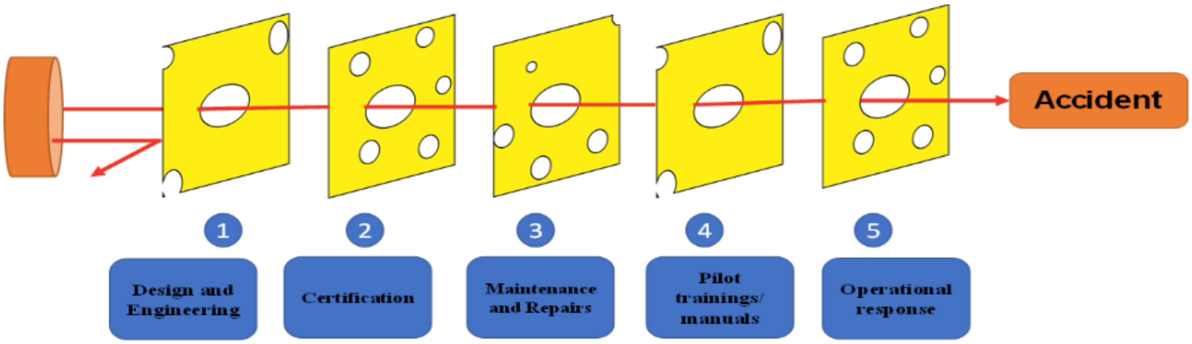

Fig. 3. Causation factors using the Swiss cheese model

Fig. 3 reveals the several latent conditions that aligned with erroneous AOA sensor data before the accidents occurred and hence underscoring how fragmented safeguards can allow a common hazard to penetrate defense layers, forming a clear accident pathway.

3.2. STAMP model

The STAMP model was introduced by Leveson [17], who approaches accidents as a result of inadequate control in complex socio-technical systems. It identifies accidents through three main categories: safety constraints, Hierarchical control structure, and process model. The model was designed because most traditional models focus on the sequence of events. STAMP views safety as a control problem, emphasizing how system components; people, software, hardware, and organizations interact dynamically through control actions and feedback loops.

The hierarchical control structure refers to multiple layers of control and decision-making that exist within a system. In this study, the top layer in the control structure is the Federal Aviation Administration (FAA). The FAA is the regulatory authority responsible for enforcing safety constraints, certification oversight, delegation of approval through the Organizational Designation Authorization (ODA) program and investigation of accident reports. The intermediate layer is Boeing's engineering and management. They are responsible for designing and manufacturing. At the operational level are the pilots. The pilots interact directly with the aircraft's automated system forming the final control loop where feedback and humans interact. The incomplete feedback across the hierarchy from the regulators to the designers to the operators is illustrated in Fig. 4, where the missing feedback between the levels such as insufficient regulatory oversight and limited pilot understanding of the system, is captured.

