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EFFICIENT INTEGRATED RELIABILITY AND MAINTAINABILITY IN A DIGITAL ENGINEERING ENVIRONMENT AS PART OF THE ARMY TRANSFORMATION INITIATIVE

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ABSTRACT

This paper presents an efficiently structured and integrated Reliability and Maintainability (R&M) process for implementation in a Digital Engineering (DE) environment during the product design phase, in support of the Army Transformation Initiative. This process links key R&M tasks to influence their execution and clarifies the relationship between a system's design risk and its R&M performance. The significant contributions of this process are: 1) establishing intra- and inter-task linkages for R&M activities within a comprehensive, systemic design process; 2) defining the direct impact on component and system-level R&M as a function of strategic design risk mitigation activities through a central Design Failure Modes and Effects Analysis (DFMEA); and 3) executing R&M tasks within a fully integrated, closed-loop R&M modeling and risk assessment approach, supported by a DE and AI-enabled environment.

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1. INTRODUCTION

In current industrial development practices, the strategic application of key Reliability and Maintainability (R&M) tasks to quickly influence a product's design risk and its associated R&M performance is a persistent problem. R&M developmental tasks are often time-consuming, incomplete, disconnected from the current design architecture, and performed independently of one another. As a result, their findings are not effectively combined to influence design decisions at key engineering milestones.

Immediate change is necessary to expedite critical R&M design decisions and influence the system's architectural model to minimize risk to the end-user while enhancing R&M performance. Furthermore, there is a need to reduce time-consuming and costly verification efforts to deliver system designs for immediate application in the field. This paper introduces an innovative R&M process as part of the new Army Transformation Initiative (ATI) [1] that addresses these challenges.

The significant contributions of this R&M process include:

1. Clearly defined relationships between key R&M tasks and their critical path for execution within a comprehensive, integrated process that operates within key program engineering milestones.
2. The ability to define the direct impact on component and system-level reliability and maintainability as a function of strategic design risk mitigation activities, as defined through a central design risk assessment (DFMEA).
3. The ability to execute R&M tasks within a fully integrated risk assessment and R&M modeling approach using a Digital Engineering (DE) and AI-supported environment.

This paper is structured as follows: 1) the integrated Design for Reliability (DFR) process, including its tasks, relationships, execution, and efficiencies, and its transformation into a DE framework; 2) the integrated Design for Maintainability (DFM) process; and 3) the execution and management of the complete DFR/DFM process during design development in alignment with key engineering milestones.

2. DESIGN FOR RELIABILITY

2.1. Objective and Approach

Design for Reliability (DFR) is a proactive approach that strategically integrates reliability principles through specific tasks during the design development phase. Its primary goal is to predict failures, reduce risks, and optimize reliability performance. The main objective of this DFR process is to "build-in" design robustness before the creation of prototypes and system testing.

Achieving efficiency in a DFR process involves a closed-loop structure and the linkage of critical reliability tasks to transfer data for reliability risk assessment, prediction models, and comparison against subsystem reliability targets. Efficiencies are further gained by integrating various aspects of reliability tasks and linking data elements directly between them, providing a quick, real-time understanding of the reliability impact of risk assessment and mitigation.

2.2. Process Flow and Execution

The DFR process and its interdependencies for a typical vehicle reliability program can be visualized as a process flow, starting with system requirement definition and its translation into a system reliability math model for measurement and assessment. The process map in Figure 1 illustrates the flow of information and data between the DFMEA, component, and vehicle system reliability math models.

Reliability demonstration and growth potential are assessed by comparing reliability

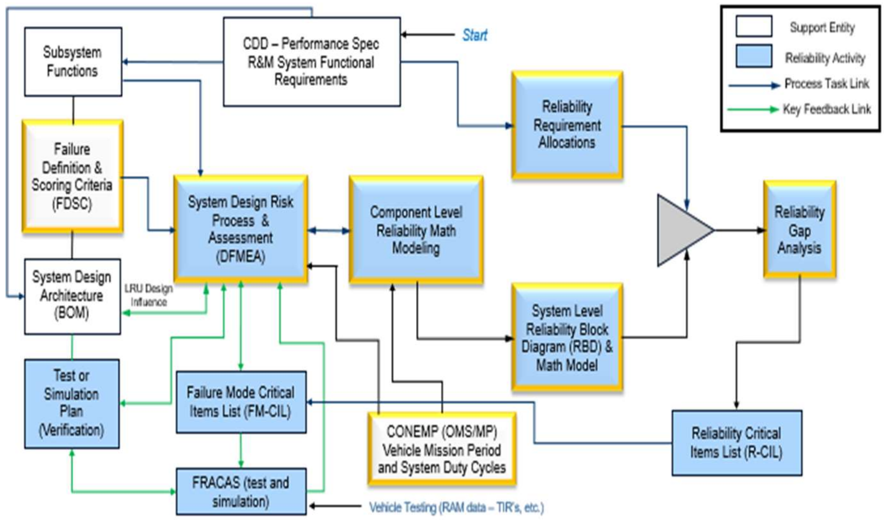


Figure 1: *Integrated DFR Process Map*

specification allocations against the most recent reliability prediction models. A reliability gap analysis, a primary output of this DFR process, evaluates the gaps in reliability, as shown in Figure 1. The gap between allocated and projected system reliability identifies priority subsystems and components for improvement. Design improvements are prioritized based on the reliability gap analysis and the DFMEA, which helps develop critical items lists that identify the hardware or software responsible for the reliability gap.

This DFR is a closed-loop process, allowing for configuration control and management of the system's design reliability as real-time changes are made to system function, architecture, or design verification. Linking the various reliability tasks allows for proper functional decomposition and application to the reliability

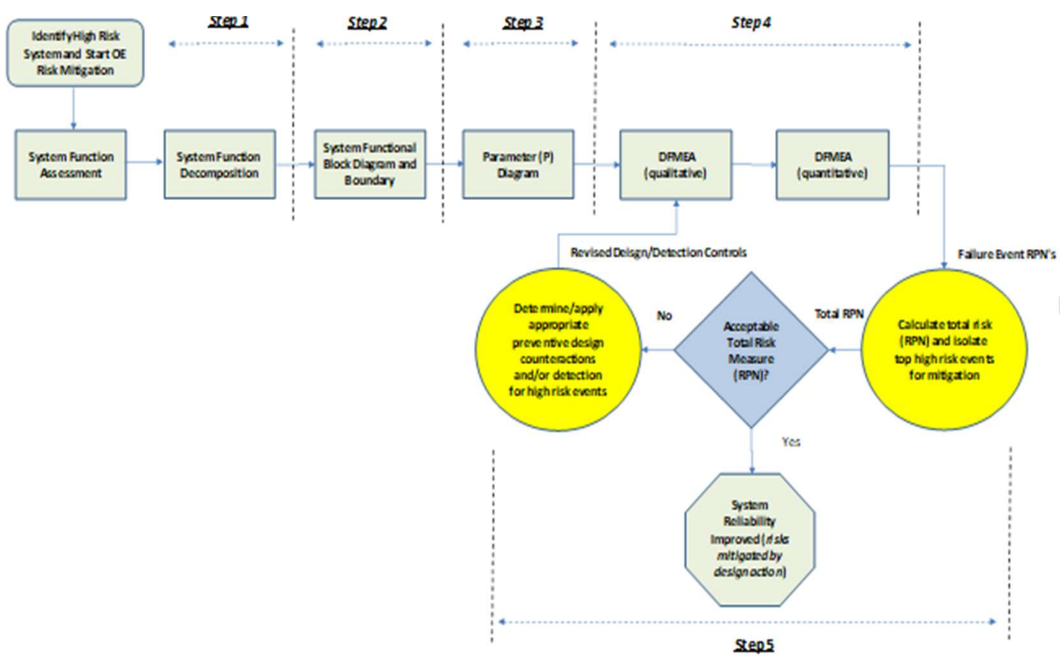


Figure 2: *DFMEA General Process Steps*

math model. Any change to the system design architecture is reflected in a reliability performance metric, which can be directly linked to a specific hardware/software element.

