

Reliability Risk Analysis of Non-Conforming Components in Turbofan Engines: A Complexity-Integrated Fault Tree Approach

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Abstract

In this paper, a process model is developed to assess the effects of using NCR (Non-Conforming Replacement) components versus the Original Equipment Manufacturer (OEM) components in terms of safety and reliability. This process links complexity management to system reliability by gradually updating the system model to incorporate each component's interactions and feedback loops. It employs an incremental, evolution-based methodology to refine system reliability predictions, using complexity metrics to assess the impact of each component. Our approach is experimental, using data relevant to a type of turbofan engine. Rather than relying on complex mathematical models that may have limited relevance for the application environment, we tailor our approach to aviation standards and complexity management algorithm development experiments to identify key defect-related predictors of quality. This process has been tested on critical components of turbofan engines, with all aspects of safety and reliability in mind. NCR components, which are approved by the design office, are assessed for their risk, and their effects on the overall reliability of the engine are calculated. The process begins with a risk analysis of each component, followed by the extraction of interactions and feedback loops using a complexity management algorithm. Finally, the reduction in engine reliability is calculated using a fault tree analysis (FTA), considering the complexity factor. The results show that complexity metrics are strong predictors of defects and test efficiency in this evolutionary process. At the end of the process, reliability changes for each component are calculated, providing a clear measure of its impact on the system. This allows comparison between components and supports informed decisions regarding the use of NCR components, even if approved by the design office.

Keywords: Safety; Complexity; Turbofan; Fault tree analysis; Reliability.

1. Introduction

The reliability and safety of critical systems, such as turbofan engines, are of paramount importance in the aviation industry [1]-[4]. The use of mismatched components, those that do not exactly match the original design specifications, can introduce significant risks to system performance and

safety [5]. As systems become increasingly complex, assessing the impact of such mismatches on reliability becomes more challenging [6], [7].

To address this challenge, we propose a novel process model that integrates a complexity management algorithm [1], [6], [7] with reliability analysis. In this paper, we introduce a flowchart that outlines a systematic process for

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evaluating the impact of Non-Conforming Replacement (NCR) components on system reliability, considering all relevant interactions and feedback loops.

This approach employs an incremental, evolution-based methodology to transition from one algorithm system to another while continuously monitoring the reliability of the system under NCR conditions. Complexity metrics are used to predict potential defects and assess their impact on system reliability, providing a comprehensive method for evaluating the effects of mismatched components on overall system safety.

In this paper, we present a process tailored specifically for turbofan engine components (3rd stage Disk from HPC), which are subject to rigorous safety and reliability standards. The process involves risk assessment of NCR components approved by the design office, followed by evaluation of their impact on engine reliability using a combination of complexity management analysis [3], [5]-[8] and Fault Tree Analysis (FTA) [9]. In addition, the various interactions it has with adjacent components are examined, reflecting the system's structural complexity and interphase engineering [4], [6], [10].

The proposed methodology relies on the expertise available within the organization. Expert judgment was applied in FMEA to determine parameter values such as severity, occurrence, detectability, failure modes, and their impacts on the system, and to construct fault tree scenarios. These assessments were cross-checked against the limited available fleet data. Likewise, the interaction matrices were completed based on expert evaluations of the specific system under study. By explicitly acknowledging these dependencies, the manuscript clarifies that the approach partially relies on expert input and system-specific assumptions, which may affect the generalizability and reproducibility of the results.

2. Complexity management algorithm for Reliability Analysis

In reliability assessments of complex systems, various methods and tools are employed to analyze and predict performance under different conditions, particularly in turbofan engines. One such tool is a complexity management algorithm, which is designed to measure and analyze the interactions between components within a system. This algorithm helps visualize the various interactions—mechanical, fluid flow, thermal, chemical, placement, functional, electrical, magnetic, vibrational, software, user interface, and data communication interactions—which are critical to understanding the overall system complexity. By identifying these interactions, we can quantify the complexity of each component within the system. This algorithm plays a crucial role in determining the complexity of the components and is essential in assessing the impact of complexity on the system's reliability, particularly when analyzing Non-Conforming Replacement (NCR) components.