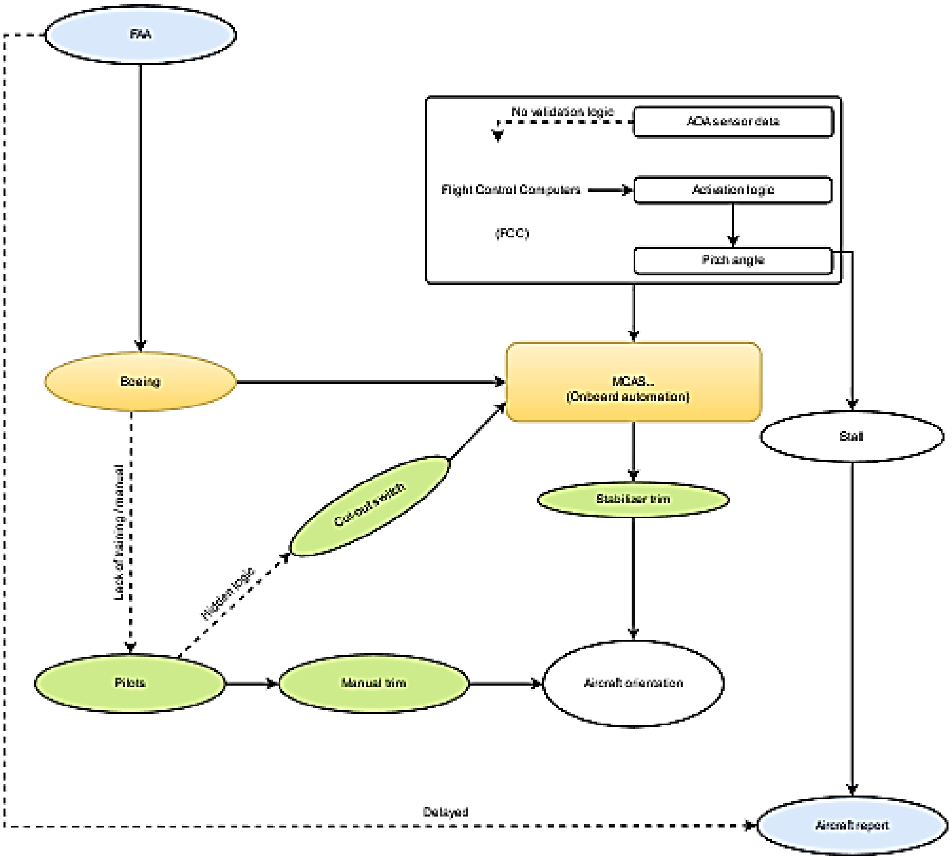

Fig. 4. MCAS analysis employing STAMP model

3.3. Interactions across system components in the STAMP Model

The interactions across the systems are further broken down to understand the interplay of factors, which include:

3.3.1. MCAS system

The MCAS system is the system of discussion, which was categorized by certain factors contributing to the accidents as follows:

- Relied on a single AOA with no validation logic or redundancy. This alone violates the basic fault-tolerance principle.
- Exhibited aggressive behavior i.e. repeatedly activating the system in short time intervals.
- The pilots did not understand the system, as it lacked an effective Human-Machine Interface (HMI) feedback mechanism.
- Omitted adequate alerting systems, which would have notified the pilots of faulty sensor data.

3.3.2. Regulatory oversight

The regulatory body responsible for regulation and oversight has been identified as the FAA, which is the top layer in the STAMP hierarchy. The FAA played a role in the accidents through:

- Delegating certification to Boeing under the ODA program. This created a structural conflict of interest during approval processes.
- Permitted Boeing's deferrals in software validation and risk reevaluations even after early sensor anomalies were reported.

3.3.3. Boeing

As the body responsible for the design and manufacture of the MCAS system, Boeing played a major role in the accidents as follows:

- Failed to disclose the system's full functionality to the flight crews and regulators, creating transparency gaps.
- Provided no detailed MCAS training or simulations. Instead, they assumed how pilots would react when faced with MCAS activations.
- Wrongly misclassified un-commanded MCAS activation as "major" and not "hazardous "as seen, this permitted the existence of the system without redundancy requirements present.
- Operated on the flawed assumption that pilots could counter repeated nose-down trim by using manual trim controls. However, simulator investigation testing showed MCAS-induced trim requires up to 40 manual turns to neutralize MCAS input [19].

3.3.4. Pilot handling

- Pilots experienced a high workload during MCAS activations.
- Automation bias: This was a result of a limited understanding of MCAS logic.

The Stamp model reveals that MCAS accidents were not the outcome of a single software error but the result of inadequate control in structures and weak feedback system levels, allowing flawed assumptions and the combination of faults to evolve into failure.

4. MCAS Redesign (Post-crash)

The 737 crash accidents are a tragic reminder and a hard lesson that oversight of Safety in systems can lead to drastic consequences. In the case of MCAS, there was the tragic loss of 346 lives and the impact on Boeing's reputation.

