WHITE PAPER

DIGITAL THREAD FOR NON-CONFORMITIES IN AEROSPACE PRODUCT MANUFACTURING LIFECYCLE

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Abstract

Aircraft manufacturing involves a complex ecosystem where quality, traceability and compliance are paramount. Managing non-conformities both before and after manufacturing requires a digitally connected data framework that ensures seamless data flow, decision-making and corrective actions across different functions like sourcing, materials, engineering and production. This paper presents a comprehensive digital thread framework for managing pre and post manufacturing non-conformities, enabling real-time visibility and control from design to delivery.

Pre-manufacturing nonconformity management focuses on early detection of issues in sourcing, materials and design through integration of Product Life Cycle Management (PLM), Manufacturing Engineering Systems (MES), Enterprise Resource Planning (ERP), Quality Management System (QMS) and supplier systems. Post-manufacturing the system extends to managing concessions, enabling structured digital workflows for identifying, evaluating and approving deviations that arise during inspection or final assembly.

By leveraging Artificial Intelligence (AI) driven anomaly detection and digital traceability, deviations are identified early, assessed collaboratively and resolved with the help of earlier resolutions for similar problems based on inputs from AI and Generative AI (Gen AI) driven inputs

By closing the loop between design, production and quality assurance, this digital thread enhances traceability, reduces delays, rework and fosters continuous improvement across the value chain. The result is a more resilient, compliant and efficient aircraft manufacturing process aligned with the demands of modern aerospace product demands. This white paper introduces a holistic digital thread framework designed to manage non-conformities across the entire manufacturing lifecycle.

Introduction

With aircraft comprising thousands of components sourced globally and subject to rigorous design, material and performance standards, any deviation during sourcing, design, or production can lead to significant quality, safety and financial consequences. Non-conformities, both pre-manufacturing and post-manufacturing are inevitable in such a complex ecosystem. However, the traditional approaches to manage these issues are often fragmented and siloed, involving disconnected systems and manual processes. This limits the ability to detect deviations early, trace root causes efficiently or make timely and compliant decisions.

In order to meet these challenges, this white paper introduces a digital thread framework as a unified, data-driven approach to manage non-conformities across the aircraft manufacturing lifecycle. By connecting enterprise systems such as PLM, ERP, MES, and QMS and integrating real-time data from suppliers, engineering teams and production lines the digital thread creates an end-to-end view of product and process quality. It supports an early detection of non-conformities, structured concession workflows, virtual design reviews and feedback loops to continuously improve design and manufacturing processes. Through the application of emerging technologies like AI framework enhances predictability, traceability, accelerates the resolution cycles, reduces rework and strengthens regulatory compliance.

Nonconformities in aircraft product life cycle

Managing non-conformities across the aircraft product lifecycle requires a unified, traceable and intelligent workflow that ensures alignment from early planning to final delivery. This section outlines a digitally enabled process that spans both pre and post manufacturing phases, allowing teams to detect, assess and resolve deviations at the earliest possible stage. By integrating change control, sourcing, execution and concession management into a connected ecosystem, manufacturers can significantly reduce rework, enhance quality and ensure compliance with airworthiness and regulatory requirements.

Figure 1 below presents an integrated digital thread workflow for managing non-conformities across the pre-manufacturing and post-manufacturing phases. The process includes pre-production AI-based conformity checks and post-production AI-enabled concession management, ensuring that deviations are identified early and resolved efficiently.