2.3. DFMEA and the Reliability Model

A significant challenge in current industry practice is relating a system's design risk to its reliability model to understand the influence of a design’s failure opportunities and countermeasures. There is often a lack of understanding of how a component's design risk is related to its reliability math model representation.

A central task in the DFR process is the Design Failure Modes and Effects Analysis (DFMEA), a tool for evaluating design risk relative to component, subsystem, or system failure modes and their root causes. The DFMEA helps define preventive and detective controls to avoid future failures. It promotes corrective actions by identifying potential failure risks and maintainability issues early, so that corrective actions can be taken to eliminate or control high-risk items, improving operational readiness and reducing life cycle costs.

The DFMEA forecasts what can go wrong and seeks ways to address each possible failure. It ranks risks according to set criteria, helping to focus resources on those that are most severe, have safety implications, are costly, or directly influence the user. The quantification of design risk in the DFMEA is a function of severity (S), probability of occurrence (O), and detectability (D). The measure of design risk importance is the Risk Priority Number (RPN), which is the mathematical product of these rankings:

RPN = S x O x D

The DFMEA is the central R&M design activity and the key link to other R&M tasks. There are five important steps in performing a DFMEA, as shown in Figure 2. These steps support the qualitative and quantitative development of the design risk assessment.

The detailed execution of the DFMEA involves developing a logical representation of design risk

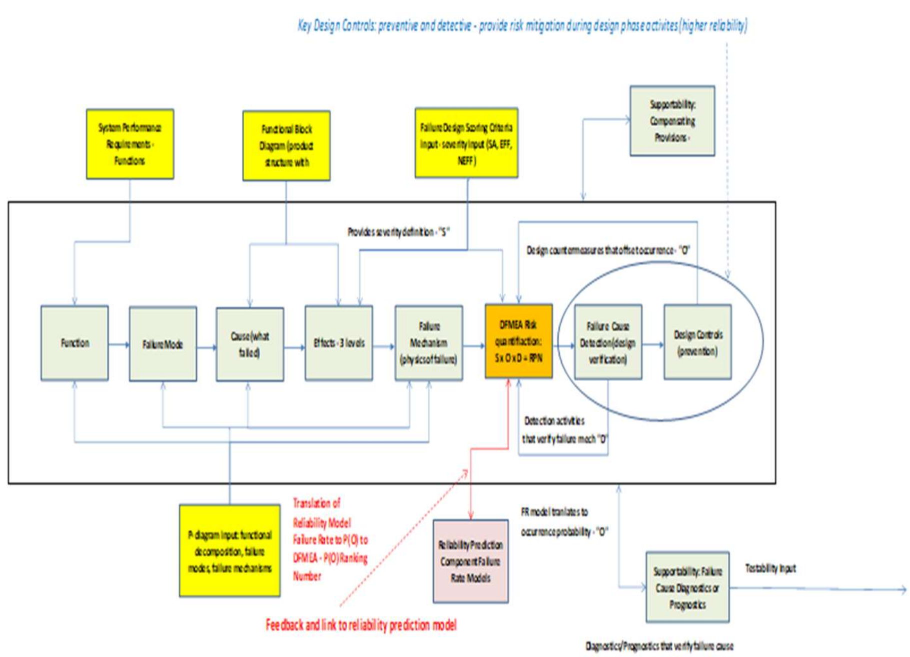


Figure 3: *DFMEA Detailed Execution Process*

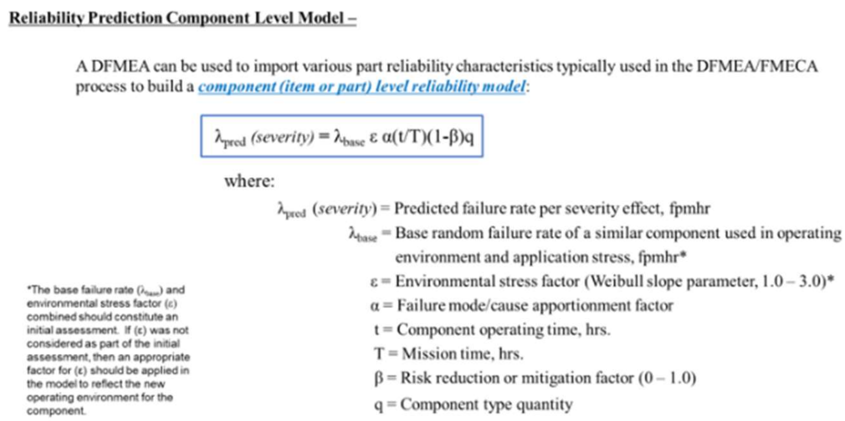


Figure 4: *Hardware Projected Failure Rate Model*

elements (failure modes, causes, preventive and detection controls) for all hardware and software elements that contribute to the system's performance, as shown in Figure 3.

A critical link in the closed-loop DFR process is the integration of a hardware (HW)/software (SW) component failure rate model. This model develops a probability of failure occurrence parameter that directly links to the DFMEA, tying reliability performance to HW/SW risk. This link between the failure rate model and the DFMEA risk enables the analyst to manage critical failure events within the DFMEA by incorporating a risk reduction factor in the failure rate model, which is associated with a specific design countermeasure.

A general HW projected failure rate model as shown in **Error! Reference source not found.** contains key parameters that can affect the final reliability performance of a hardware component. The risk reduction factor within the failure rate model provides the primary ability to influence the magnitude of the effect of the design countermeasure on the specific component's failure mechanism.