4.1. Effect of MAX crashes on boeing's deliveries

Before the MAX crashes, the 737 MAX had become one of Boeing's fastest-selling aircraft in history. By the end of 2018, 737 MAX had achieved nearly 330 deliveries and over 4700 firm orders, marking a major commercial success in the narrow-body passenger aircraft market [20]. However, following the grounding of the fleet in 2019, Boeing's deliveries dropped significantly. This allowed Airbus to gain a competitive advantage in the single-aisle market. Table 3 shows comparative data on Airbus and Boeing's deliveries from 2018 to 2025.

Table 3. Annual deliveries of Boeing 737 vs Airbus A320

Deliveries	Boeing 737	Airbus 320
2018	580	626
2019	127	642
2020	43	446
2021	263	483
2022	387	516
2023	396	571
2024	265(MAX only)	602
2025(Half year)	209	232

The data in Table 3 highlights how the 737MAX grounding disrupted Boring's delivery schedule.

4.2. Direct costs boeing incurred post-MCAS incidents

Following the MCAS crashes, over 380 MAX aircraft worldwide were grounded. This resulted in significant financial losses across Boeing and its customer airlines. Fig. 5 illustrates the distribution of direct costs Boeing incurred post-accidents expressed as a percentage.

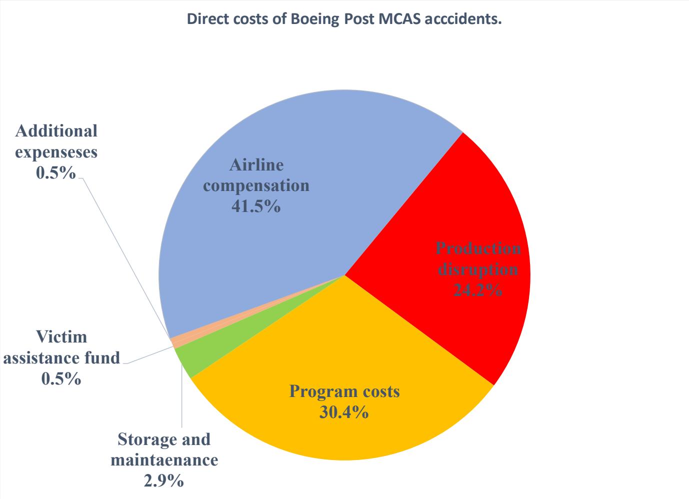

Fig. 5. Pie chart showing the direct costs of Boeing Post MCAS incidents

From Fig. 5, the largest portion with 41.5% of losses, was attributed to airline compensation, this reflects financial settlements required to offset the disruption of their customer airline. Program costs account for about 30.4%, representing the redesign, re-certification, and software update efforts that were carried out following regulatory investigations. Production disruption costs attributed to 24%, arising from the suspension and delayed assembly of the 737 MAX. Also, about 3% to storage and maintenance charges, 1% to victim-assistance and 1% to miscellaneous expenses.

In total, the crisis cost Boeing an estimated over $20.7 billion in expenditures [21], more than four times the $5 billion that would have been required to implement comprehensive simulator training for all 737 MAX pilots before the accidents. This lesson highlights the economic magnitude of implementing proper safety measures and transparency. Importantly, training on aviation systems is not an optional cost but an essential safety investment.

4.3. Timeline of MCAS systems with respect to pilot trainings

Evidence shows that comprehensively training pilots on MCAS could have prevented the accidents. If the flight crew had been trained on the system's logic, activation triggers, and proper procedures for response, they would have recognized MCAS activation and reacted appropriately, using the stabilizer trim CUTOUT switches.

In both crashes, the pilots struggled continuously with the system, attempting to regain control when MCAS was repeatedly commanding nose-down activations. This occurred approximately 21 times before impact. These events highlight the importance of comprehensive training, and the danger of making assumptions about pilots' reactions, especially under high-pressure conditions. Boeing engineers had assumed pilots would instinctively counter MCAS inputs through manual trim control, however, this assumption proved flawed in real-world events [22, 23]. Fig. 6 presents the timeline from the certification to the implementation of training of the 737MAX aircraft.

