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ADAPTING QUALITY PLANNING TOOLS TO EVOLVING PRODUCTS AND MANUFACTURING PROCESSES: THE CASE OF FMEA

PRILAGODITEV ORODIJ ZA NAČRTOVANJE KAKOVOSTI RAZVIJAJOČIM SE IZDELKOM IN PROIZVODNIM PROCESOM; PRIMER ANALIZE NAČINOV IN UČINKOV ODPOVEDI PROCESA

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This study examines the evolution of design failure mode and effects analysis (DFMEA) in response to the automotive product transformation from conventional to mechatronic systems. The research combines a literature review with case studies to identify key changes in risk assessment methodology. The analysis compares severity ratings between conventional and mechatronic systems, with reference to the corresponding process failure mode and effects analysis (PFMEA) changes. Results indicate systematic increases in the severity of failure modes in the mechatronic DFMEA and decreasing differences between DFMEA and PFMEA risk assessments, reflecting the blurring of the boundaries between design and process risks. The study confirms the need for a more systemic risk analysis that considers complex component interactions and the increased impact of the production process on modern mechatronic product functionality.

Keywords: FMEA, PDCA, quality planning tools, Industry 4.0 in quality management

V tem članku avtorja predstavljajta študijo, ki preučuje razvoj analize načinov in učinkov odpovedi zasnove (DFMEA, angl.: Development of Failure Mode and Effects Analysis) kot odziv na preobrazbo avtomobilskih izdelkov iz konvencionalnih v mehatronske sisteme. Raziskava združuje pregled literature s študijami primerov, da bi opredelila ključne spremembe v metodologiji ocenjevanja tveganja. Analiza načinov in učinkov odpovedi procesa (PFMEA, angl.:. Failure Mode and Effects Analysis) primerja ocene resnosti med konvencionalnimi in mehatronskimi sistemi s sklicevanjem na ustrezne spremembe. Rezultati kažejo na sistematično povečanje resnosti mehatronskih DFMEA in zmanjšanje razlik med ocenami tveganja DFMEA in PFMEA, kar odraža zamegljenost meja med tveganjem pri zasnovi in procesu. Študija potrjuje potrebo po bolj sistematičnem pristopu k analizi tveganja, ki upošteva kompleksne interakcije komponent in povečan vpliv proizvodnega procesa na funkcionalnost sodobnih mehatronskih izdelkov.

Ključne besede: FMEA, PDCA, orodja za načrtovanje kakovosti, Industrija 4.0 v upravljanju kakovosti

1 INTRODUCTION

The automotive industry is undergoing unprecedented transformation from conventional mechanical systems to complex mechatronic platforms that integrate mechanics, electronics, and software. This evolution fundamentally changes potential risks in modern vehicles, supplementing mechanical wear modes with software bugs, communication errors, and subsystem integration issues. This evolution demands parallel transformation of risk analysis tools, particularly DFMEA, which must adapt to address complex system interactions absent in conventional vehicles. The methodology requires a significant adaptation to effectively identify risks in modern automotive systems, where failures may propagate across multiple subsystems with greater severity.

When literature covers quality management methods, it often separates DFMEA and PFMEA without addressing their evolving relationship during product transformation. As products become more complex, the boundary between design and process risks blurs, necessitating a more integrated approach. This study analyses how automotive product evolution impacts the DFMEA methodology and cascades to PFMEA, focusing on severity rating differences between conventional and mechatronic systems.[1]

2 EXPERIMENTAL PART

This study employed a theoretical analysis based on the literature and case studies to evaluate the evolution of quality planning tools in automotive product transformation. Research examined variations in severity ratings be-

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Table 1: Risk and safety impact in mechatronic vs conventional systems (our elaboration)

POTENTIAL RISK: Steering Assist Failure	**PFMEA Severity values for illustration only*
Severity – Mechatronic Systems: **9** (*PFMEA Severity: **7**)	Severity – Conventional Systems: **7** (*PFMEA Severity: **5**)
In conventional systems, loss of steering assist increases driver effort without directly affecting safety. In mechatronic systems, an electronic failure can cause a sudden loss of primary steering function, posing a high safety risk, especially at high speeds.	
POTENTIAL RISK: ABS (Anti-Lock Braking System) Malfunction	
Severity – Mechatronic Systems: **9** (*PFMEA Severity **8**)	Severity – Conventional Systems: **6** (*PFMEA Severity: **4**)
Conventional ABS relies mainly on mechanical components, where failures rarely affect vehicle stability. In mechatronic ABS, a malfunction can cause an immediate loss of braking control, directly compromising safety by impairing the primary braking function.	
POTENTIAL RISK: Communication Failure between Electronic Modules	
Severity – Mechatronic Systems: **8** (*PFMEA Severity: **6**)	Severity – Conventional Systems: **Not Applicable**
In conventional systems, communication between components has minimal impact on vehicle functionality. In mechatronic systems, communication errors between modules (e.g., between the braking system and ECU) can disrupt component interaction, leading to partial loss of critical functions and impacting safety.	
POTENTIAL RISK: Engine Control Unit (ECU) Failure	
Severity – Mechatronic Systems: **9** (*PFMEA Severity: **8**)	Severity – Conventional Systems: **Not Applicable**
In mechatronic systems, the ECU controls essential engine functions. Its failure results in a complete loss of primary drive function, potentially immobilising the vehicle in hazardous situations and posing a significant safety threat.	
POTENTIAL RISK: Autonomous Parking Function Disruption	
Severity – Mechatronic Systems: **8** (*PFMEA Severity: **6**)	Severity – Conventional Systems: **Not Applicable**
In conventional vehicles, parking is handled by the driver, so disruptions do not affect safety. In autonomous systems, a disruption can lead to a loss of primary automated control function, increasing the risk of collisions with surrounding objects.	