The resulting change to the component's failure rate model will allow a linked calculation of the

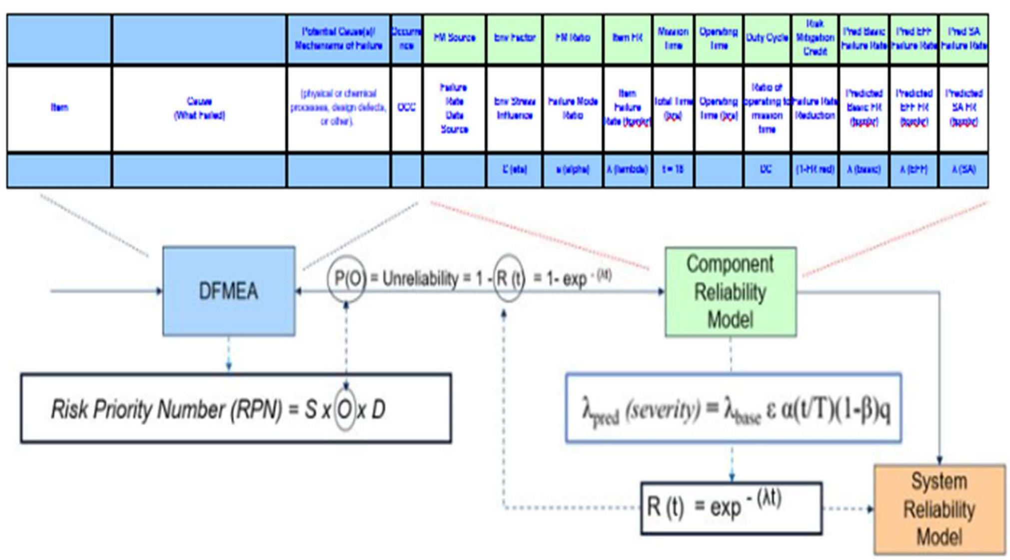


Figure 5: *DFMEA Link to Failure Rate Model*

probability of occurrence (O) in the DFMEA, as illustrated in Figure 5. A change in the projected failure rate for a hardware item directly impacts its design risk potential by lowering the probability of occurrence.

The resulting change to the component's failure rate model as a function of its failure mechanism will allow a linked calculation of a probability of occurrence.

If all the component's failure event risk measures (RPNs) are summed along with the associated failure rate models, a direct relationship can be established between the component or its associated system design risk and its corresponding failure rate (or MTBF), as defined in Figure 6. A decrease in a system's design risk (RPN), as measured in the DFMEA, will create a corresponding increase in the system's reliability or Mean Miles Between Failure (MMBF).

2.4. DFR Process Efficiencies

There are several efficiencies within this DFR process:

- First, the integrated approach of linking key reliability and support tasks facilitates data exchange and improves the execution of individual reliability tasks while keeping them current with changes in the product system during the design phase. The support of Digital Engineering and AI enables the connectivity and execution of these DFR tasks to provide updated results and prompt strategic decisions to improve product design reliability.
- Second, the ability to use the DFMEA as the central body of product design knowledge allows for key data links with reliability modeling and assessment processes to better understand the impact on system reliability as a function of risk management. The embedded integration within the DFMEA of combining risk assessment parameters with component failure rate modeling algorithms provides an expedient understanding of reliability performance as a function of design risk mitigations.

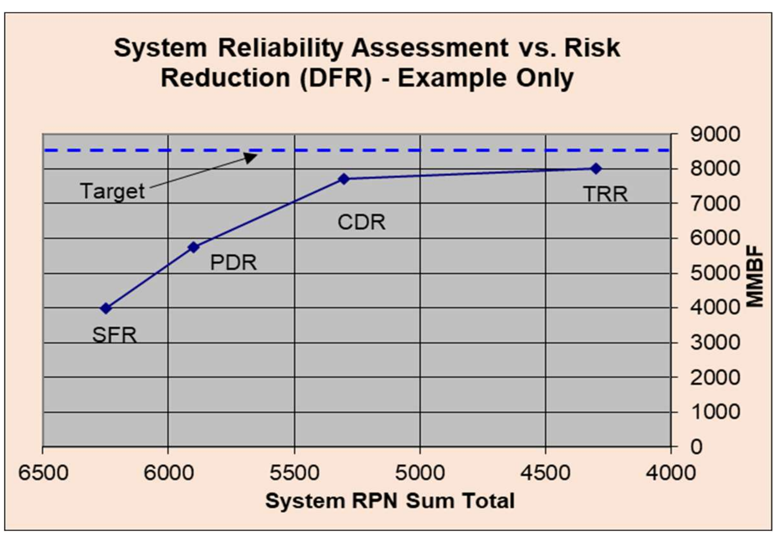


Figure 6: *Reliability (MMBF) versus Design Risk*

- Finally, the closed-loop arrangement of various reliability and support tasks allows for immediate design for reliability execution and feedback of key reliability assessment and critical item list results.

2.5. The Challenge with Traditional DFR and the Digital Solution

Traditionally, DFR activities have relied on large, complex, and error-prone spreadsheets that are difficult to link with other engineering tools. As a system design evolves, keeping these spreadsheets up-to-date is extremely difficult, leading to inaccuracies and suboptimal designs.

To address this, we envisioned an integrated Digital Engineering (DE) approach for DFR, aligning with the Army's mandate to implement a digital engineering strategy across the enterprise [2]. We translated the traditional process flowchart into a Cameo-based Systems Modeling Language (SysML) model (**Error! Reference source not found.**). This Internal Block Diagram (IBD) mapped out key DFR data sources and the data connections between them. Although most linkages did not initially exist in a digital format, this model established the essential foundation for a fully integrated, digital DFR environment.

To begin implementing this vision, we developed a SysML-based Reliability Pattern model in Cameo. This pattern provides a standardized format and structure, creating a digital thread that connects requirements, system architecture, and reliability analyses (FDSC, DFMEA, RBD) into a single, authoritative source of truth.