Additionally, Failure Modes and Effects Analysis (FMEA) is a critical methodology used to identify and prioritize potential risks by analyzing failure modes, their impacts on system performance, and extracting the probabilities of failures. Risk assessment is conducted through FMEA in combination with expert opinions, where the criticality of each component and its failure modes are identified. Expert judgment is employed to evaluate the severity of these failure modes, their likelihood, and the potential impact on system performance. According to the failure mode severity and likelihood score, by using the risk matrix method, we can assess the risk level of each failure mode and identify the low-risk, moderate-risk, and high-risk ones [3], [8]. This approach helps determine which components are considered critical and allows for the identification of the associated failure modes that could compromise system safety and reliability. FMEA is applied here to evaluate the consequences of mismatched components (such as NCR components) on the reliability of turbofan engines.

Fault Tree Analysis (FTA) is a technique used to identify the root causes of system failures by analyzing the relationships between faults and their impact on system performance. It is particularly useful for simulating critical conditions and predicting failures in sensitive systems like turbofan engines. Originally, FTA is a qualitative tool, but when system reliability needs to be calculated, it can be used in a quantitative manner. For this purpose, a probability distribution is assumed, and we chose the exponential distribution due to its simplicity and data availability.

To gather the required failure data, we searched three sources. First, we extracted failure rates from the NPRD handbook [11], which compiles fleet statistics. Second, we compared these rates with rough data from a risk analysis datasheet. Finally, we performed a structural analysis on each part to calculate a more accurate failure rate. After importing the failure data for each basic event, we calculate the system reliability and identify the critical cut sets. By specifying the most critical cut sets, we can prioritize the system repair process, ensuring that the most significant failures are addressed first.

All calculations and the utilization of these tools are based on aviation standards, with particular adherence to APR 4761 standards[1]. The process outlined in this paper for evaluating the impact of NCR (Non-Conforming Replacement) components on reliability is conducted in accordance with these standards, ensuring that the results meet the safety and performance requirements necessary for critical industries like aviation.

3. Flowchart for Analyzing and Calculating the Effects of NCR Components

The flowchart begins by assessing the criticality of the component and identifying potential failure modes. For each failure condition, it should be determined how the system will satisfy the safety objectives. Using the

complexity management algorithm, the complexity of the component is then estimated. If the component is deemed critical and its complexity is high, reliability analysis must be conducted to evaluate its potential impact on system safety and performance.

Once the criticality and complexity are determined, the algorithm is employed to identify various interactions of the component. These interactions include mechanical, fluid flow, thermal, chemical, placement, functional, electrical, magnetic, vibrational, software, user interface, and data communication interactions. This analysis helps in understanding how the component behaves under different operational conditions and how it may affect other parts of the system.

Subsequently, the critical feedback loop, which involves the NCR component, is extracted. The analysis focuses on determining and calculating the new failure rate for the NCR component. This step acknowledges that the presence of NCR increases the failure probability in the FMEA (Failure Modes and Effects Analysis). The analysis guides how to approach the verification of failure modes categorized as Major, which is often the most challenging aspect to assess in reliability evaluations.

For each failure condition, it should be determined how the system will satisfy the safety objective. The flowchart as an evolutionary process depicted in Fig. 1 provides guidance in defining a verification plan for the Reliability analysis in a given system. This approach addresses system reliability analysis by considering the effects of NCR-affected components on failures.