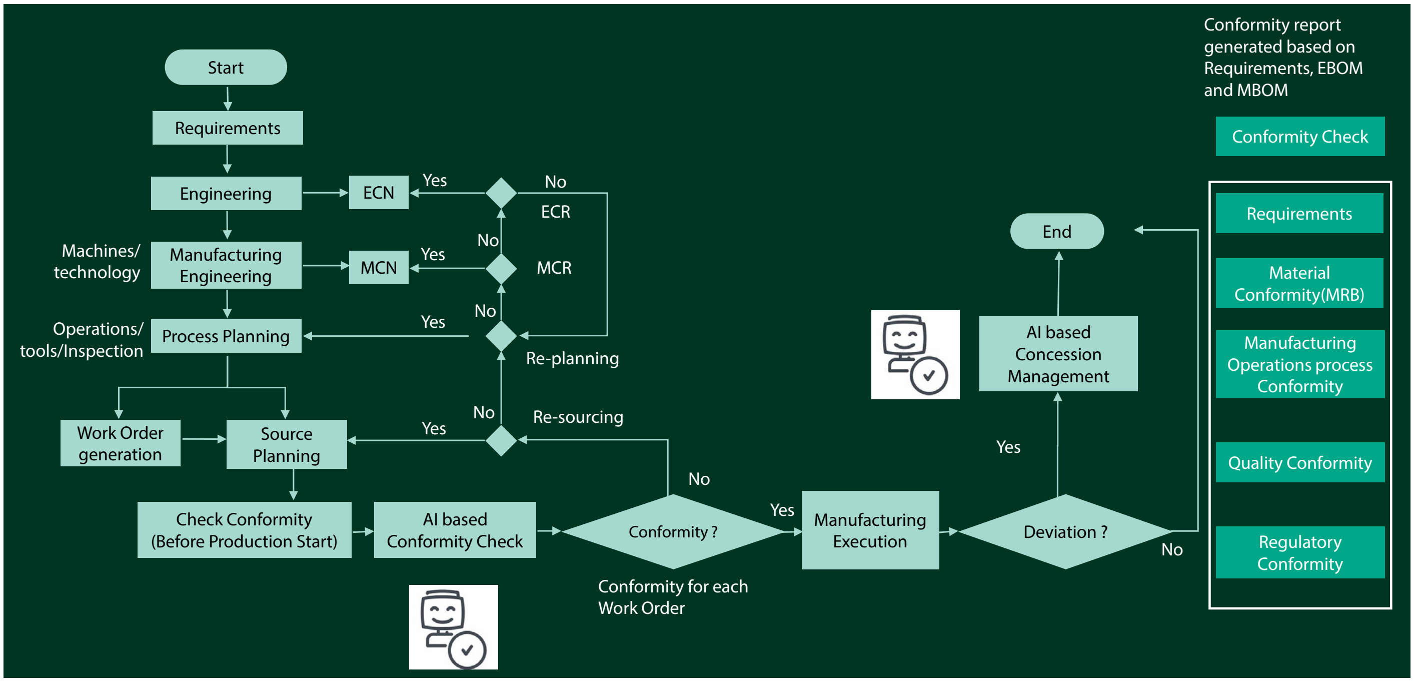


Figure 1: Integrated digital thread for pre & post manufacturing non-conformity

In the early stages of the lifecycle, non-conformities often stem from gaps in requirement interpretation, design-data misalignment, tooling strategy, or sourcing issues. A closed-loop system ensures these are addressed before production begins. Typical nonconformities prior to manufacturing are listed below in Table 1.

Category	Manufacturing Planning Stage Non-Conformity examples	Non-conformity type
Material Substitution	Replacing titanium with aluminum-lithium alloy for certain airframe components to reduce weight and cost, while still maintaining the required strength and corrosion resistance.	Material
Geometry Modification	Redesigning the shape of a turbine blade to eliminate sharp corners that are difficult to machine, thereby simplifying the manufacturing process and reducing tool wear.	Manufacturing Operations
Tolerance Adjustment	Adjusting the tolerance range for the diameter of a rivet hole from ±0.005 inches to ±0.010 inches, making it easier to achieve with standard machining processes without compromising the assembly's integrity.	Manufacturing Operations
Joining Techniques	Switching from traditional riveting to friction stir welding for joining aluminum panels, which can provide a stronger bond and reduce the need for additional fasteners.	Manufacturing Operations
Manufacturing Process Changes	Using selective laser melting (a type of additive manufacturing) to produce complex fuel nozzle assemblies that would be difficult or impossible to create with conventional machining, thereby reducing material waste and lead times.	Manufacturing Operations
Tooling Design	Designing a new fixture to hold a composite wing section in place during curing, which improves alignment and reduces the potential for defects.	Manufacturing Operations
Component Standardization	Standardizing the use of a specific type of high-strength bolt across multiple assemblies to reduce the number of unique parts that need to be stocked and managed.	Engineering
Ergonomic Improvements	Redesigning an access panel to include quick-release latches instead of screws, making it easier and faster for maintenance crews to perform inspections and repairs.	Engineering
Quality Control Enhancements	Adding alignment holes and reference marks on large fuselage sections to facilitate easier and more accurate assembly and inspection using laser alignment tools.	Inspection

Table 1 – Pre-Manufacturing Non-Conformities

Once manufacturing execution is underway, deviations may arise due to operational errors, part fitment, assembly variation or inspection outcomes. Managing these deviations efficiently is critical to ensure delivery timelines and maintain compliance. Typical concessions post manufacturing is listed in Table 2.

Non-Conformity	Source	Mandatory Information
Spalling/Flaking/De-lamination at hole edge	• Incorrect drilling	• Nominal hole diameter • Length/width/depth of NC • Relative location
Unwanted drill start	• Damage • Design evolution • Drawing error	• Diameter/length/width • Depth
Unwanted hole	• Drawing error • Manufacturing holes	• Diameter/length/width
Impact marks/Scratch	• Tool impact • Damage during handling	• Nominal hole diameter • Length/width/depth of NC • Relative location • Dent/crack geometry
De-lamination/Blended area/Porosity	• Manufacturing process	• Length/width/area of NC • Affected number of plies • Thickness
Curing cycle	• Manufacturing process	• Nominal & actual curing cycle diagram • Divergence curve (Pressure, Temperature, Vacuum)
Geometric non-conformity	• Manufacturing process	• Non-conformed dimension • Theoretical and actual dimensions and deviations

Table 2 Post manufacturing Concessions

In both pre and post manufacturing scenarios, if a deviation is detected, it is routed to an AI-powered nonconformity management system that assesses whether it can be accepted or requires rework. The system supports impact analysis using historical data and recommends disposition actions such as use-as-is, repair, or scrap.

Pre-Manufacturing Non-Conformity detailed workflow

Before physical production begins, the aerospace manufacturing team carries out a rigorous process of transforming design intent into executable manufacturing plans. This phase involves multiple data exchanges and validations between design and manufacturing engineering to ensure that what has been designed can be produced. However, deviations can arise at this early stage often due to misalignments between as-designed data and the realities of manufacturing resources, processes, or material constraints. These are addressed through a pre-manufacturing nonconformity workflow, designed to identify and resolve discrepancies before they reach the shop floor.