tween DFMEA and PFMEA for identical vehicle systems, identifying patterns as products evolve from conventional to mechatronic. A comparative analysis revealed key differences in risk assessment approaches, with a focus on AIAG and VDA harmonisation reflecting the trend toward integrated risk analysis.[2]

3 RESULTS

3.1 Evolution of the FMEA method as an example of adaptation in quality planning

The FMEA method originated in the 1940s, used for the defence industry failure identification and was adopted by NASA in the 1960s for spacecraft reliability. The automotive industry initially implemented it for mechanical components before expanding it to electronic systems. During the 1980s–1990s period, two distinct versions emerged: AIAG (process efficiency) and VDA (quality documentation). This divergence created challenges for global suppliers, increasing costs and complexity. In 2019, AIAG & VDA introduced a unified standard that streamlined methodology, improved communication, enhanced collaboration, facilitated decision-making, and improved production consistency.[3]

3.2 Evolution of products and its impact on quality planning tools

As the automotive industry progresses through technological phases, risk analysis methodologies must evolve accordingly. This transformation fundamentally changes the approach to quality planning, particularly within the interaction between DFMEA and PFMEA: Mechatronic components – integrated elements combining mechanics, electronics, and software – enabling autonomous operation and real-time control. Conventional components – traditional mechanical, electrical, and hydraulic components – operating without digital integration, relying on manual or physical control and lacking real-time data exchange.

Table 1 illustrates how these technological differences translate into risk assessments. Mechatronic systems exhibit higher DFMEA severity ratings (8–9) than conventional systems (6–7), reflecting the greater safety implications of electronic failures, given their potential for sudden functional loss, unlike the gradual degradation typical of conventional systems. The transformation of products has necessitated a fundamental shift in how risk information flows between design and manufacturing teams. While DFMEA and PFMEA once operated as distinct analyses with limited interaction, modern quality planning requires seamless information transfer between these domains. This evolution is particularly evident in critical systems such as electronic steering and braking, where manufacturing processes, such as calibration and parameter setting, directly influence core functionality, creating new interdependencies between design specifications and production controls that must be reflected in coordinated risk assessment methodologies.[4]

3.3 Relation between DFMEA and PFMEA risk assessment

According to the AIAG-VDA FMEA methodology, severity ratings cascade from DFMEA to PFMEA but are typically reduced by 1–2 points during a manufacturing analysis. This occurs because DFMEA focuses on end-user impacts of design flaws, while PFMEA examines process failures in controlled environments using established detection methods. For safety-critical systems (ECU, ABS), the reduction is minimal (typically 1 point) due to high residual risk. For non-critical functions (communication systems), the reduction is greater (typically 2 points), reflecting better detection opportunities through end-of-line testing. Conventional systems exhibit larger severity reductions (2–3 points) due to their mature manufacturing processes including standardized gauging techniques, mechanical Poka-Yoke fixtures, and established visual inspection criteria, as well as having their redundant verification methods refined over decades of production experience.[5–6]

4 DISCUSSION

This study's findings reveal the significant evolution of quality planning methodologies created in response to automotive product transformation. The convergence of severity differentials between DFMEA and PFMEA in mechatronic systems demonstrates how the traditional boundaries between design and manufacturing quality planning are increasingly blurred. Particularly noteworthy is the shift from independent risk assessments toward integrated approaches that acknowledge the critical interdependencies between design specifications and manufacturing processes in modern vehicles. Future research should explore empirical validation through longitudinal studies that track severity assessments across complete vehicle development cycles. Additionally, investigating machine learning applications for predictive failure analysis could enhance risk identification for emerging technologies like autonomous driving systems. The integration of real-time data from connected vehicles into FMEA methods offers opportunities to build dynamic risk assessment frameworks that adapt to emerging failure modes. Developing specialised severity classification frameworks for different vehicle systems would support industry standardisation and improve consistency in risk evaluation across the complex automotive technology landscape.[7–8]

5 CONCLUSIONS

The evolution of DFMEA methodology in response to automotive product transformation necessitates adapting quality planning approaches to technological advances. As mechanical systems evolve into mechatronic platforms, risk assessment must similarly transform, with greater integration into the design process. The narrowing severity differential between DFMEA and PFMEA in mechatronic systems confirms the blurring of boundaries between design and manufacturing risks. The harmonised AIAG-VDA standard provides a framework for holistic risk assessment that reflects the interdependent nature of modern automotive systems.

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