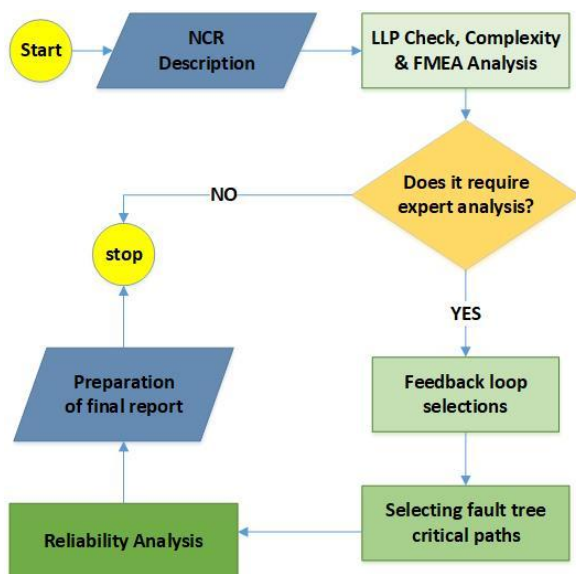


Figure 1. evolutionary process

Using NCR description, Complexity analysis, and FMEA approach to update failure rate, reliability analyses are calculated through FTA. The results from FTA are then compared with the previous state, where the NCR component was not present. This comparison shows the overall impact on system reliability when using an

NCR component, allowing for better-informed decisions regarding its inclusion.

This structured process, as shown in the flowchart, ensures a comprehensive assessment of the NCR component's effects on system performance, helping to meet safety objectives and facilitating optimal decision-making.

4. Calculations and Results

To assess the risk associated with the 3rd Level (Fig. 2), the analysis follows the established procedure and utilizes the appropriate tools. Initially, the type of non-conformance report (NCR) and the nature of the defect are identified. Inspection reveals a slight protrusion at the interface between the disk and the blade, exceeding the permissible tolerance and preventing the blade from being properly secured in its designated position. Consequently, the risk analysis process is initiated. A review of the engine documentation indicates that the disk is classified as a life-limited part (LLP) with an operational lifespan of approximately 9,600 cycles. Based on this information, the first item in the risk analysis is triggered.

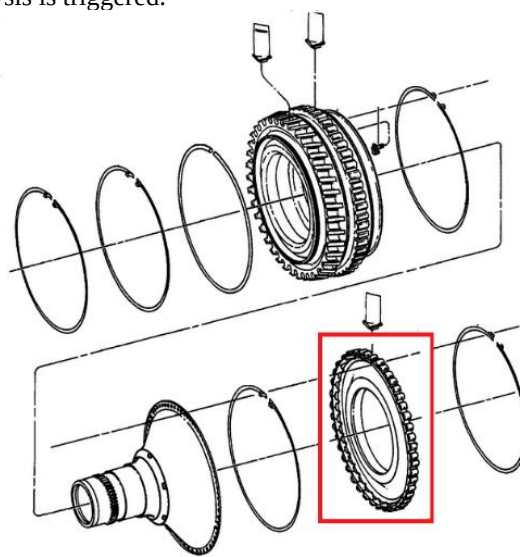


Figure 2. Rotor Assembly Compressor [12]

In the 3rd Level of the process, the complexity of the component within its associated assembly is evaluated. This begins with the illustration of the Product Breakdown Structure (PBS) for the selected system and assembly. As shown in Fig. 3, the PBS is developed to level six for the system under analysis. At this point, the Integrity & Complexity Management algorithm is utilized to create a database that captures the integrity and dependency (I&D) relationships, along with their associated diversity. This study employs a twelve-fold classification of I&D, encompassing mechanical, fluid flow, thermal, chemical, placement, functional, electrical, magnetic, vibrational, software, user interface, and data communication interactions.

