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ADAPTING D-FMEA TO INCREASING PRODUCT COMPLEXITY: A STUDY OF CONVENTIONAL AND MECHATRONIC SHOCK ABSORBERS

Lukasz Rudolf^{1,*}, Marek Roszak², Lenka Kuchariková³

¹Silesian University of Technology, Faculty of Mechanical Engineering, Gliwice, Poland

²Silesian University of Technology, Faculty of Mechanical Engineering, Department of Engineering Materials and Biomaterials, Gliwice, Poland

³University of Zilina, Faculty of Mechanical Engineering Department of Materials Engineering, Zilina, Slovakia

*E-mail of corresponding author: lukasz.rudolf@outlook.com

Łukasz Rudolf 0000-0001-9430-8513,
Lenka Kuchariková 0000-0002-2688-1075

Marek Roszak 0000-0002-4035-8360,

Resume

The risk analysis is essential in product development, particularly as technical complexity increases. In this article the focus was on Design Failure Mode and Effects Analysis (D-FMEA) in the automotive industry. The conventional and electronically controlled shock absorbers as examples of a transition from a mechanical-hydraulic product to a more complex mechatronic system, are compared. In the study was considered how increasing complexity affects analysis boundaries, decomposition level, function description, interactions between components and subsystems, and the link between risk analysis and product validation. Based on industrial practice, a model is proposed to show how D-FMEA should evolve with product complexity.

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Nomenclature

FMEA: Failure Mode and Effects Analysis; a preventive method used to identify potential failure modes, their effects and causes, in order to reduce risk.

D-FMEA: Design Failure Mode and Effects Analysis; a type of FMEA focused on product design and design-related risk.

BOM: Bill of Materials; a structured list of product components, used here as an indicator of product complexity.

RPN: Risk Priority Number; an index based on Severity, Occurrence and Detection, used in D-FMEA and applied here to compare product-related risk.

AP: Action Priority; a priority level in AIAG & VDA FMEA indicating how urgently risk-reduction action should be considered.

APQP: Advanced Product Quality Planning; a structured automotive framework supporting product and process development from planning to serial production.

PLM: Product Lifecycle Management; an organizational approach to managing product data, processes, engineering changes, and traceability throughout the product lifecycle, typically supported by an integrated digital environment.

1 Introduction

The subject of this study were the automotive shock absorbers, which are analysed into two product groups: conventional and mechatronic. The first group includes shock absorbers with a classical mechanical-hydraulic architecture, while the second includes electronically controlled shock absorbers, in which the damping function requires the interaction of mechanical, hydraulic, and electronic components and subsystems [1-2]. The differences between the analysed products concern not only their design, but the scope of the functions performed, the degree of connections with other subsystems, and the validation requirements, as well. This makes them a suitable subject for analysing

how design risk assessment should be adapted to increasing product complexity.

The Failure Mode and Effects Analysis (FMEA) is one of the basic preventive methods of technical risk analysis used in product and process development. Its origins can be traced back to reliability analyses developed for military applications; one of the earliest formal reference points is the MIL-P-1629 procedure from 1949, which structured the identification of potential failures, their effects, and their criticality. In the following decades, the method was further developed in the aerospace sector, where particular emphasis was placed on a system-level understanding of function, reliability, and safety. The FMEA was then widely adopted in many branches of industry, including the automotive sector, where it evolved from a tool originally focused mainly on component reliability into a structured method supporting quality planning, product development, and risk reduction during product preparation [3]. According to the current automotive approach presented by AIAG & VDA, FMEA is a structured method carried out by an interdisciplinary team to identify potential failure modes, their effects, causes, and actions intended to reduce risk [4]. In automotive practice, two main areas of application are usually distinguished: Design Failure Mode and Effects Analysis (D-FMEA), which addresses risks associated with product design, and Process Failure Mode and Effects Analysis (P-FMEA), which addresses risks associated with the manufacturing process. In this article, the main focus is on D-FMEA, because it is at the design stage that the analysis boundaries, product architecture, functions, and relationships between components, subsystems, and the system are defined.