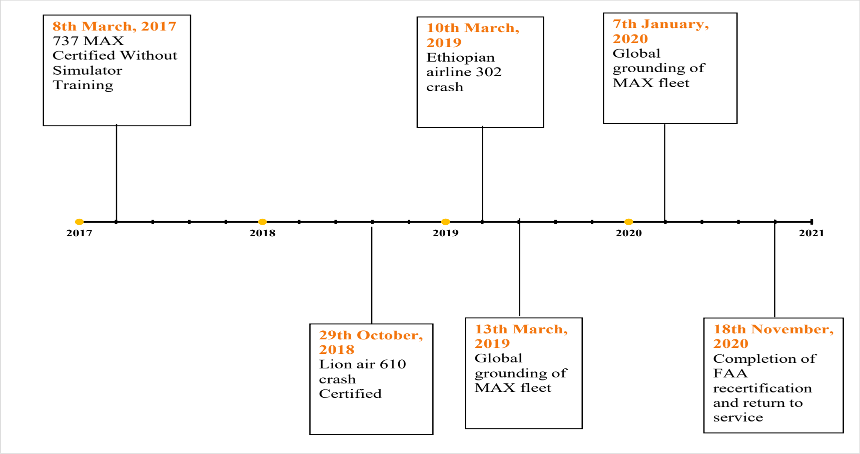

Fig. 6. Simulator training event timeline of 737 MAX

Preceding the 737 MAX crashes, the aircraft experienced a worldwide grounding. This prompted extensive investigations, major regulatory and engineering revisions of the MCAS system [15]. These modifications were implemented to restore safety, public trust and ensure compliance with renewed oversight standards. After a series of evaluations and validations by regulatory bodies, the 737 MAX was ultimately cleared to return to service [24].

4.4. Qualitative comparison evaluation

This section includes a qualitative comparison between the originally designed MCAS termed MCAS-1 and the redesigned MCAS termed MCAS-2 for this study. The comparison was conducted across key operational safety metrics highlighting the design logic, and training enhancements introduced after the crashes. This was carried out to ensure modifications directly addressed the specific failures in the original system. The comparison in Table 4 clearly shows that the redesign of the MCAS moved away from a single-point-failure system and toward one that is redundant, pilot-controlled, and more fault-tolerant. All taken together, these improvements address technical fixes as well as a systemic shift toward transparency, pilot preparedness, and sound automation design.

Table 4. Comparative evaluation of MCAS-1 and MCAS-2 post-accident assessment

Metrics	MCAS-1	MCAS-2
Angle of Attack (AOA)	Single sensor dependency.	Dual AOA sensors, with a 5.5° disagreement threshold
Pitch Rate command	Repetitive nose-down movements at a rate of 0.27°/s	Single, limited input per elevated AOA event
Stabilizer movement and time	Commanded stabilizer about 2.5° nose-down at a rate of 0.27°/s for up to 9.26 seconds.	The magnitude of nose-down input is restricted to a single-instance command.
Activation Logic	Repeated automatic trims -5-second loop	One-time activation, reset logic, and no trim repeat
Override Capability	The system had control authority	Pilots now hold more authority, can override the system using the yoke trim switch or cutout switch to override MCAS (manually)
Pilot training	Pilots were subjected to only	Mandatory pilot simulator training on MCAS behavior
Post-redesign safety	Two accidents in 400,000 hrs.	Zero accidents in over 3M+ hrs.