The process begins with the handover of design inputs such as the Engineering Bill of Materials (EBOM), 3D CAD models, annotated engineering drawings, material specifications and inspection standards. The manufacturing engineering and process planning teams interpret these to develop the Manufacturing BOM (MBOM), create detailed process plans Engineering Work Instructions (EWIs), define tooling & fixture requirements and outline quality and assembly protocols. During this translation from "as-designed" to "as-planned" a structured conformity check is initiated to identify any deviations that might affect producibility or compliance.

If a discrepancy such as tolerance stacking issues, incompatible tooling paths, material substitutions, or inspection inaccessibility is identified a pre-manufacturing concession is raised. This may involve cross-functional inputs from design, manufacturing, quality, and sourcing teams. The objective is to assess whether the deviation can be accepted, requires rework in the digital plan, or necessitates a formal change in the design. These decisions are facilitated by integrated tools across PLM and MES platforms, ensuring all changes are digitally tracked and approved before release.

Approved pre-manufacturing nonconformities result in updates to the MBOM, work instructions, inspection plans, or even engineering drawings. The revised data then feeds into finalized outputs such as work orders, tooling packages, prototype parts, and production schedules. Figure 2 illustrates the pre-manufacturing conformity flow, highlighting how design engineering inputs are translated into executable manufacturing procedures.

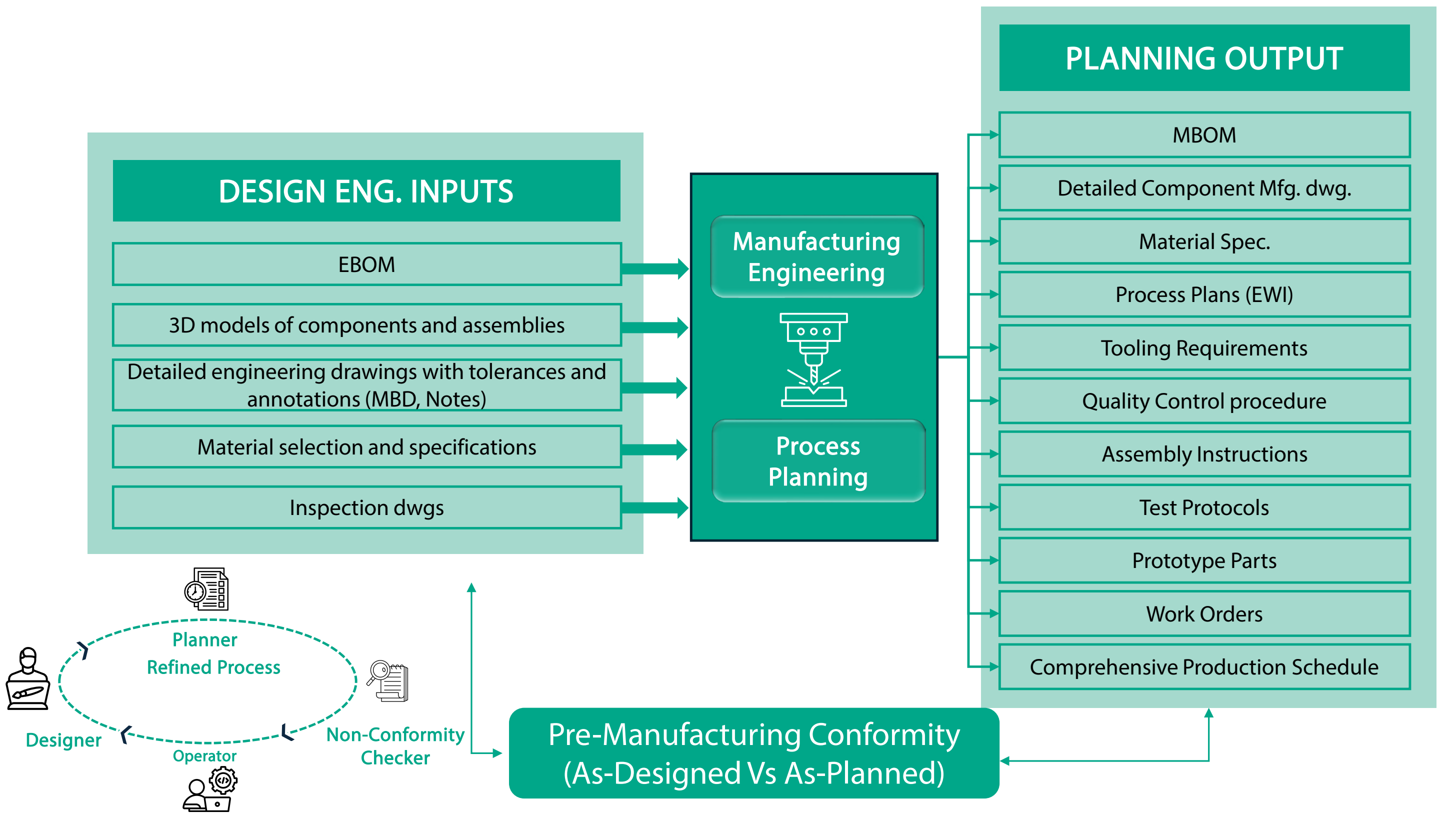


Figure 2: Pre manufacturing conformity workflow

Post-Manufacturing Non-Conformity/Concession detailed workflow

In case of an identified deviation after the manufacturing process is complete, a structured concession process is triggered to evaluate whether the non-conforming condition can be accepted, repaired, or must be rejected. This process is crucial in maintaining compliance with airworthiness standards while minimizing unnecessary rework or delays. Typically, these deviations are discovered during final inspections, Quality Assurance (QA) checks, or as part of supplier-provided quality documentation. The first formal step is the initiation of a Quality Notification (QN) by either the QA inspector or supplier via the MES, which documents the issue and flags it for further evaluation.