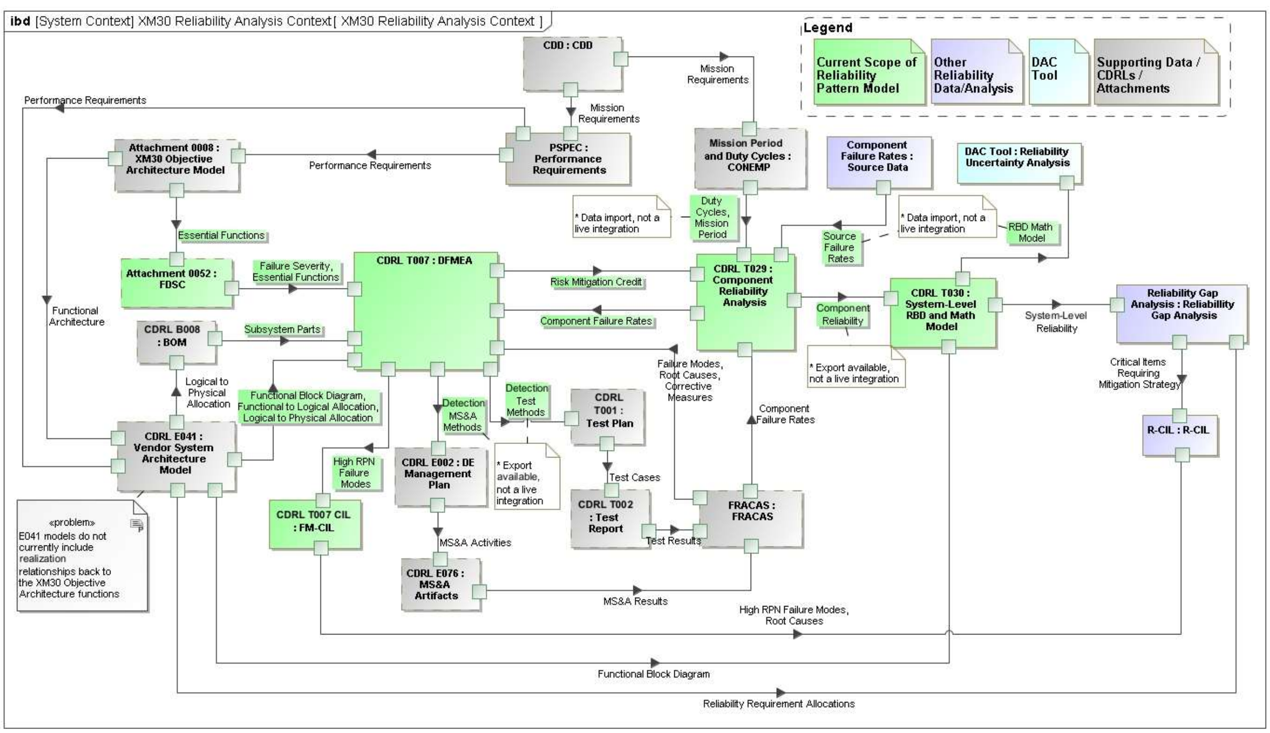


Figure 7: *Digital DFR Internal Block Diagram*

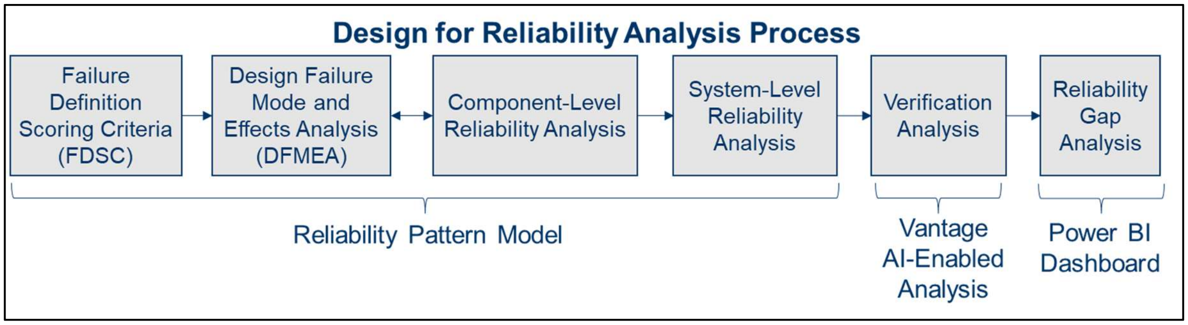


Figure 8: *Digital DFR Process*

2.6. The Key Stages of the Integrated Digital DFR Process

The key stages of this process, summarized in **Error! Reference source not found.**, were implemented using three main tools: Cameo for the Reliability Pattern model, Army Vantage for AI-enabled analysis, and Power BI for dashboarding and visualization.

2.7. Digital Failure Definition Scoring Criteria (FDSC)

The FDSC document describes a system's essential functions and categorizes the severity of potential failures. Typically document-based, FDSCs often lack a clear identification scheme, making it difficult to trace failures to other analyses. The FDSC is a critical input for determining the severity of failures in a DFMEA, making digitizing it essential. As shown in **Error! Reference source not found.**, we translated the document-based FDSC into a model-based pattern. This digitization enables failure definitions to be directly linked to the model-based DFMEA, ensuring failure severity definitions are applied consistently across the digital DFR ecosystem.

