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Advancing Cascading Effects Analysis in Aviation: A Systematic Literature Review

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With technological advancements, modern aircraft are incorporating new functions and features, along with increased levels of automation. As a result, aircraft systems are becoming more integrated and complex, making safety analyses increasingly challenging without the support of appropriate methods and tools. The high degree of system integration and the extensive interconnections between components can trigger cascading failures, potentially causing undesirable effects at the highest levels of aircraft functions. Cascading Effects Analysis (CEA) is a bottom-up technique, proposed by SAE ARP-4761A to assess the effects of such failures. However, the traditional CEA approach relies on manual processes, requires data from multiple sources, is time-consuming, and heavily depends on the safety engineer's expertise, making the analysis subjective and error-prone. This paper conducts a literature review on the state-of-the-art methods and techniques for Cascading Effects Analysis, with a focus on identifying gaps and limitations in current techniques. Using the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) methodology, 359 papers were initially identified, with 15 selected for in-depth review. The review considered the following aspects: proposal, scope, methods and tools, case study, results, and conclusion. Based on this review, the paper aims to highlight new perspectives and opportunities for advancing Cascading Effects Analysis methodologies.

Keywords: cascading failure, cascading effects, CEA, failure propagation.

1. Introduction

Complexity, according to SAE ARP-4754B (2023), refers to an attribute of functions, systems or items, that indicates how difficult it is to understand their operational logic, failure modes, and failure effects without the help of analytical tools for a systematic and comprehensive analysis. Hollnagel and Goteman (2004) define complex systems as those made up of numerous subsystems that encompass multiple functions, and although they are designed to operate in a standardized and predictable manner, their interactions produce variable results, both positive and negative. Avizienis et al. (2004) address complexity as a critical factor in computational systems, emphasizing that the complexity of systems represents a challenge. The authors note that this increasing complexity may exceed human comprehension, making it difficult to identify the causes and consequences of failures.

In modern aircraft, the level of complexity is being increased with the introduction of many functionalities, automated systems and resources to support them. To address this complexity, advanced high-performance computing platforms performing multiple functions are used, while optimizing space and weight through a highly integrated approach (DO-297, 2005).

Until the 1970s, aeronautical systems were purely analog, with federated systems and a low level of integration and complexity. In the 1980s, aircraft began using digital systems, data buses, and multiple sensors, resulting in increasing integration between systems (Spitzer et al., 2017). In 1988, the first commercial aircraft with a fully digital fly-by-wire (FBW) system entered into service, the Airbus A320 (Nicolin and Nicolin, 2019; Airbus, 2025). From the 1990s onward, there was a growing evolution in aeronautical systems with the use of IMA (Integrated Modular Avionics) architectures and fully integrated

standardized digital buses, increasing the level of complexity (RTCA DO-297, 2005).

However, since highly integrated computing platforms perform, control and monitor multiple functions, and interface with other equipment and systems, they are susceptible to triggering failures, that may cause undesired effects on aircraft-level functions. This type of failure is referred to as "cascading failure", which originates from an initiating failure mode and causes subsequent failures, directly and indirectly, due to dependency between systems and equipment (SAE ARP-4761A, 2023). Failure (or fault) propagation is another term commonly used to describe the phenomenon of the cascading failure.

SAE ARP-4761A (2023) establishes the Cascading Effects Analysis (CEA) as a qualitative bottom-up analysis technique for evaluating the effects of cascading failures. CEA focuses on initiating failures modes involving resources systems that share power, signals or information across multiple systems.

It is important to emphasize the difference between Cascading Effects Analysis (CEA), Fault Tree Analysis (FTA) and Failure Mode and Effects Analysis (FMEA). According to SAE ARP-4761A (2023), FTA is a top-down analysis, both quantitative and qualitative, which focuses on one particular undesired event to determine causes of such event; while FMEA is a bottom-up method of identifying the failure modes of a system, or item and determining the effects on next higher level.

Therefore, these methods are understood to be complementary and sequential. FMEA identifies the sources of local failures; CEA shows how these failures can interact and propagate across interdependent systems; and FTA integrates failure modes into a logical cause-and-effect structure that quantifies risk.

Over the years, numerous studies have been conducted to enhance these analysis methods by developing system models, simulating failures, and automating the evaluation processes.