Once a QN is initiated, it undergoes QA validation to confirm that the deviation warrants technical assessment. The validated QN is then routed to Liaison Engineering (LE), who conducts an initial evaluation of the deviation in its physical and operational context. If the deviation is determined to require a formal concession process, a concession record is originated in the system. This leads to a collaborative technical review involving the design, stress, and quality engineering teams. The design assessment team evaluates the deviation against CAD and PLM models to determine if the part can still meet functional and fit requirements. If so, the deviation proceeds for design approval by the appropriate authority.

Following design approval, the stress assessment team conducts simulations or calculations to evaluate whether the deviation poses any structural failure or fatigue risk. This ensures that any acceptance decision is technically justified and does not compromise the integrity or safety of the product. Once the stress team signs off on the concession, it returns to the QA team for final approval. This step acts as a gate to ensure that all technical disciplines have reviewed the deviation, and that the concession is backed by complete documentation and traceability.

Depending on the nature of deviation, the process may also require OEM-level approval, particularly if the component is subject to customer-specific or regulatory constraints. In some cases, material review or vendor engagement is needed if raw material properties are in question. The manufacturing team also assesses whether the proposed repair or deviation can be implemented feasibly on the shop floor. A final compliance check ensures that all aspects from documentation to airworthiness impact have been considered. Once approved, the concession leads to a revised work order or manufacturing plan, which is uploaded back into the PLM system to ensure configuration accuracy and traceability. This process ensures that post-manufacturing deviations are managed systematically, safely, and in a digitally traceable manner.

Figure 3 illustrates the end-to-end workflow for post-manufacturing concession management, capturing each stage from QN initiation through to final approval and implementation. It highlights the integration between MES, PLM, CAD, CAE, and CAM systems, and the collaborative decision-making across quality, design, stress, manufacturing, and OEM stakeholders