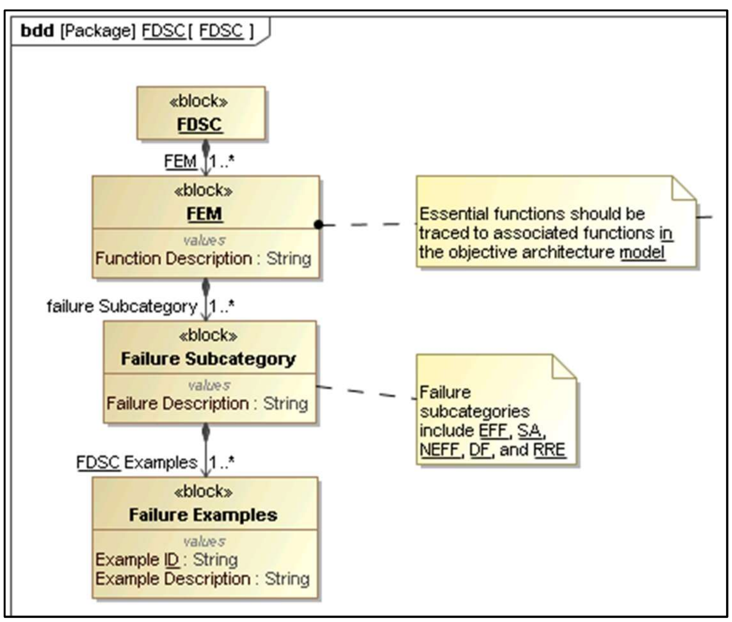


Figure 9: *Model-Based FDSC Pattern*

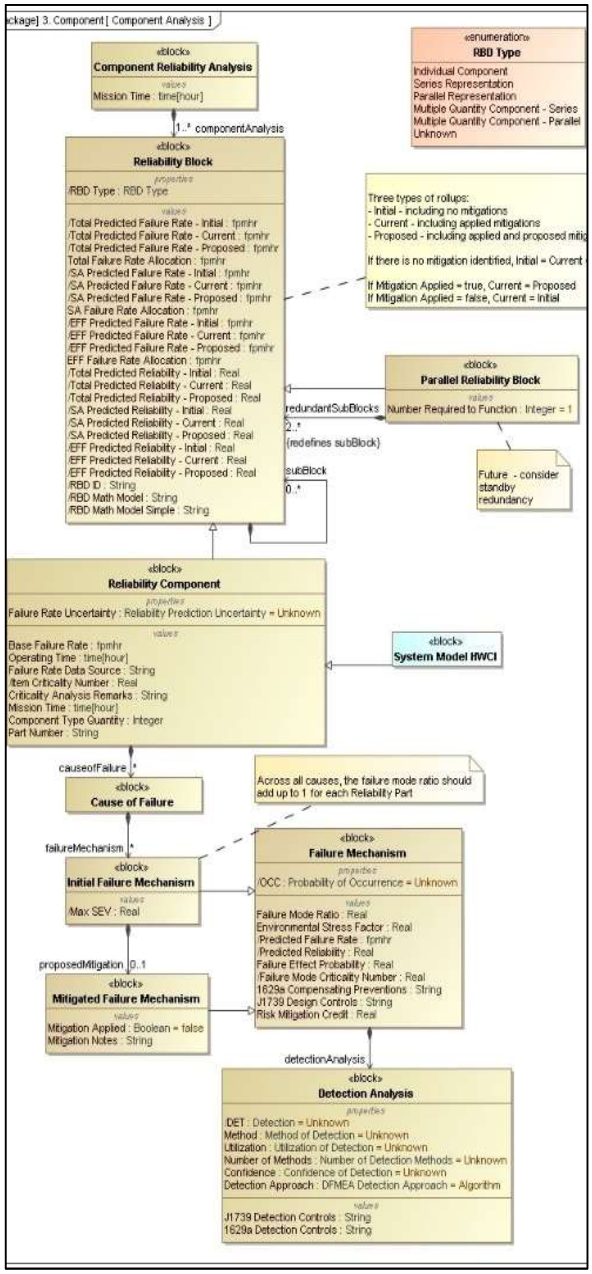


Figure 10: *Component Reliability Analysis Pattern*

2.8. Model-Based Component-Level Analysis

A component-level analysis captures the failure mechanisms and reliability characteristics of each physical part, including failure rates and expected time between failures. This results in an Occurrence (O) rating for each component. The analysis also assesses Failure Detection, producing a Detection (D) rating based on the method, utilization, and confidence of noticing a failure. By digitizing this analysis in a Cameo-based pattern (**Error! Reference source not found.**) and connecting it to the digital thread, we can directly assess the gap between current and target failure rates and show a direct relationship from the components with the highest gaps to the most critical system functions.

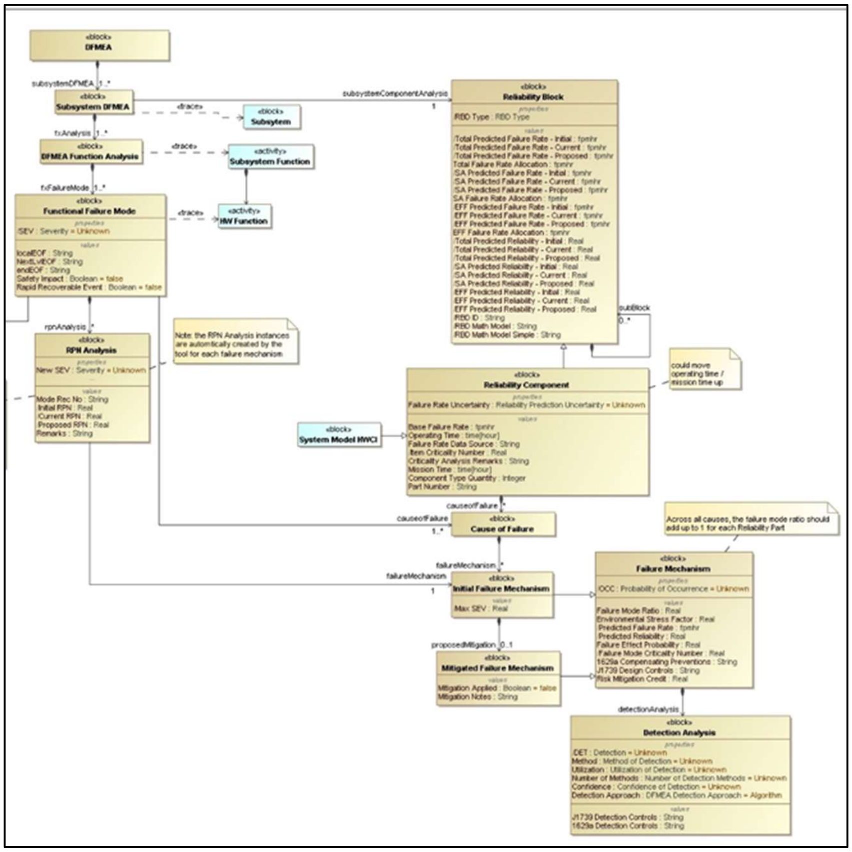


Figure 11: *DFMEA Pattern Integrated with the Component-Level Analysis Pattern*

2.9. Model-Based DFMEA Pattern

Establishing a model-based DFMEA (**Error! Reference source not found.**) is a foundational step in developing the digital DFR environment. This pattern contains a functional analysis of subsystems and their failure modes, completing the mapping from an individual component's failure to its effect on the system as a whole. The DFMEA pattern automatically quantifies a Risk Priority Number (RPN) for each failure event by calculating Severity (S) x Detection (D) x Occurrence (O). The integration of the FDSC, Component-Level Analysis, and DFMEA enables the automated calculation of RPN values, allowing the DFMEA to dynamically adapt to design changes.

2.10. Automated System Reliability Block Diagram (RBD) Rollup

The combined data from the previous stages is used to construct a Reliability Block Diagram (RBD), as seen in **Error! Reference source not found.**. This model, which reflects the system architecture with components in series and parallel, automates the calculation of overall system reliability. It assigns unique RBD IDs to each component and rolls up individual component data to the subsystem and system levels. The model accounts for initial and proposed values, allowing it to track the benefits of mitigations as they are designed and implemented. The output dynamically updates, eliminating many opportunities for human error as design changes are made over time.

2.11. AI-Enabled Verification Coverage Analysis

A digital connection was also established between the DFMEA and the Testing and Modeling, Simulation, and Analysis (MS&A)