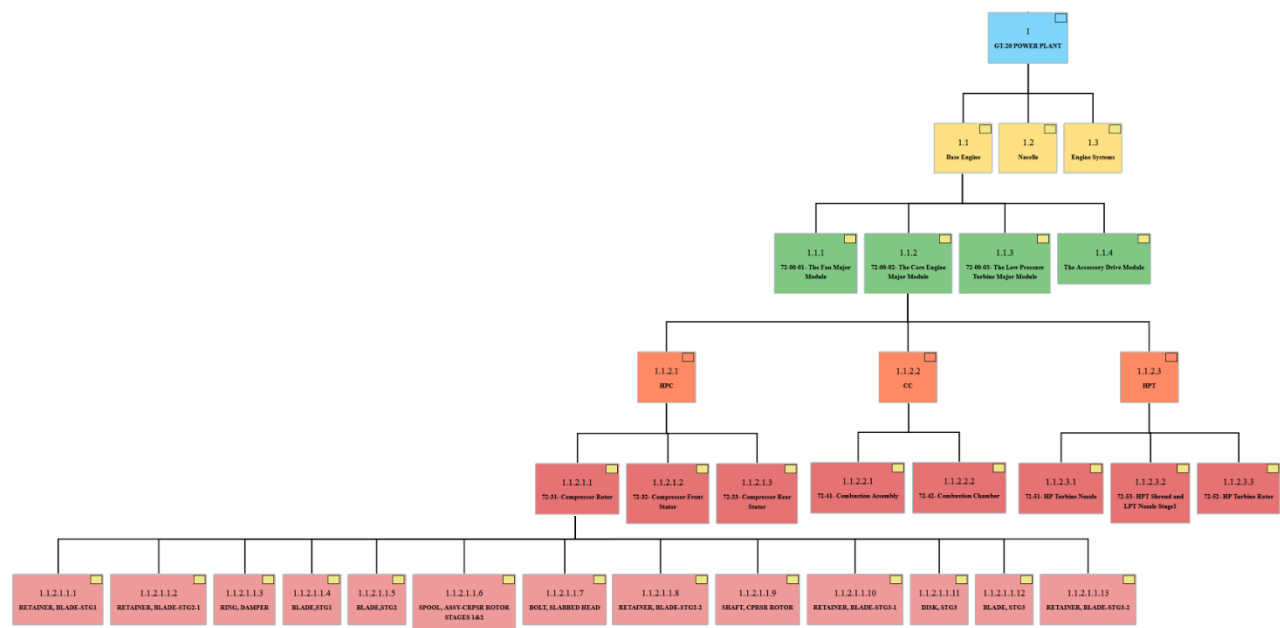


Figure 3. Product Breakdown Structure for an HPC

Upon completion of the database, the complexity management framework generates the system's Design Structure Matrix (DSM) and the corresponding interaction graph, as shown in Figure 4. The DSM quantifies overall system complexity based on the number and diversity of identified I&D types among components, enabling the simulation and analysis of interaction pathways and feedback loops.

In Figure 4, interaction diversity is represented using graded color contours, while the twelve defined interaction types are distinguished by color-coded lines (Figure 4(b)). For example, between BLADE, ST G1 and BLADE, ST G2, the DSM shows a Level 3 influence from ST G1 to ST G2 and a Level 1 influence in the reverse direction. In the interaction graph, Functional and Fluid Flow interactions are unidirectional (from ST G1 to ST G2), whereas the Vibration interaction is bidirectional. Accordingly, the influence (α) and susceptibility (β) values for each component are derived from these graded interaction levels ($\alpha=3, \beta=1$ for ST G1, and vice versa for ST G2).

All interaction types, directions, and intensity levels were defined and validated through expert elicitation. These relationships were encoded into the DSM and translated into the interaction graph. The complexity value of each component is then calculated by aggregating its influence and susceptibility measures, adjusted by the defined weighting coefficients described in the manuscript.