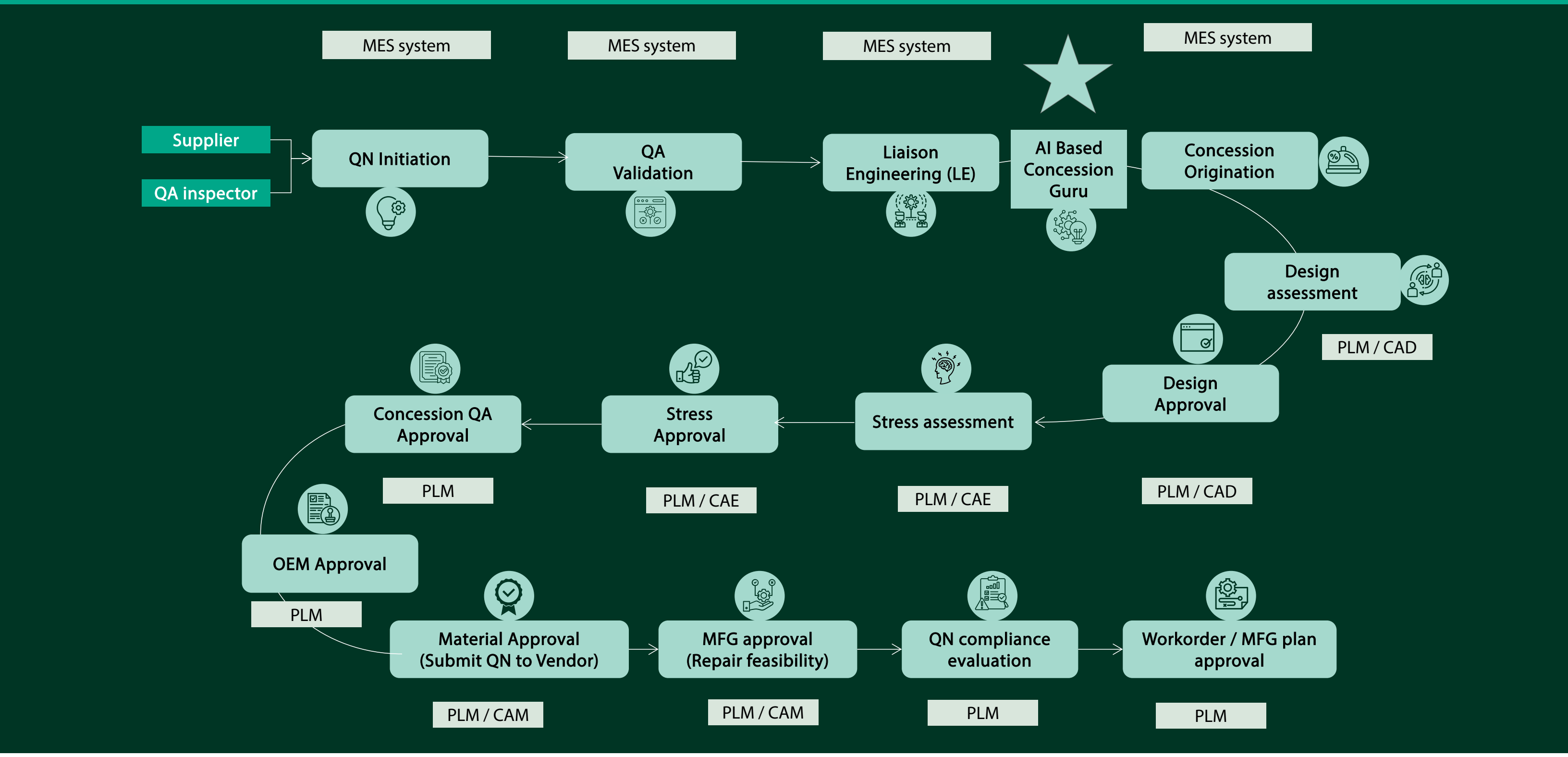


Figure 3: Post manufacturing concession management work flow

Digital data flow across technology applications

a. Pre manufacturing

In the foregoing explanation on pre-manufacturing nonconformities, many types of deviations are highlighted. The concept of resolving such nonconformities for **material substitution** is detailed out below.

Material substitution is a common nonconformity in aerospace pre manufacturing phase, especially when the specified engineering material is unavailable, cost-prohibitive, or infeasible to procure within required timelines. These substitutions, however, introduce a potential risk of non-conformity if they deviate from the original design requirements in terms of mechanical properties, form factors, or regulatory compliance. A structured process ensures that any material deviation is evaluated, approved, and documented before release to manufacturing.

The process begins during material selection and planning, where the manufacturing or sourcing team identifies a potential issue with the originally specified material typically due to long lead times, excessive cost, or limited stock. For instance, materials like Aluminum-Lithium may be ideal in terms of weight and strength but are often categorized as rare or long-lead raw materials. In such cases, a more readily available substitute, such as conventional aluminum, may be proposed. This triggers an internal conformity check against engineering requirements, often using digital validation tools within the PLM system.

If a mismatch is detected, the system prompts a review for substitution. The nature of the substitution determines the type of change process. Once the substitution is flagged, it goes through a cross-functional review involving quality assurance, manufacturing engineering, and design engineering. Digital simulations (if applicable) are run to validate form, fit, and function. If the deviation poses no significant impact and remains within allowable thresholds, it is approved and documented within the concession library. If not, it may result in re-engineering, supplier negotiation, or outright rejection.

The final decision to approve, rework, or reject the substitution is integrated into the digital manufacturing plan. All actions are logged within the PLM/MES system to maintain full traceability. Where concessions are accepted, a unique identifier is attached to the part record, ensuring downstream teams are aware of the variation.

Figure 4 outlines the structured process for handling material substitution non-conformities during the pre-manufacturing phase. It highlights how deviations such as replacing rare or high-cost materials, using alternative hardness grades, or selecting standard billet sizes are identified, evaluated and approved through a digitally integrated workflow. This ensures that material changes are validated without compromising design intent, cost efficiency, or regulatory compliance.