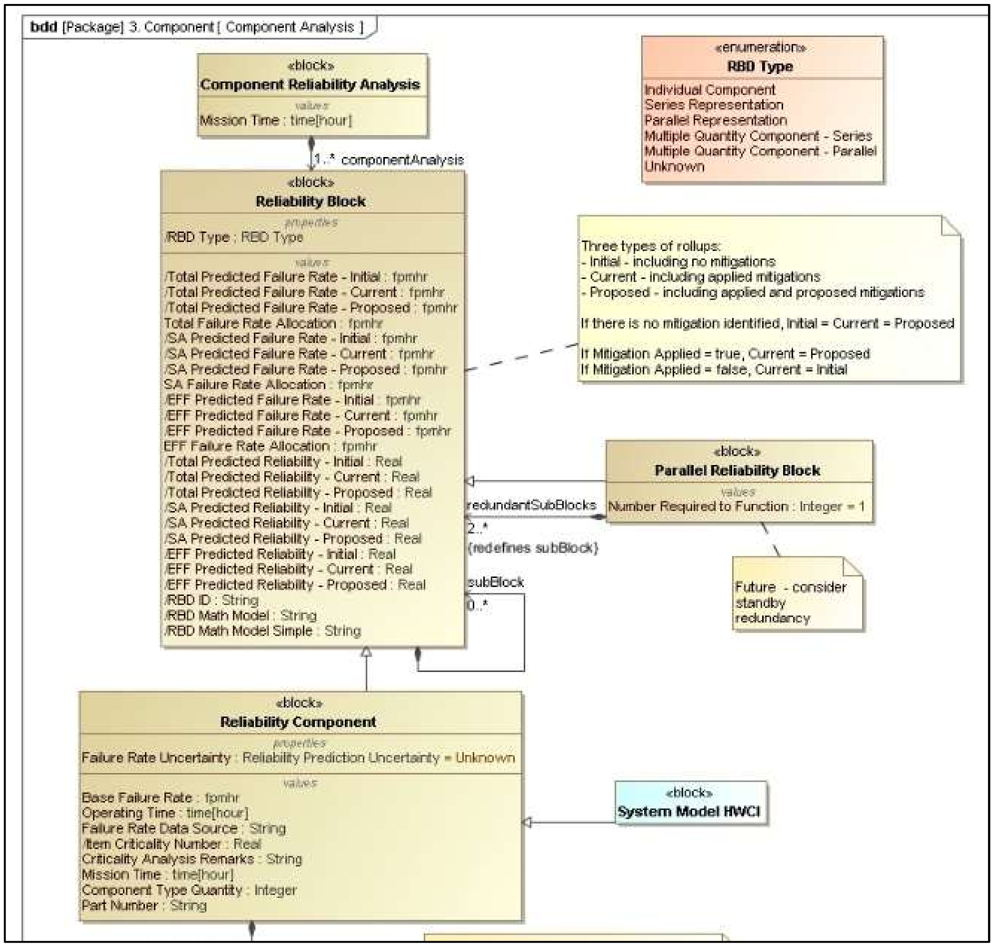


Figure 12: *Model-Based RBD Pattern*

documentation. An AI analysis in Army Vantage ingests and interprets these documents, automatically mapping verification activities to the corresponding failure events and detection methods in the DFMEA. The high-level process for this analysis is shown in **Error! Reference source not found.**. This connection provides both R&M and T&E engineers with powerful insights, highlighting which critical failure events have sufficient test coverage and where gaps may exist. The analysis can also recommend actions to improve coverage and identify duplicative activities, allowing for a more efficient verification plan.

2.12. Dynamic Visualization & Gap Analysis

Interpretation of the complex DFR Process results is necessary to draw actionable insights out of the analysis. The data outputs must be organized, formatted, and presented in a way that facilitates intuitive exploration of the results with a focus on answering key questions quickly and effectively. We use Power BI for this purpose, which is well-suited to the task due to its flexibility in data import controls and extensive library of customizable visuals and graphics. R&M experts must contribute to the development of the dashboards to arrive at an efficient and comprehensive representation of the analysis's most impactful findings.

Summary and detailed reports are created to identify the gaps between current and target reliability scores. A summary report view

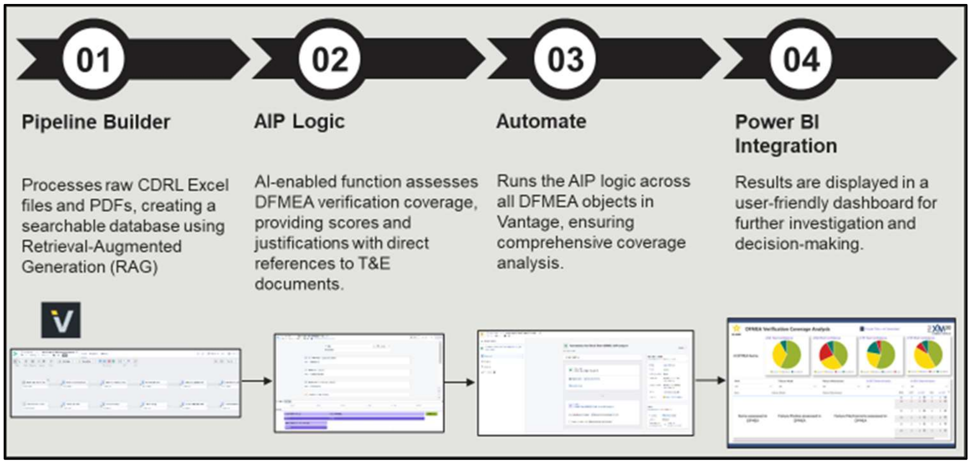


Figure 13: *Verification Coverage Analysis Process in Army Vantage*

showcasing the system's mean time between failure, system-level RPN value, and critical failure events provides an executive-level overview for leadership. R&M engineers who need more detail can filter reports by level of Severity, RPN, affected subsystem or function, and other fields to choose individual components to explore more deeply. Detailed reports like **Error! Reference source not found.** provide information on an individual component targeted for improvement, guiding R&M efforts as mitigations are applied.

Other reports are valuable for identifying gaps in testing coverage. A dashboard is created to show the intersection of the various sources assessed in the DFR Process. In this dashboard, tables of the highest risk failure events in the FDSC can be identified using the severity, occurrence, and detection ratings found in the DFMEA and Component-Level Analysis. Test coverage of these high-RPN failure events is assessed and summarized, allowing a R&M reviewer to determine if the existing coverage is sufficient. Summary reports filtered by overall