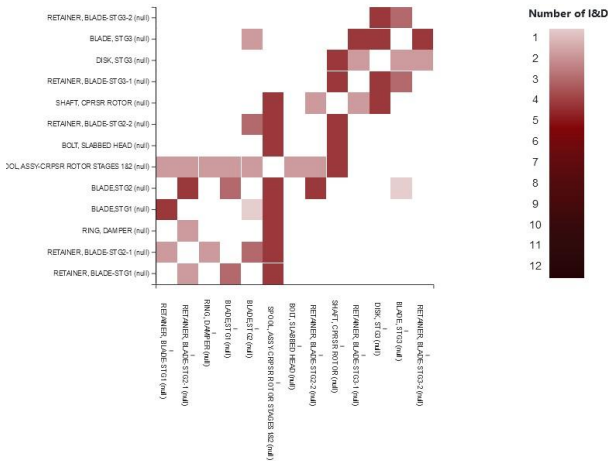


Figure 4. (a) Dependency Structure Matrix

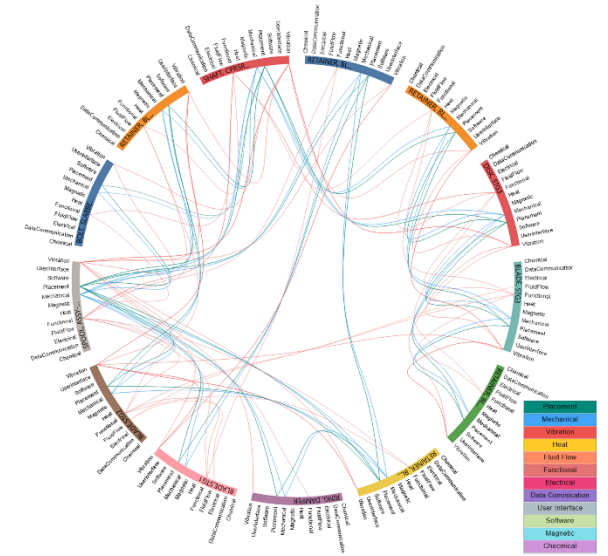


Figure 4. (b) DSM Graph

The 3rd-stage disk ranks third in complexity among the 13 components analyzed. As it falls within the top 33% in terms of complexity, it is categorized as a “High Complexity” component. The ranking of components by complexity is summarized in Table 1, providing a comparative view of the complexity levels across different parts.

Based on the interaction matrix and the completed I&Ds for the studied set, the complexity calculation is structured around the number of influencing interactions (α) and influenced interactions (β), adjusted by weighting coefficients reflecting the type of I&D (W_i), the importance and diversity multiplicity of I&Ds (W_p), and the expertise factor (W_m). In simplified conceptual form, the relationship can be expressed as:

Complexity $\propto (\alpha \times \beta) \times (W_i \times W_p \times W_m)$

Table 1. Complexity Analysis of HPC

Part name	Complexity level	NCR Component
SPOOL, ASSY-CRPSR ROTOR STAGES 1&2	High	
SHAFT, CPRSR ROTOR	High	
DISK, STG3	High	✓
BLADE, STG2	High	
RETAINER, BLADE-STG2-1	Moderate	
BLADE, STG3	Moderate	
RETAINER, BLADE-STG3-1	Moderate	
RETAINER, BLADE-STG2-2	Moderate	
RETAINER, BLADE-STG1	Moderate	
BLADE, STG1	Low	
RETAINER, BLADE-STG3-2	Low	
RING, DAMPER	Low	
BOLT, SLABBED HEAD	Low	

As a result, the second attribute for this component is classified as Type H. In the 4th Level, an FMEA is conducted to assess the potential failure modes and associated risks for the component.

In accordance with the defined methodology, both pre- and post-NCR conditions are evaluated to assess the impact of the identified non-conformity on component behavior. The estimation of failure rates was performed within the regulatory framework of EASA Part 21 (notably §21.1309) and CS-E (AMC E 510) [13], which define acceptable safety objectives specifically, that the probability of hazardous engine effects must not exceed 10^{-7} per engine flight hour and that of major engine effects must not exceed 10^{-5} per engine flight hour. Using the risk matrix method, the failure rate of each failure mode was derived from its likelihood score as documented in the FMECA risk analysis datasheet.

For NCR cases in particular, failure rate values were primarily estimated through structured expert judgment. For major components, these estimations were cross-checked against data from similar fleets and, where applicable, supported by structural analysis calculations. Detailed structural assessment procedures are beyond the

scope of this paper and are therefore not elaborated. Ultimately, the values reported in Table 2 represent validated expert-elicited results, aligned with regulatory safety criteria and benchmarked, where feasible, against comparable systems. As ae listed in Table 2, the highlighted row presents the NCR effect in the failure rate of sub-components.