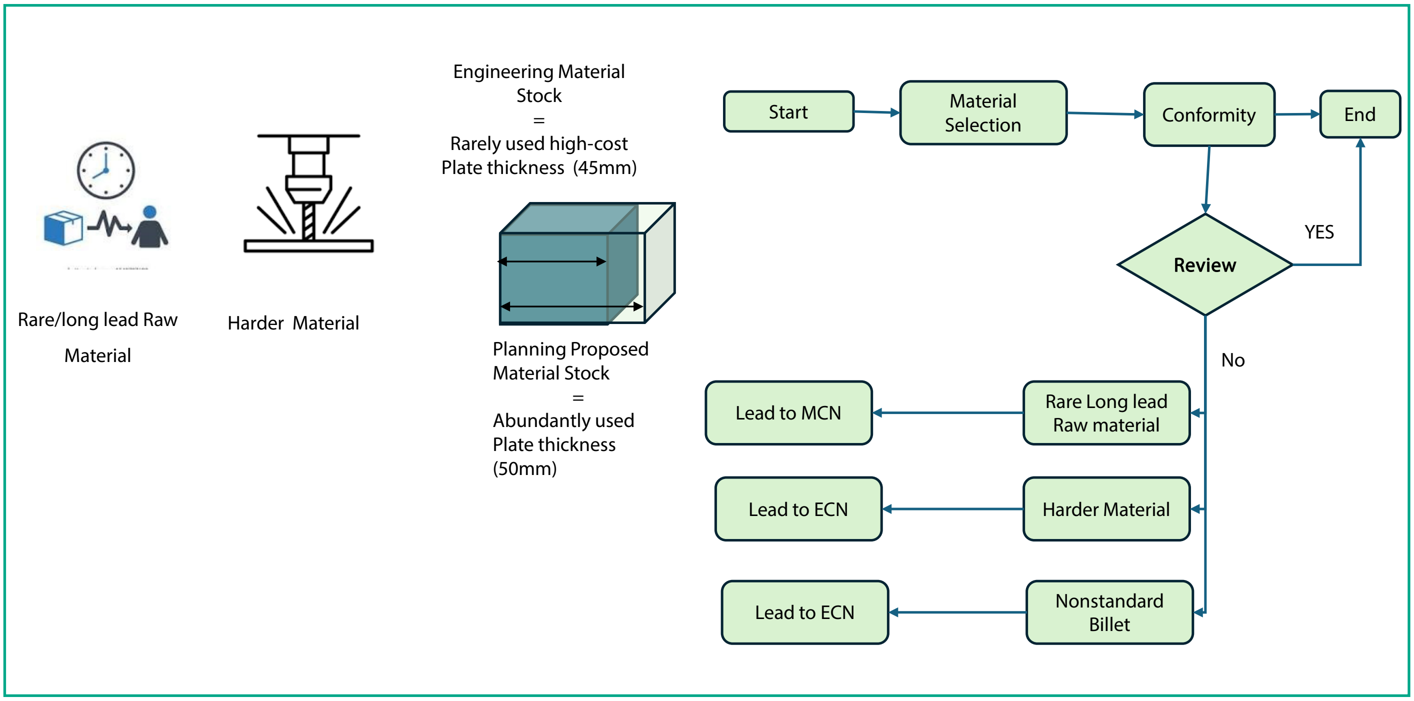


Figure 4: Workflow for Material substitution nonconformity

b. Post manufacturing

The post manufacturing concession process benefits significantly from digital integration across MES, PLM, and analytics systems. The use of AI and system interconnectivity ensures faster decision-making, deeper traceability, and long-term process improvement. The following workflow outlines how a deviation is digitally captured, analyzed, and resolved once a part or assembly is found non-compliant during inspection.

The process begins when an Inspection Order is created with defined tolerances. Upon inspection, a QA inspector enters data into the MES system, which is then validated automatically. If the part is compliant, the process ends. If not, a Non-Conformance Report (NCR) is generated, triggering a pathway for concession analysis. The system checks concession applicability, and if the deviation appears eligible, it progresses through QA and liaison engineering validation.

Once validated, the concession request is formally generated and routed through a digital approval process. At this point, the system checks if a similar concession has been raised before. If yes, the prior decision can guide the current resolution. If not, the process moves into the Concession Guru an AI-based engine that analyzes historical trends (e.g., duration, approval rate, risks), and supports engineering teams with simulations and impact analyses.

Based on this, the system supports the generation of change actions, categorization of issues, and creation of an object for the concession. After technical review, the deviation is classified into one of several dispositions like accept, reject, rework or Use-as- is.

If a change in material or design is required, a Change Order is raised, and approvals are obtained from OEM and regulatory stakeholders. Once disposition is finalized, the MES system updates inventory records, links the Non-Conformance Report (NCR) to the work order, and if applicable, generates a rework or repair order. Final QA inspections are conducted, and upon completion, the NCR is closed with full digital traceability.

Figure 5 illustrates the end-to-end digital data flow for managing post-manufacturing concessions. The process ensures timely, traceable resolutions while also enabling continuous improvement through data analytics and closed-loop feedback.