Despite the widespread use of FMEA in industrial practice, there are relatively few empirical studies that show how D-FMEA should be performed as the product complexity increases [5-6]. This is especially important in cases where the product evolves, as in the development of shock absorbers from a conventional architecture to a mechatronic one, where not only the number of components changes, but also the scope of functions, the number of relationships between subsystems, and the validation requirements. The research gap, therefore, concerns not the use of D-FMEA itself, but the principles for adapting it to increasing product complexity. The aim of this article was to provide a comparative analysis of the two groups of automotive shock absorbers, conventional and mechatronic products, based on research conducted in industrial conditions, and to develop a model showing how the way D-FMEA is performed changes as product complexity increases. In the following sections, product complexity is considered not only descriptively, but in relation to product structure, the organisation of risk analysis, and the scope of activities related to quality planning and its validation, as well.

2 Research background and methodology

In this study, the logic of D-FMEA was adopted in line with the AIAG & VDA approach, in which design risk analysis is not limited only to the assessment of Severity (S), Occurrence (O), and Detection (D), but is treated as a structured process including planning and preparation, structure analysis, function analysis, failure analysis, risk analysis, optimisation, and documentation of product-related results [7-8]. This means that a reliable risk assessment requires the proper definition of the analysis boundaries, the level of the analysed product, and the relationships between the function, the potential failure mode, its effect, and its cause. According to the AIAG & VDA methodology, the priorities of the risk-reduction actions should be determined using the Action Priority (AP) approach, rather than only on the basis of the Risk Priority Number (RPN). At the same time, for the purposes of this study, the RPN values were retained as a supporting analytical indicator for comparing the two product groups in terms of overall design risk burden. In this article, therefore, the RPN does not serve a decision-making function, but a comparative and reference function, while the logic for interpreting the need for action remains consistent with the AP approach.

The research material used in this article comes from the authors own studies conducted in industrial conditions at Tenneco Automotive Eastern Europe as part of an implementation-oriented doctoral project. The comparative analysis covered two product groups: conventional shock absorbers, treated as the reference group, and electronically controlled shock absorbers, hereinafter referred to as mechatronic products. It was assumed that the second group represents solutions from the Monroe Intelligent Suspension product family, in which damping is achieved through the interaction of mechanical, hydraulic, and electronic subsystems, along with control via an ECU (Electronic Control Unit) and sensor signals [9-10]. This research setting enabled comparison of two levels of product architecture complexity in a real development and industrialisation environment, while maintaining alignment with the quality requirements typical of the automotive industry.

In this study, product complexity was not assessed solely descriptively, but rather using comparable data on both product structure and the scope of activities associated with quality planning [11]. This approach made it possible to analyse product complexity not only from the perspectives of the number of components and the organisation of the product structure, but also from the perspectives of the activities required to confirm the performed product functions and to plan and carry out product validation [12]. As a result, it was possible to link the features of product architecture with the way D-FMEA is conducted.

The research procedure included four main stages.

In the first stage, the comparison scope and the analysis boundaries were defined for both product groups. In the second stage, the available D-FMEA studies for selected shock absorber types were analysed, with a focus on product structure, function description, potential failure modes, and the interpretation of design risk. In the third stage, the data describing product complexity were compiled and then subjected to the comparative analysis. In the final stage, the results were interpreted in accordance with the D-FMEA methodology, and a model was developed to organise the observed changes in the way D-FMEA is conducted as product complexity increases.

3 Results

The results of the analysis show that the studied product groups differ not only in design, but also in the scope of the functions performed, the degree of relationships between components and subsystems, and the validation requirements. These differences are reflected in both the product's structural features and the way D-FMEA results are developed and interpreted. The research results are presented in a structure that covers successive aspects of the complexity of the analysed products and their significance for design risk assessment. In the final part of the section, a model

is presented to organise these observations from the perspective of D-FMEA.

3.1 System-level context relevant to D-FMEA

The comparative analysis began at the vehicle level, with the vehicle understood as the final product intended for use by the end user. This perspective allows the shock absorber to be considered not as an isolated component, but as part of a wider system responsible for functions related to vehicle behaviour, ride comfort, and driving stability.

Figure 1 presents an illustrative comparison of components and subsystems found in vehicles equipped with conventional shock absorbers and in vehicles using the KINETIC® solution from the Monroe Intelligent Suspension product family [13]. The radial scale indicates the number of elements of each type included in the analysed vehicle-level system. The presented data are illustrative and are intended to show the typical level of complexity of both solutions at the system level, without fully representing all variants of the analysed products. This comparison indicates that, for the mechatronic product, the damping function is implemented within a broader system that includes more interacting components and subsystems than in the conventional solution.