Given this introduction, this paper intends to map the state-of-the-art on methods and tools developed for cascading failure analysis. The purpose is to evaluate gaps and limitations of current techniques in order to identify new perspectives and ideas for further development in the field of cascading failure analysis methods.

2. Research methodology

This literature review follows the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) methodology (Page et al. 2021), ensuring a transparent and systematic selection of relevant studies.

The research question was structured according to a PICO framework (Population, Intervention, Comparison, Outcome), adapted to engineering systems, to answer the following questions: RQ1: How do advanced modelling approaches support cascading failure analysis in complex aeronautical systems compared to traditional safety assessment methods? RQ2: What methods have been proposed in the literature, and what gaps and limitations remain in current cascading failure analysis approaches?

The search terms were combined into the following search string, which was applied to titles, abstracts, and keywords:

("failure propagation" OR "fault propagation" OR "cascad failure" OR "cascad* effect analysis" OR CEA OR "multiple failure*" OR "common mode") AND (system OR systems) AND (aircraft OR aviation OR aeronautic OR aerospace) AND safety*

Queries were conducted in Scopus, IEEE Xplore Digital Library and Web of Science databases, initially in April 2025 and updated in October 2025. A total of 346 records were retrieved from databases, and 13 additional records were identified from other sources, resulting in 359 records.

The time frame selected for the search was based on the Bibliometric Analysis presented in section 3. This time range between 2019 and 2025 shows a growing trend in publications within the study topic and encompasses the most recent advances in the research area.

Following the PRISMA process, duplicate records were removed and titles and abstracts were screened to exclude records outside the scope, including those published before 2019. Full-text reports were then assessed against predefined eligibility criteria. Reports unrelated to the topic, employing only traditional methods without methodological innovation, focusing solely on tool implementation, or unavailable in full text were excluded. After the application of the eligibility criteria, 15 studies were included for in-depth review. Figure 1 presents the PRISMA flowchart for the selecting process.

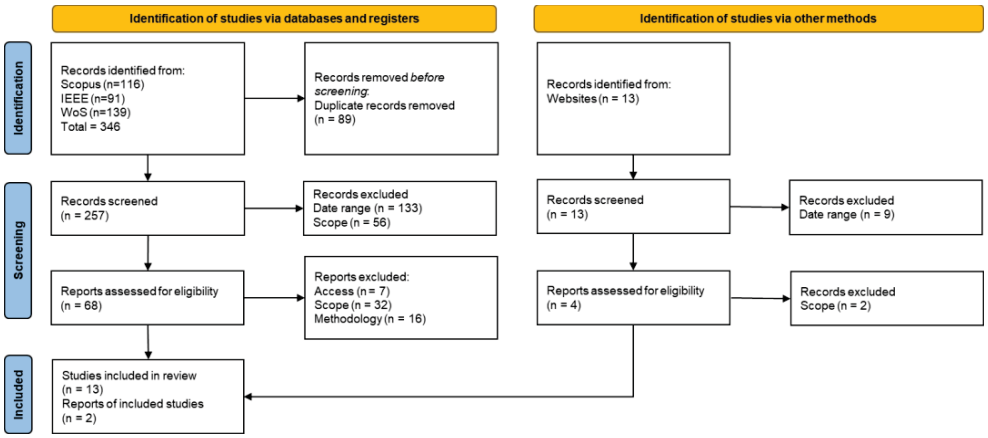

Figure 1: PRISMA flowchart

3. Bibliometric analysis

A preliminary dataset regarding all data range was exported to Excel for bibliometric analysis, with the annual distribution of publications and citations shown in Figure 2.

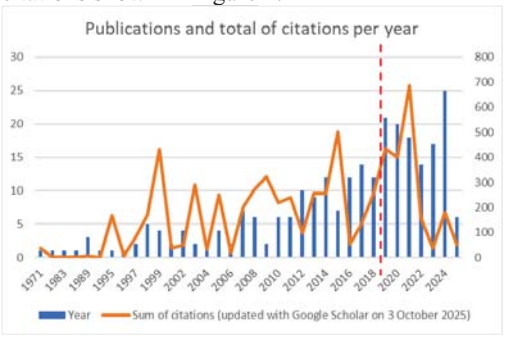

Figure 2: Publications and total of citations per year

4. Background

By the late 1990s, advances in aeronautical systems, particularly the adoption of IMA architectures and standardized digital buses, stimulated research on cascading failure and propagation within the Model-Based Safety Analysis (MBSA) context. MBSA is a framework that supports fault modelling, automated safety assessment and risk validation (Sun et al., 2024).