4.5. Quantitative comparison- Root Mean Square Error Performance Evaluation

In addition to the qualitative safety improvements and system redesigns, a qualitative performance comparison was carried out using the Root Mean Square Error (RMSE) method in the evaluation of the accuracy of MCAS-1 and MCAS-2 under a step input scenario. The RMSE simulation was carried out on the pitch trim response and systems aggressiveness calculated using:

$$\text{RMSE} = \sqrt{\frac{1}{N}\sum_{I=1}^{N}(y_i - \hat{y}_i)^2} \tag{2}$$

Root Mean Square Error (RMSE) calculation for MCAS-1 and MCAS-2 under the 10-second and 0.5-second sampling interval step-input scenario shows a substantially reduced deviation of the trim reference state of MCAS-2. This reflects improved control accuracy and system stability.

Note, The RMSE values for MCAS-1 and MCAS-2 are used here to show how accurately each system follows the intended control response. However, RMSE only indicates differences in performance, it does not fully represent the overall system. MCAS-1 has a higher RMSE value of 1.68° (Table 5), which means it produces larger and more aggressive trim movements reaching a maximum of 2.5° and leading to repetitive trim events. While MCAS-2 has a lower RMSE value of 0.7889° showing improvements and a more stable behavior due to limited control authority. A reduced maximum trim deflection of 0.9° and a one-time activation.

Table 5. RMSE arithmetic simulation values

I	Time (s)	MCAS-1 Stabilizer Deflection (°)	Reference Trim (°)	Squared Error (°²)	MCAS-2 Stabilizer Deflection (°)	Reference Trim (°)
1	0.0	0.000000	0	0.000000	0	0
2	0.5	-0.135000	0	0.018225	-0.135	0.018225
3	1	-0.270000	0	0.072900	-0.27	0.0729
4	1.5	-0.405000	0	0.164025	-0.405	0.164025
5	2	-0.540000	0	0.291600	-0.54	0.2916
6	2.5	-0.675000	0	0.455625	-0.675	0.455625
7	3	-0.810000	0	0.656100	-0.81	0.6561
8	3.5	-0.945000	0	0.893025	-0.9	0.810000
9	4	-1.215000	0	1.476225	-0.9	0.810000
10	4.5	-1.350000	0	1.822500	-0.9	0.810000
11	5	-1.485000	0	2.205225	-0.9	0.810000
12	5.5	-1.620000	0	2.624400	-0.9	0.810000
13	6	-1.755000	0	3.080025	-0.9	0.810000
14	6.5	-1.890000	0	3.572100	-0.9	0.810000
15	7	-2.025000	0	4.100625	-0.9	0.810000
16	7.5	-2.160000	0	4.665600	-0.9	0.810000
17	8	-2.295000	0	5.267025	-0.9	0.810000
18	8.5	-2.430000	0	5.904900	-0.9	0.810000
19	9	-2.565000	0	6.579225	-0.9	0.810000
20	9.5	-2.700000	0	7.290000	-0.9	0.810000
21	10	-2.835000	0	8.037225	-0.9	0.810000
			SSE MCAS 1	59.176575	SSE MCAS 2	12.998475
			MSE	2.817932	MSE	0.618975
			RMSE	1.678669754	RMSE	0.786749643

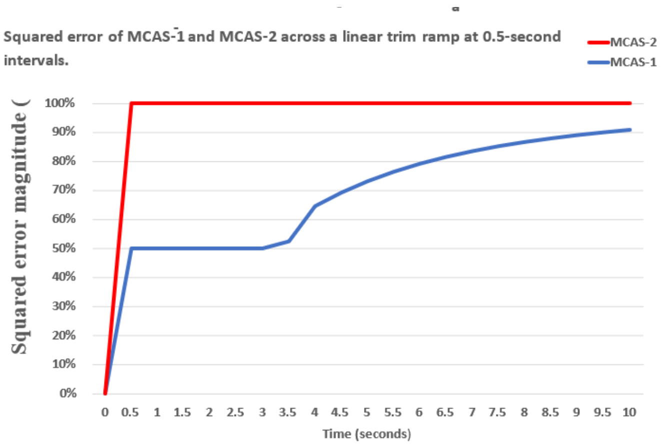

Fig. 7. Line chart showing the squared error of MCAS-1 and MCAS-2 across a linear trim ramp

The additional changes on the redesigned MCAS ascertain that the redesigned MCAS can achieve greater control stability and reliability, demonstrating the effectiveness of the modifications in reducing risk, reinforcing redundancy, and ensuring sustained regulatory compliance [25].