Table2. Failure rate estimation for HPC

Failure Mode	Failure rate	
	OEM	NCR
Scattered surface damage	5E-07	5E-07
Balance weight flange tang bent and cracked	2.8E-06	1.22E-05
Air seal and rotation tang wear	6E-07	6E-07
Bolt hole crack	1.41E-06	2.41E-06
Blade root area (upper disk lug) cracks	2.8E-06	1.22E-05
Blade root area (blade pressure face) galling	1E-06	1E-06
Blade root area (blade pressure face) nicks, dents, and scratches	5E-07	5E-07
Blade root area (blade pressure face) cracks	2.3E-06	3.3E-06
Blade root area (lower slot mismatch) nicks, dents, and scratches	1E-07	1E-07
Blade root area (lower slot mismatch) cracks	2.8E-06	1.22E-05
HPC Failure rate:	1.48E-05	4.5E-05

Based on the NCR classification, the following failure modes—Balance weight flange tang bent and crack, Bolt hole crack, Blade root area (upper disk lug) cracks, Blade root area (blade pressure face) cracks, and Blade root area (lower slot mismatch) cracks—show increased Occurrence values. The results of the FMEA indicate that the component presents a high level of risk.

In the 5th Level of the flowchart, a decision is made regarding whether the component requires further examination and analysis. Since all three evaluated criteria indicate the component's criticality—and considering that the presence of even a single critical indicator is sufficient to warrant further analysis—the process proceeds to the next Level.

In the 6th level, the component's feedback loops are identified using a complexity management algorithm. A total of 34 distinct feedback loops are extracted. Among them, one loop of the placement type—corresponding to the nature of the NCR—is selected for further examination. This feedback loop includes five components, all of which are classified as critical. Based on this, it can be concluded that the component resides in a sensitive region of the engine and necessitates more detailed evaluation. (Note: if more than 30% of the

components in a feedback loop are deemed critical, the entire loop is classified as critical.) The specific NCR, categorized as a Dimensional issue occurring between the

disk and the blade, is mapped and visualized within the selected feedback loop (see Fig. 5).

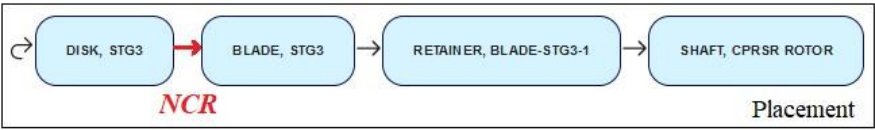


Figure 5. Sample of Feedback for Disk's I&D

Subsequently, based on the updated values in the FMEA (Table 2), the failure rates are calculated using the Occurrence scores for both the OEM part and NCR-affected conditions of the component. This comparative metric quantifies the impact of the NCR by expressing the percentage change in the reliability of the main module. The calculated failure rates are 1.48e-5 for the OEM part and 4.5e-5 for the NCR-affected condition. These values are then used to determine the reliability of the fan module over varying operational durations. The results show a notable decline in reliability due to the NCR. After 79 hours of operation, reliability drops from 99.81% to 99.57%. After 150 hours, it decreases from 99.63% to 99.18%. Over a longer duration of 1,000 hours, reliability is reduced from 94.8% to 92%. The operational significance of these reliability variations must be interpreted against predefined safety margins and risk acceptance criteria established by the applicant, operator, or regulatory framework (e.g., compliance with Part 21 §21.1309 safety objectives). Although no universal numerical threshold defines an acceptable reliability drop, the quantified differences provide a structured, risk-informed basis for comparison, supporting the identification and prioritization of high-impact NCR components within the system.

An analysis of the FTA and critical path in Level 7 identifies the most critical failure scenario for the disk: the initiation and propagation of cracks. As a result, it is recommended that this issue be closely monitored during scheduled inspections. Any occurrence of cracks should be promptly reported and addressed. The process form implemented for disk segment NCR risk analysis is as shown in Figure 6. In the proposed framework, complexity assessment enhances the identification of inter-component interactions, propagation paths, and feedback loops. By embedding these structured interactions into the Fault Tree Analysis (FTA), the system captures additional failure scenarios and the impact of NCR components on neighboring parts. Consequently, new failure modes may be added to the FMEA, and the occurrence probabilities of existing failure modes can increase, leading to updated failure rate estimations. This ensures that the influence of component complexity is systematically reflected in reliability assessments.

5. Comparative Evaluation and Advantages of the Complexity-Based Proposed Approach

To assess the added value of the proposed framework, a controlled comparison was performed between reliability analysis with and without complexity screening.