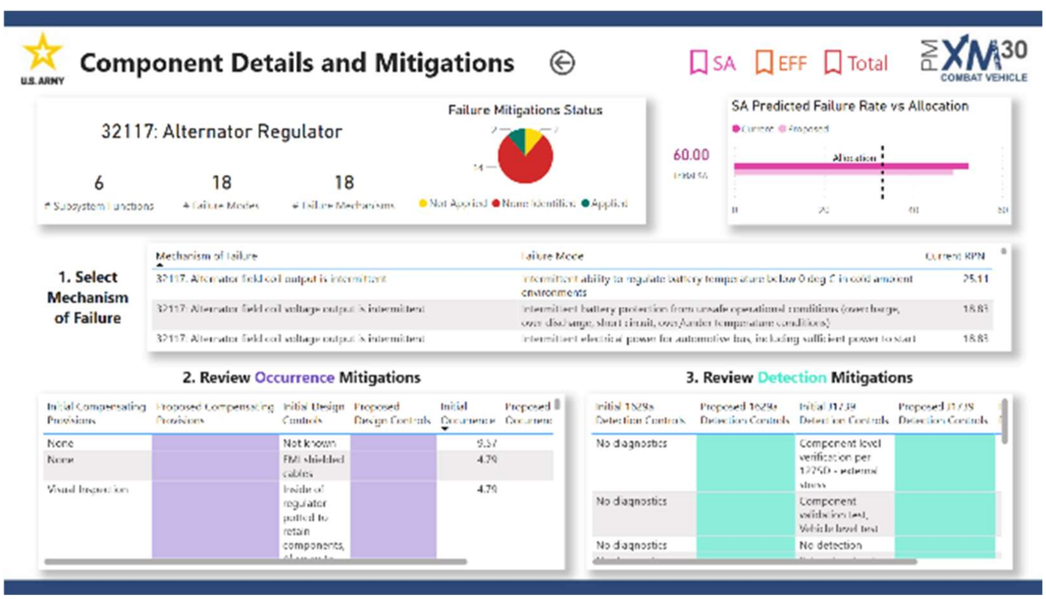


Figure 14: *Identifying Mitigation Opportunities*

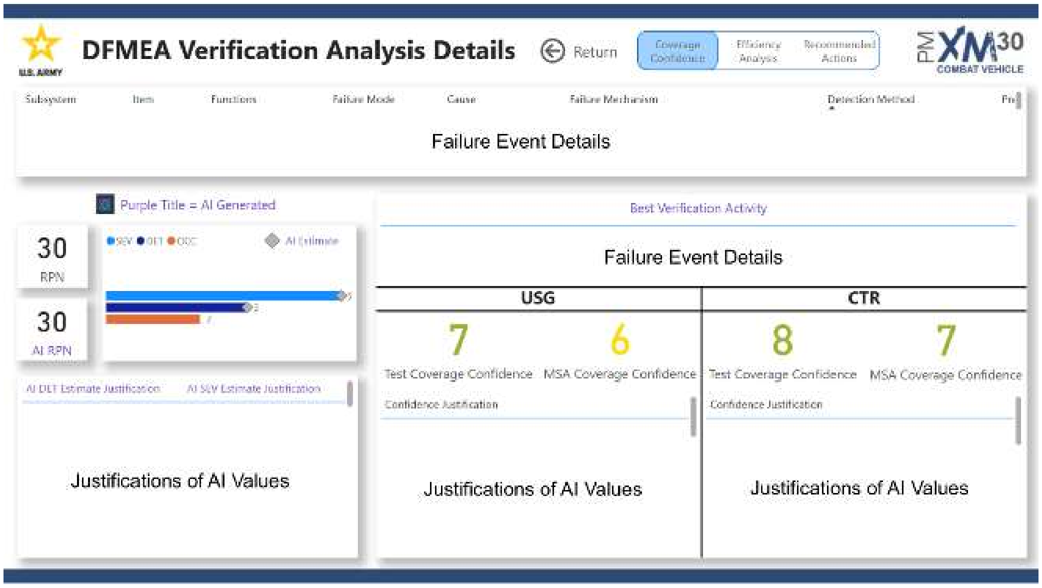


Figure 15: *AI Analysis of Test and MS&A Activities*

coverage confidence, RPN factors like Severity, Detection, and Occurrence, and subsystem help narrow down the list of the highest risk failure events. Once again, detailed reports on individual failure events like that seen in **Error! Reference source not found.** guide reviews and quickly identify areas of strong coverage that can be prioritized to improve verification efficiency.

The successful and impactful interpretation of the results of the DFR Process output determines the utility of the analysis and results in a more effective, more efficient R&M process when done correctly. Visualization tools like Power BI are used to guide reviews and simplify reporting efforts, enabling R&M engineers to direct more time and energy toward improving system reliability.

2.13. Validation and Future Work

To test and validate this process, we translated a traditional, spreadsheet-based DFMEA for a Lithium-Ion Battery subsystem into our model-based environment. This effort successfully demonstrated a complete, end-to-end digital thread from functional decomposition to system-level reliability rollup.

Future work will focus on implementing this process with additional vendor data, which is challenging due to varying formats and processes across OEMs. Further expansion will also include creating linkages from the digital DFR environment to live test results in the FRACAS (Failure Reporting, Analysis, and Corrective Action System) and expanding into maintainability artifacts.

3. DESIGN FOR MAINTAINABILITY

3.1. Objective and Approach

Design for Maintainability (DFM) is a proactive approach that integrates maintainability principles through specific tasks during the design phase. It helps predict maintenance measures such as Mean Time to Repair (MTTR) or Maintenance Ratio (MR), reduce maintenance risks, and optimize maintenance performance. Like DFR, the main objective of DFM is to "build-in" maintenance capability into the system before building prototypes.

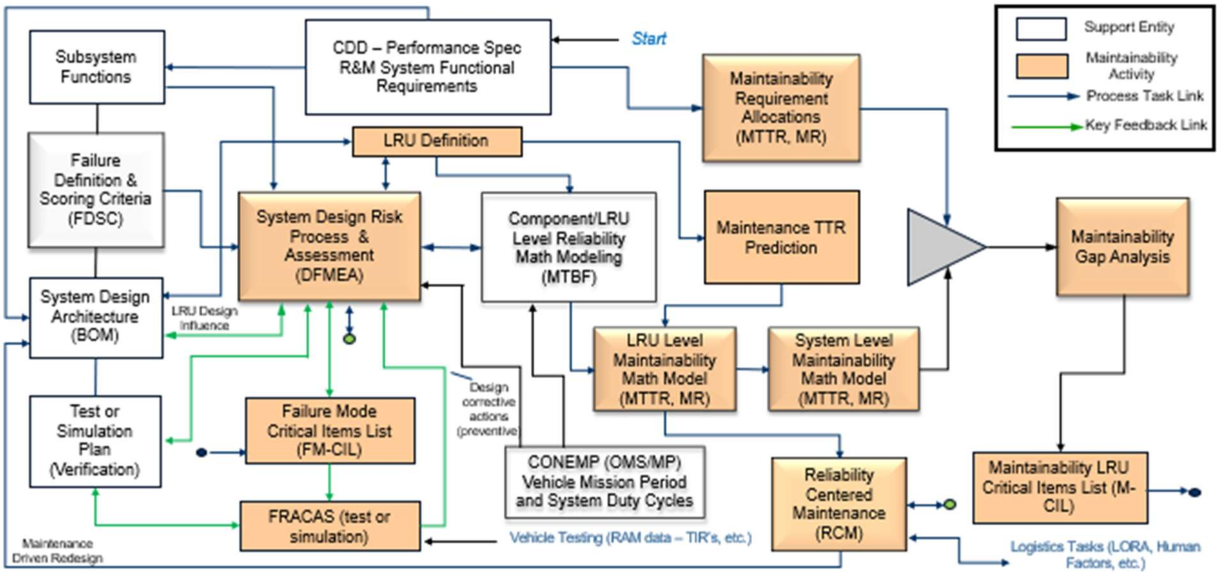


Figure 16: *Integrated DFM Process Map*

Achieving efficiency in a DFM process involves a closed-loop structure and linkage of critical maintainability tasks, like the DFR process.

3.2. Process Flow and Execution

The DFM process and its interdependencies can be shown as a basic process flow starting with system requirements and translating them into a system maintainability math model. The process map in Figure 16 provides a relationship between information and data flow between the DFMEA, LRU, and vehicle system maintainability math models.

A maintainability gap analysis, a primary output of this DFM process, evaluates the gaps between the allocated and projected system maintainability to help identify priorities for improvement. This DFM is a closed-loop process, allowing for configuration control and management of the design's maintainability potential as real-time changes are made.