Following this perspective several authors have conducted research to develop methods and tools aligned with the MBSA approach.

Papadopoulos et al. (1999) propose the HiP-HOPS (Hierarchically Performed Hazard Origin and Propagation Studies) method, addressing system complexity and enabling integrated analysis from the functional to the component level.

The projects ESACS (Enhanced Safety Assessment for Complex Systems, Bozzano et al., 2003) and ISAAC (Improvement of Safety Activities on Aeronautical Complex Systems, Akerlund et al., 2007) propose methodologies and platforms to integrate and support safety activities, from the early stages of the project, based on formal models and automatic verification methods, supported by commercial tools. From ESACS and ISAAC projects, FSAP-NuSMV-SA platform emerged as an integrated environment for modelling, simulation, and failure analysis, based on formal system model (Bozzano and Villafiorita, 2007). These projects later evolved into the COMPASS toolset (Bozzano et al., 2019) and subsequently into xSAP (Bittner et al., 2016).

Joshi et al. (2005) propose an extension of the system development model (Extended System Model), incorporating fault information into the system model. Nevertheless, this could compromise future code generation for software implementation and hinder the evolution of the extended model.

Over the years, in line with the MBSA approach, additional methods and modelling languages have been proposed. Methods such as FPTC (Fault Propagation and Transformation Notation) and FPTN (Fault Propagation and Transformation Calculus) (Wallace, 2005), and FFIP (Functional Failure Identification and

Propagation) (Kurtoglu and Tumer, 2007) represent a transition from conventional failure analysis techniques to dynamic, model-based approaches. Modelling languages such as AltaRica (Arnold et al., 1999; Prosvirnova et al., 2013) and AADL/AADL-EMV2 (Feiler et al., 2004; Procter and Feiler, 2020) aims to automate safety analysis regarding dysfunctional behaviour.

5. Literature Review

When dealing with complex systems, it is essential to consider the system's hierarchical structure and to clearly establish the coupling relationships between functions and components. Jiang et al. (2020) propose a formal method for analysing the coupling correlation of hierarchical structures based on the task-function-resource (T-F-R) model. Furthermore, based on multidimensional theory (probability, severity, time) the authors applied mathematical and algorithmic techniques to quantify the coupling relationships in the hierarchical structure; but the method does not map the effects of the failures. Grounded on a similar hierarchical task-function-resource model as proposed by Jiang et al. (2020), Dong et al. (2024) propose a mathematical and probabilistic model of fault propagation based on a discrete dynamic system, yet it is limited to IMA system.

SysML is a widely used graphical modelling language to aid in the specification and design of complex systems, representing hierarchy and interconnections between elements; yet, due to a lack of formal semantics, SysML is not effective for fault analysis without specific extensions (Hu et al., 2019).

On this basis, various research projects are being developed to create extensions and plugins, and to apply SysML to safety analysis. Wu et al. (2020) proposes an operational state-oriented safety analysis method for cascading failures analysis, through dynamic and dimensional safety analyses using SysML to map the propagation paths, root cause and minimum cut-sets. Even so, the method is more similar to FTA.

Hecht and Baum (2019) present a method for modelling fault propagation within SysML to enable automated FMEA generation, incorporating an integrated analysis of cybersecurity, reliability, and safety. In a related work, Hecht et al. (2020) present a method for automating FMEA generation using the SysML modelling language, implemented via a custom-developed plug-in. In both methods yet, a fundamental limitation is the reliance on expert inputs to define failure modes and evaluate results.

Graph-based methods are widely used in fault propagation analysis because they provide a structured and visual representation of causal relationships. Timed Failure Propagation Graphs (TFPG) is a directed causal graph method that models fault propagation, their effects, and captures the temporal aspects of the process.

Several variations of the method are proposed, such as the Real-Valued Timed Failure Propagation Graphs (rTFPG), proposed by Chen et al. (2021), which expands the TFPG method to continuous signal domains. Still, because this approach combines human expertise with computational precision, it is not fully automated. Peng and Zeng (2022) also propose an extension of the TFPG method, based on evidence uncertainty quantification theory, Evidential Belief Time Failure Propagation Graphs (ETFPG), adding failure occurrence uncertainty attributes to calculate the final Belief Interval (BI) occurrence classification. Despite this advancement, the ETFPG model is constructed manually, and as the model becomes more complex, the computational cost associated with BI calculations tends to increase.