Without complexity screening, the fault tree relies mainly on local component relationships, with limited system-level dependencies. Feedback loops and failure propagation chains are not explicitly modeled, which can lead to unrealistic or redundant failure scenarios and increase computational burden.

In contrast, complexity screening identifies structural and functional dependencies, feedback loops, and failure propagation paths before fault tree restructuring. This eliminates weak or unrealistic paths, improves scenario realism, enhances system-level reliability estimation, and reduces computational effort.

Operationally, the framework improves Non-Conformance Report (NCR) evaluation. By embedding the component within the full system architecture, it quantifies its contribution to higher-level failures and overall reliability indices, supporting reliability-informed decision-making beyond localized judgment.

Direct comparison with historical fleet data was not possible due to incomplete and inconsistent datasets;

	Mapna Aero Engineering Company	Part number	-
		NCR Total number	1
NCR TEST RISK	Risk Process of DISK, STG3-HPC	Classification	Dimensional
		Rev:	0
		Date:	2024/2025
LEVEL 1	NCR DESCRIPTION		
comment1	In this NCR, the part connecting the disk to the blade has an excessive protrusion that interferes with the blade.		
LEVEL 2	LLP		
LEVEL 3	Complexity		
Complexity (Graph & Matrix)			
Criticality Rate in Assembly	3 of 13		
LEVEL 4	FMEA		
LEVEL 5	Does it Require Analysis?		
	Continue Analysis		
LEVEL 6	Feedback Loops		
number of feedback loops	34	number of max node	5
number of Critical part in the longest feedback loop	5	Special review	Yes
The longest and most critical feedback loop			
LEVEL 7	Fault Tree Analysis		
	Reliability		
	79h	150h	1000h
Failure rate (Based part)	99.81%	99.63%	94.80%
Failure rate (After NCR)	99.57%	99.18%	92.00%
4.50E-05	0.24%	0.45%	2.95%
Reliability degradation			
Critical scenario of FTA	Various Fault Tree scenarios are included in this section.		

Figure 6. Implemented a process form for NCR risk analysis of disk segments

validation was instead performed through controlled comparison of model configurations.

Overall, the complexity-based framework shifts reliability assessment from a local to an integrated system-level approach, enhancing accuracy, efficiency, and decision-making support.

6. Conclusion

This paper presents a comprehensive process and flowchart for assessing the impact of Non-Conforming Replacement (NCR) components on the safety and reliability of turbofan engines. By integrating complexity metrics with traditional reliability analysis methods such as Failure Modes and Effects Analysis (FMEA) and Fault Tree Analysis (FTA), this process provides a precise evaluation of the risks associated with NCR components. The results demonstrate that both the complexity of components and their interactions within the system are crucial factors in predicting defects and reducing overall system performance.

Through the use of a complexity management algorithm, the study effectively quantifies the interactions and feedback loops of critical components, offering valuable insights into how NCR components affect system reliability. Specifically, the complexity analysis and failure modes of NCR components show an increased failure probability, which directly impacts the overall reliability of the engine. The results indicate a significant decline in reliability, with NCR components leading to higher failure rates and reduced system performance over time.

Additionally, the proposed process provides a structured method for evaluating and mitigating the risks associated with NCR components, ensuring that safety objectives are met. By adhering to established aviation standards, this approach guarantees that the results are reliable for real-world systems and supports informed decision-making regarding the inclusion of NCR components in critical systems such as turbofan engines.

Ultimately, the findings of this study contribute to improving safety and reliability in the aviation industry, providing a robust framework for evaluating the effects of NCR components on system performance. While this study focused on the 3rd stage disk, the proposed methodology is not limited to a single component or system. Given its effectiveness in supporting NCR decision-making within one of the most complex aviation systems, the approach can be generalized and applied to other engine subsystems or even non-aviation industries, wherever structured complexity assessment and risk-informed evaluation of non-conformities are required. This approach can be extended to other complex systems, offering a valuable tool for maintaining high safety and reliability standards across various industries.

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Conflict of interest

No conflict of interest has been expressed by the authors.

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