3.3. DFM Process Efficiencies

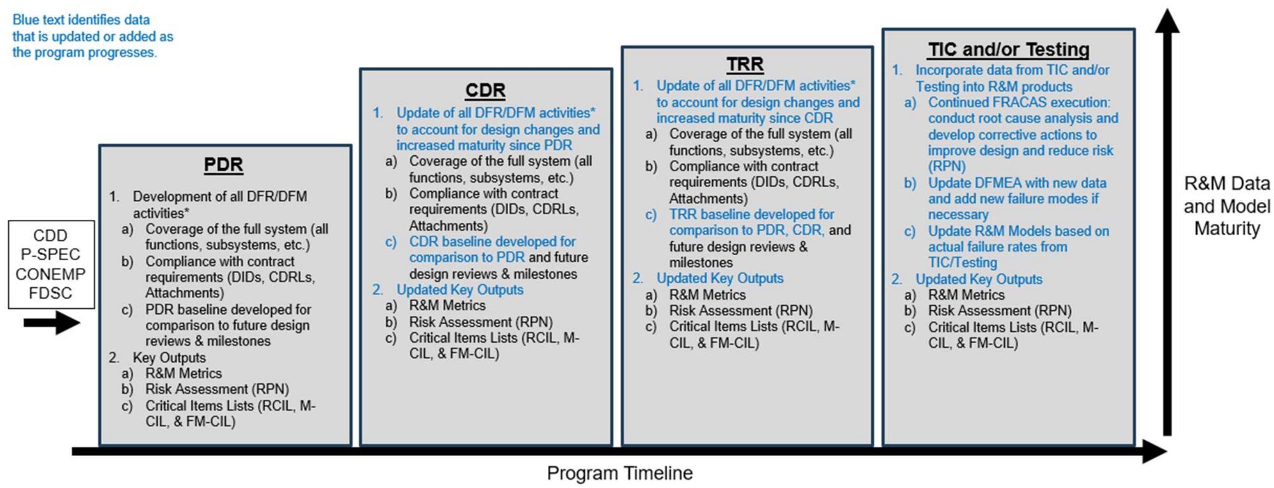
This DFM process has several efficiencies in common with the DFR process:

- The integrated approach of linking key maintainability tasks facilitates data exchange and improves the execution of individual tasks.
- The use of the DFMEA as the central tool for design risk management allows for key data links with maintainability modeling to better understand the impact on system maintainability.
- The closed-loop arrangement of various maintainability, reliability, and support tasks allows for immediate DFM execution and feedback.

3.4. Implementing an Integrated Digital Engineering Environment for DFM

The DFM process is improved through a digital engineering approach in many of the same ways as the DFR process. As seen in Figure 16, the DFMEA is connected to Test and MS&A Documents, Component-Level Math Modeling, FDSC, and other maintainability activities that mirror the structure of the DFR process. This approach streamlines the identification of necessary improvements to the system's maintainability.

4. Execution of the Integrated DFR/DFM Process



*DFR and DFM Activities (from Integrated Process Maps)
DFR: System Design Risk Process & Assessment (DFMEA), Component Level Reliability Math Modeling, System Level Reliability Block Diagram (RBD) & Math Model, Reliability Requirement Allocations, Reliability Gap Analysis, Reliability Critical Items List (R-CIL), Failure Mode Critical Items List (FM-CIL), Test or Simulation Plan (Verification), FRACAS (test and simulation)

DFM: System Design Risk Process & Assessment (DFMEA), LRU Definition, Maintenance TTR Prediction, LRU Level Maintainability Math Model (MTTR, MR), System Level Maintainability Math Model (MTTR, MR), Maintainability Requirement Allocations (MTTR, MR), Maintainability Gap Analysis, Maintainability LRU Critical Items Lists (M-CIL), Failure Mode Critical Items List (FM-CIL), FRACAS (test or simulation), Reliability Centered Maintenance (RCM)

Figure 17: *DFR and DFM Throughout the Lifecycle*

4.1 Management and Control at Program Milestones

Executing DFR and DFM activities early in a program's lifecycle is critical to ensuring that R&M are "designed-in" to the system rather than viewed as an afterthought to be addressed when problems are found during system testing and fielding. Therefore, the R&M activities identified in **Error! Reference source not found.** and **Error! Reference source not found.** should be executed by a program's Preliminary Design Review (PDR) at the latest. This provides a baseline that can be compared to future design reviews. For example, the R&M PDR baseline will allow the program to efficiently track how any design changes implemented between PDR and Critical Design Review (CDR) impacted R&M.

This baseline and tracking process can continue through Test Readiness Reviews (TRRs) as well as future technical reviews or program milestones. **Error! Reference source not found.** shows an example of this process and how the DFR and DFM activities are updated at technical reviews, resulting in increased R&M data and model maturity over time. The **Error! Reference source not found.** example also incorporates system testing and Transformation in Contact (TIC) events, as system usage during these events can identify new failure modes, provide data to refine R&M models, and drive further design improvements.

4.2 Management and Monitoring Between Program Milestones

An advantage of conducting the integrated R&M process within a Digital Engineering Environment is the ability to analyze Contractor progress more frequently. Rather than being limited to seeing Contractor R&M deliverables only at program reviews and at specific Contract Data Requirements List (CDRL) prescribed dates, the program can view R&M progress in the DE environment without burdening the Contractor with frequent, formal R&M CDRL deliveries. **Error! Reference source not found.** shows an example Power BI dashboard where part numbers from three different sources (DFMEA, Component Reliability Model, and Bill of Materials) are compared to help the program identify discrepancies and completeness across deliverables. This regular monitoring between program milestones using various

***Figure 18:** Example Part Number Comparison Dashboard*

dashboards can help efficiently identify and resolve issues earlier in a program's lifecycle.

5. CONCLUSION

This paper has presented an efficient and integrated Reliability and Maintainability (R&M) process within a Digital Engineering (DE) environment. This process offers several key efficiencies:

First, the establishment of an integrated and systemic design process for R&M provides for the quick and direct transfer of vital information. This enables an immediate understanding of system R&M performance as a function of design risk throughout the design phase. Executing R&M tasks within a fully integrated risk assessment and modeling approach, supported by DE and AI, allows for better focus on managing key system design risks.

Second, this paper defines the direct relationship between component and system-level R&M and design risk mitigation, as defined through the central DFMEA. This provides the opportunity to efficiently use the DFMEA to manage design risk and measure R&M, focusing more time on the management of high-risk failure modes and their verification.

Finally, the closed-loop arrangement of R&M tasks allows for immediate design for R&M execution and feedback for proper assessment, management, and the creation of critical item lists to impact product design.

The embodiment of these process efficiencies, obtained through the strategic integration of R&M tasks within a digital engineering and AI structure, helps to remedy many of the R&M developmental issues experienced by industry.

6. REFERENCES

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7. ACKNOWLEDGMENT

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8. AI DISCLOSURE

GenAI.mil (Gemini 2.5) was used solely for language editing (grammar, wording, and readability). All concepts, methodologies, results, and conclusions are the authors' original work.

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10. ACRONYMS

GVSC	Ground Vehicle System Center
ATI	Army Transformation Initiative
R&M	Reliability & Maintainability
AI	Artificial Intelligence
DE	Digital Engineering
DFMEA	Design Failure Modes Effects Analysis
DFR	Design for Reliability
DFM	Design for Maintainability
FRACAS	Failure Reporting Corrective Action System
HW	Hardware
SW	Software
LRU	Line Replaceable Unit
MMBF	Mean Miles Between Failure
MTTR	Mean Time to Repair
MR	Maintenance Ratio
RBD	Reliability Block Diagram
SysML	Systems Modelling Language
O	Probability of Occurrence
D	Detection
S	Severity
IBD	Internal Block Diagram
CDRL	Contract Data Requirements List
FDSC	Failure Description Scoring Criteria
TIC	Transformation in Contact
PDR	Preliminary Design Review
CDR	Critical Design Review
TRR	Test Readiness Review
MS&A	Modelling, Simulation, & Analysis