Signed Directed Graph (SDG) method models the propagation of faults in complex process systems to identify fault propagation paths and root causes. Jiao and Zhen (2020) adopt the SDG method to model the avionics system and uses a matrix form to represent the directed graph model for studying fault propagation. Ma et al. (2024) propose a method based on network modelling to analyse failure propagation in avionics systems and how this impacts maintenance in civil aviation airlines. Nonetheless, the focus of these studies is for fault diagnosis and troubleshooting in maintenance line.

Integrated System Failure Analysis (IFSA) is an inductive method for qualitative digital system failure analysis, combining FFIP for hardware failures and Failure Propagation and Simulation Approach (FPSA) for software failures (Mutha et al., 2013). Mansoor et al.

(2023) propose an inversion of the IFSA method. The authors introduce a deductive method for tracing backward failure propagation paths, progressing from functional level down to the component level. The method employs Propositional logic (PL) to reverse the IFSA technique. The model, however, is still abstract, and requires simplification for large systems.

Fuzzy logic is a branch of mathematics that address uncertainty and imprecision using degrees of membership between 0 and 1 rather than binary values, enabling more realistic modelling of ambiguous information (Zadeh and Aliev, 2018; Tamir et al., 2015). Several studies have applied fuzzy logic to represent the complexity of faults in highly integrated systems. Although Wang et al. (2021) do not specifically address aeronautical systems, they propose an expert-based method that integrates FFIP with fuzzy logic to assess the risk of functional failures, modelling failure correlations and addressing limited data and uncertainty. Compared with the traditional approaches, Fuzzy-FFIP enhances risk granularity and reduces uncertainty, on the other hand, its effectiveness depends on the specification of membership functions and supporting values.

Ezhilarasu and Jennions (2020) propose a diagnostic method focusing on detecting and isolating faults that propagate to other systems. The method combines a realistic digital twin with a neuro-fuzzy monitor for systemic failure detection, however the method does not cover multiple or simultaneous failures.

Petri Nets are a formal modelling language that integrates mathematical theory with graphical representation, widely employed to model, analyse, and visualize the dynamic behaviour of discrete-event systems (Wang, 2016, p. 297). Liu et al. (2023) propose a method for analysing failure propagation paths by combining FMEA, Petri Nets and Fuzzy logic. Petri Nets allows modelling the dynamics and logic of failure propagation, while fuzzy logic allows modelling the uncertainty and complexity inherent in the cause-and-effect relationships of failures, making the analysis more realistic. However, few technical details regarding the application of the method are provided. Zeng and Sun (2023) present a reliability analysis technique for complex system incorporating fuzzy failure probabilities and failure dynamic behaviour. The method combines Generalized Stochastic Petri Nets (GSPN) and Dynamic Fault Trees (DFT), and employs a more refined Monte Carlo simulation through Latin Hypercube Sampling (LHS). Yet, method does not take into account fuzzy numbers with more complex membership functions.

The methodology proposed by Mathou et al. (2024) integrates operational procedures with system architecture to enhance safety analysis, revealing failure paths and interactions not evident when analysed separately. Implemented using the AltaRica DataFlow (ADF) language within the Cecilia Workshop environment, the approach generates fault trees and computes minimum cut sets. Although some inconsistencies were noted during validation, the study highlights the potential of MBSA to support automated safety evaluations and suggests further development using FRAM (Functional Resonance Analysis Method) and higher-order programming languages.

6. Discussion

Table 1 summarizes the main modelling methods and languages employed in the articles analysed in this literature review and lists the main gaps and limitations.

Since the late 1990s, several modelling methods and languages, such as HiP-HOPS, AltaRica, AADL, FPTN/FPTC, and FFIP, have been explored. Although traditional SAE ARP-4761A (2023) methods, including FTA and FMEA, are widely used, they do not explicitly address cascading failures. CEA introduced in SAE ARP-4761A (2023) targets cascading effects but remains largely theoretical and lacks automation. In parallel, SysML-based and graphical approaches, such as TFPG and SDG, have been extensively applied and studied.