5. Results and Discussion

This study combined two complementary causation frameworks (Swiss Cheese and STAMP) with a quantitative control-performance comparison (RMSE) and qualitative comparison to evaluate the MCAS failures and the effectiveness of the post-crash redesign. Findings demonstrate that the MCAS accidents were not isolated technical failures but the result of interacting weaknesses across design, certification, maintenance, and training. The Swiss Cheese mapping of Table 2 and Fig. 3 illustrated how the Lion Air 610 and Ethiopian 302 crashes followed nearly identical paths: latent system design flaws, inadequate monitoring of certification, poor maintenance verification, and omitted pilot training synchronized with the concurrent failure of faulty AOA data. These synchronized "holes" through consecutive layers of protection provided a continuous accident pathway. The STAMP model in Fig. 4 showed how inadequate feedback and control propagation across levels of the hierarchy—FAA → Boeing → Flight crew—allowed unsafe system logic to persist. Delegated certification within the ODA framework, "major" classification of the MCAS failure mode, and lack of clear flight-crew communication or alerts were all significant contributors.

Quantitatively, the RMSE difference between the initial and redesigned systems showed statistically significant control stability improvement. Under a 10-second, 0.5-second interval instant-activation simulation, MCAS-1 had an RMSE of 1.68° and MCAS-2 had 0.79°, a 53% reduction in control deviation, capturing the performance improvement precisely as the redesign's technological changes: dual-AOA input, bound single-activation logic, reduced stabilizer authority, and increased pilot override as seen in Table 5 and Fig. 7. Operational evidence reveals the accidents occurred approximately 400 000 hours to MCAS design, but no occurrence in over three million hours of flight since redesign has been reported.

The study presented significant economic losses that Boeing encountered following the crash. An estimate of 20.7 billion US dollars, with airline compensation amounting to ≈41.5% and Program costs ≈30% as contained in Fig. 5. The resulting loss was significantly higher than the estimated 5 billion US dollars required for simulator training expense which could have prevented the accident occurrence. This shows that safety investment is not only ethical but financially prudent.

Collectively, the Swiss Cheese and STAMP validate the occurrence of accidents from a combination of failures from design flaws, organizational control gaps etc. while RMSE and operational performance measures quantified the improvement achieved in the redesigned system. The results corroborate that safety is achieved by system-wide transparency, redundancy, and strict regulatory scrutiny rather than a fragmented technical solution.

6. Conclusions

The current study conducted an analysis on Boeing 737 MAX MCAS accidents utilizing an integrated model approach. The data utilized in the models were obtained from regulatory bodies and the Boeing website. The Swiss cheese model and STAMP model ascertained that accidents were not merely technical but a combination of failed structures across the design, certification, and training of the system. This enables a better understanding of the sequence of failure occurrences as aviation accidents are usually a combination of several factors. Furthermore, a simplified RSME simulation was carried out to get a numerical value on the control performance of the MCAS system. The findings determined that MCAS-2 can achieve measurable control accuracy and improvements to the MCAS system addressed the technical concerns of flight safety. Furthermore, the study emphasized that deficiencies in communication, certification, and human-automation integration are central to the original system's breakdown. Hence effective safety reform must prioritize redundancy at the design stage, transparent disclosure of automation functions and rigorous independent certification and testing before operational release.

7. Future Work

Results from the study suggest that future work should build on the integration of the Swiss Cheese and STAMP models on other aircraft systems and other high-risk automation domains. To enable the identification of recurring patterns in systems, the future research may consider the RMSE analysis using higher-fidelity simulations that include pilot inputs and environmental factors, to provide a better assessment of MCAS behavior.

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