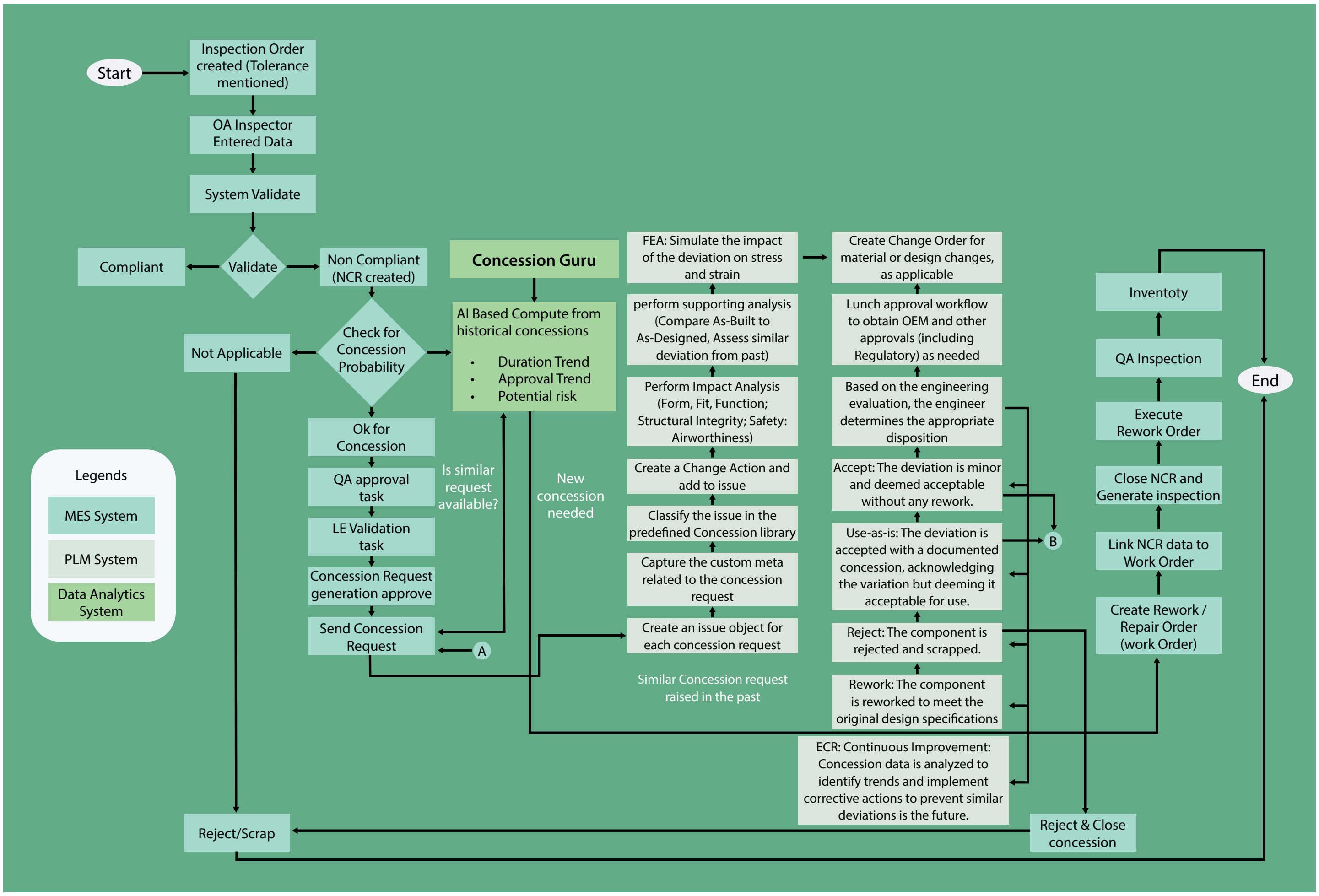


Figure 5 Digital data flow for concession management

AI Concession Guru for faster concession resolution

Managing concessions efficiently is critical to minimizing production delays, improving quality assurance and ensuring compliance in aerospace manufacturing. Traditional concession handling involves manual reviews, dependency on historical records, and iterative approval loops, all of which slow down decision-making. The Generative AI-enabled "Concession Guru" addresses these challenges by combining semantic search, predictive analytics, and large language model (LLM) capabilities to deliver fast, consistent and data-backed concession decisions.

Receiving and Interpreting Concession Requests

The process begins when a new Concession Request (CR) is raised—typically triggered by a deviation detected during inspection or review. The AI tool first interprets this CR using structured and unstructured data inputs, initiating a smart retrieval process.

Semantic Search of Similar Historical Cases

The engine performs a semantic search against a Historical Concession Data Repository, using hybrid search rules and a knowledge graph to locate past CRs that closely match the current scenario. This helps quickly identify similar dispositions, materials, part types, or structural impacts that have been addressed previously. By referencing prior successful resolutions, the tool provides a contextual foundation for current decision-making.

Concession Acceptance Predictor

Since similar cases are retrieved, the system uses a machine learning model to analyze key variables such as material properties, type of deviation, functional impact, and resolution outcome. It generates a confidence score indicating the likelihood of the current CR being accepted based on historical trends. This Concession Acceptance Predictor enables engineers and QA teams to focus only on cases that need further intervention.

Concession Report Co-Pilot (LLM Integration)

The tool then passes the structured findings to a Generative AI-based Co-Pilot, which uses a LLM to auto-generate a draft concession report. This includes recommended disposition, engineering rationale, risk impact (form, fit, function, fatigue, airworthiness), and links to reference cases. This dramatically reduces the time spent authoring documentation and ensures consistency in report quality and format.

Advanced Analytics and Decision Metrics

The system also surfaces duration statistics, approval time trends, cost implications, and success ratios of similar past concessions. This allows decision-makers to weigh time vs. risk and select the most efficient resolution pathway—accept, rework, reject, or escalate.

Reporting and Feedback Loop

Once the concession is finalized and approved, the tool logs the case into the historical repository, enhancing its ability to learn and recommend more accurate outcomes in the future. Additionally, the insights derived contribute to continuous improvement initiatives, helping identify patterns and drive proactive design or process changes.

Figure 6 illustrates the architecture and data flow of the AI-enabled Concession Guru system. By leveraging semantic search, machine learning, and generative AI, this tool accelerates concession resolution by referencing historical cases, predicting acceptance probability, and auto-generating detailed concession reports. It transforms a traditional manual process into a fast, intelligent, and traceable digital workflow