More recently, other techniques for risk analysis have emerged in this research area, including Petri Nets (such as GSPNs), Bayesian Nets (BN), and fuzzy theory. These techniques may be combined with other methods, such as FMEA and FTA, to improve the failure analysis in complex systems.

Table 1: Approaches to Systems Safety Modelling and Analysis

Author/year	Methods	Gaps / Limitations
Hecht and Baum, 2019	SysML	Reliance on expert input.
Jiang et al., 2020	T-F-R model	Does not map the effects of the failures.
Wu et al., 2020	SysML	Similar to FTA.
Jiao and Zhen, 2020	SDG	Focus on fault diagnosis and troubleshooting.
Hecht et al., 2020	SysML	Reliance on expert input.
Ezhilarasu and Jennions, 2020	Fuzzy	Does not cover multiple or simultaneous failures.
Chen et al., 2021	rTFPG	Not fully automated.
Wang et al., 2021	FFIP/ Fuzzy	Depends on membership functions and supporting values.
Peng and Zeng, 2022	ETFPG	High computational cost.
Mansoor et al., 2023	IFSA	Still abstract, requires simplification for large systems.
Zeng and Sun, 2023	Petri-nets	Does not consider fuzzy numbers with more complex membership functions.
Liu et al., 2023	Fuzzy/ Petri-nets	Few technical details.
Dong et al., 2024	T-F-R model	Limited to IMA system.
Ma et al., 2024	SDG	Focus on fault diagnosis and troubleshooting.
Mathou et al., 2024	ADF / FRAM	Further development using FRAM and higher-order programming languages.

Petri Nets allows modelling the dynamics and logic of failure propagation. Bayesian Nets may provide inference and analysis of uncertainty and causal dependence. Fuzzy theory may be applied to model the uncertainty and complexity inherent to cascading failure in complex system.

The Functional Resonance Analysis Method (FRAM) is a method designed to investigate accidents, but with the appropriate modifications, it can allow for prospective risk assessments. Mathou et al. (2024) suggests further development using FRAM for modelling failure propagation. Some important points yet must be observed when using FRAM. It is not an automated method, requiring considerable manual effort to input information into the model. Furthermore, FRAM adopts a qualitative approach, focusing on studying the variability and dynamics of the system (Hollnagel, 2012). In this way, combining FRAM with quantitative techniques, such as Fuzzy theory, Monte Carlo simulation, and others, is often a promising way to have a quantitative approach. Additionally, FRAM's capability to model the absorption of variability offers an interesting perspective for representing fault propagation in complex systems, as it captures the influence of redundancies and mitigation strategies.

7. Conclusion

This literature review evaluated the state-of-the-art methods and techniques for cascading failures analysis and highlighted new perspectives for advancing these methodologies.

The reviewed articles indicated that traditional methods, such as FTA, FMEA and CEA, as described in SAE ARP 4761A (2023), remain well established in practice. However, these methods generally provide limited support for automation and for representing complex interdependencies in highly integrated systems.

Methods that emerged with the advancement of MBSA, including HiP-HOPS, AltaRica, AADL and SysML, have been widely investigated in the literature and provide improved support for architectural modelling and automated analysis.

In addition, techniques not originally developed for cascading failure analysis, such as Petri Nets, Bayesian Nets, Fuzzy theory, and Monte Carlo, have received increasing attention in recent years. These approaches are particularly useful for modelling complex and dynamic systems, as well as handling uncertainties and inaccuracies inherent in faults in complex systems.

Another key challenge identified in the literature is the proper modelling of hierarchical structure and couplings in complex systems. In aeronautical products, this typically involves the representation of aircraft-level functions, decomposing them into system-level functions, and mapping them onto the physical architecture and its components. Jiang et al. (2020) and Dong et al. (2024) present insightful applications of the formal task-function-resource model to represent a hierarchical system structure, indicating opportunities for further development.

The review also highlights opportunities for advancing the application of FRAM in cascading failure analysis, as discussed by Mathou et al. (2024). FRAM enables the modelling of hierarchical structure and couplings while also addressing variability and uncertainty in system behaviour. Moreover, it allows representation of the system's ability to adapt to functional variability, showing that certain faults may be absorbed without compromising the aircraft functions.

Overall, these findings indicate that future research should focus on methods capable of representing system hierarchy, couplings, and functional variability in complex and highly integrated systems, improving the analysis of cascading failures.

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