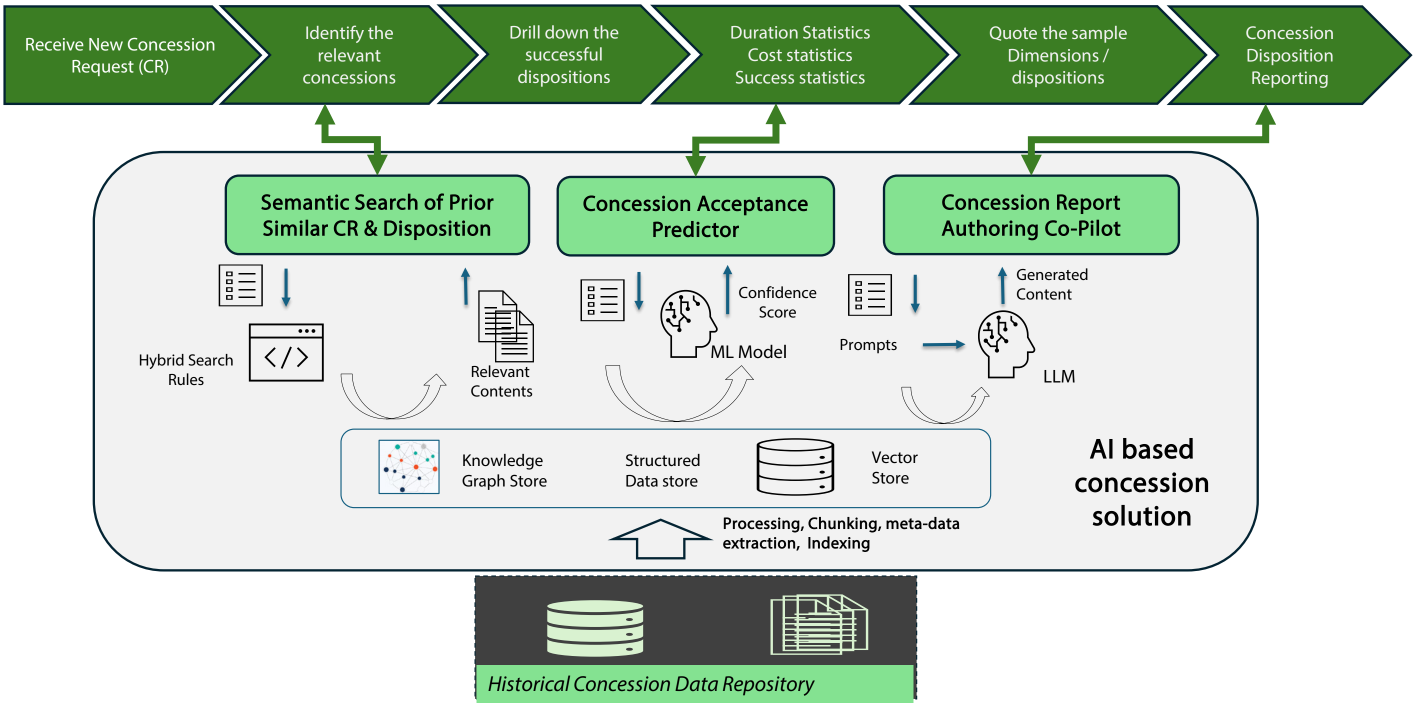
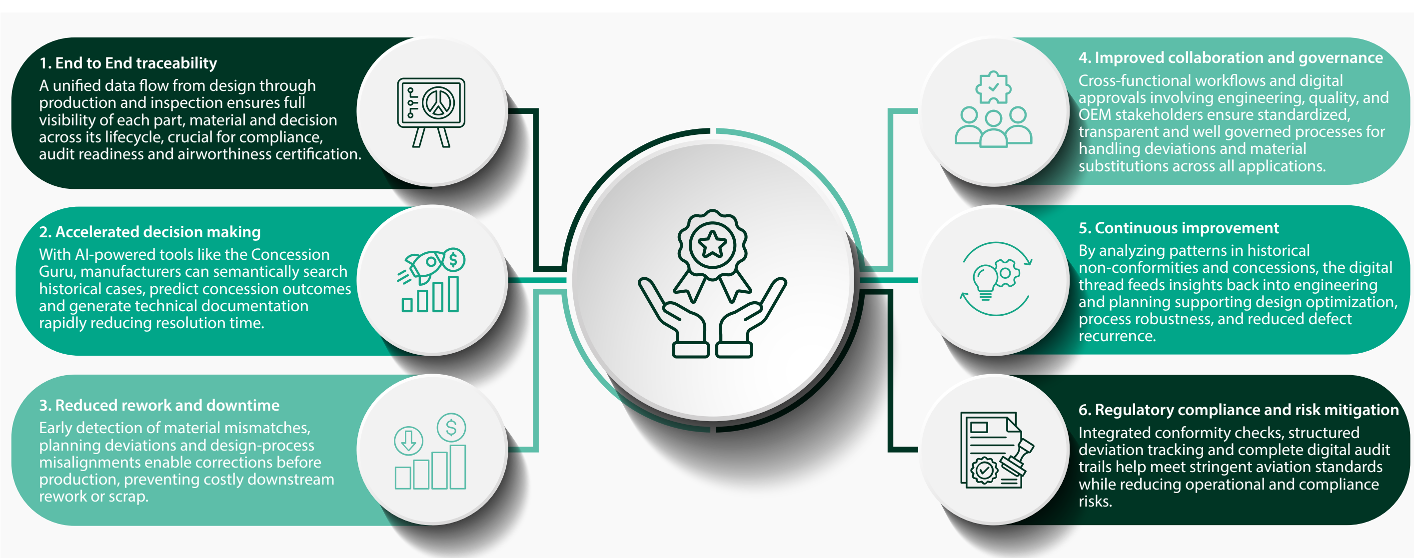


Figure 6 Architecture and data flow for AI Concession Guru

Benefits of the digital thread in nonconformity use cases

Implementing a digital thread across the aircraft product manufacturing lifecycle offers transformative benefits by connecting engineering, manufacturing, quality, and supply chain data into a single, traceable and interoperable ecosystem. Together, these capabilities make the digital thread not just a technological upgrade but a strategic enabler for leaner, faster, and safer aircraft manufacturing.



Conclusion

The current digital thread and AI-enabled concession framework lays a strong foundation with future enhancements that can elevate its capabilities further. Key areas include integrating real-time sensor data for automatic deviation detection, expanding predictive analytics for concession prevention and enabling cross-enterprise data sharing with suppliers and regulatory bodies. The use of full-scale digital twins, AI based visual inspection interpretation and automated regulatory interfaces can further streamline compliance and decision making. These advancements will shift the system from reactive quality control to a proactive, predictive and intelligent manufacturing ecosystem.

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