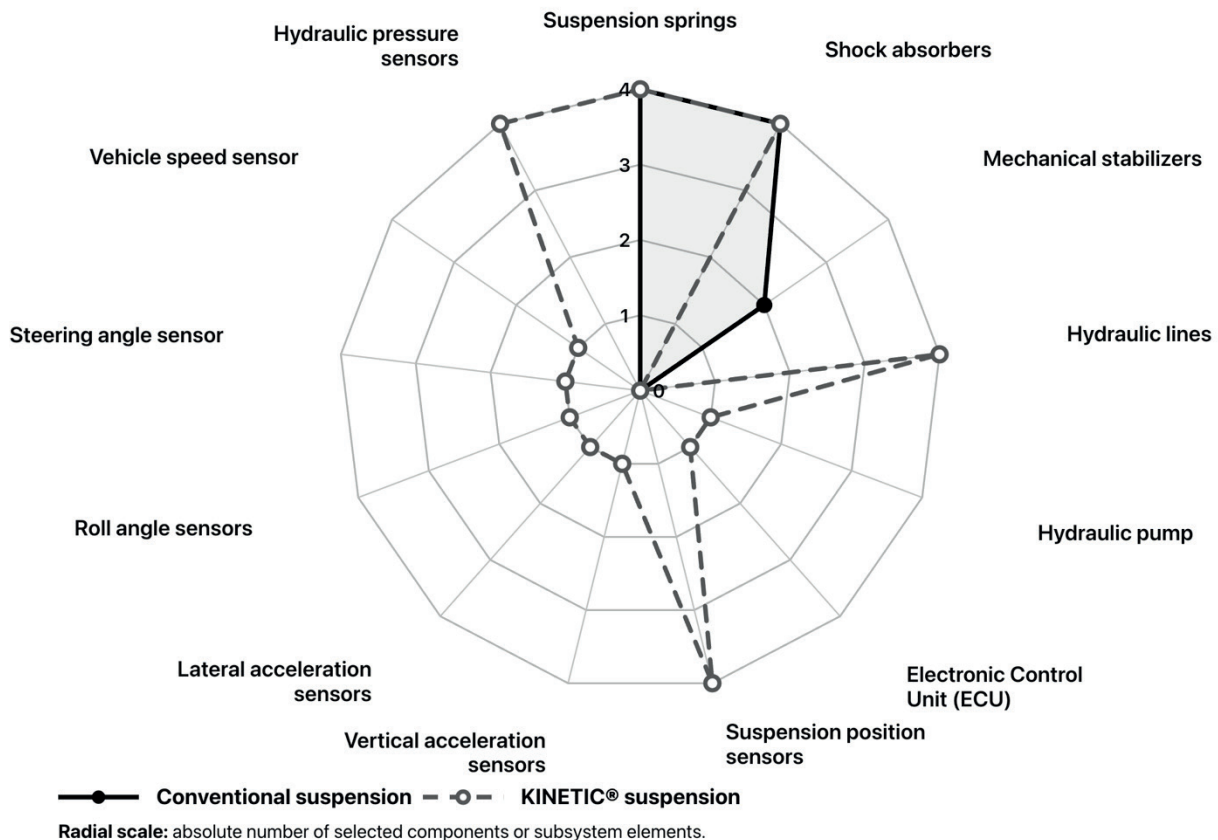


Figure 1 Comparison of selected components and subsystems in conventional suspension and the KINETIC® system

In the context of D-FMEA, the above is important mainly for defining the analysis boundaries. In the conventional product, the shock absorber's damping function can be analysed in greater detail within the component itself and its direct hydraulic subsystem. In the mechatronic product, however, it becomes necessary to consider a broader system context, since the way the function is performed also depends on the interaction of mechanical, hydraulic, electronic, and control subsystems, not only within the product itself [14]. This means that the difference between the analysed product groups is not only structural, but the system-related

as well which directly affects how the scope of further design risk analysis should be defined.

3.2 Product-level complexity relevant to D-FMEA

At the shock absorber level, the differences between the conventional product and the mechatronic product can be presented using indicators directly related to product structure, functional scope, and the burden placed on the quality planning process. The compiled data include the number of components listed in the

Table 1 Comparison of selected damper-level complexity and D-FMEA-relevant indicators for conventional and electronically controlled dampers

Area	Parameter	Conventional shock absorbers	Electronically controlled shock absorbers	Implication for DFMEA and quality planning
Product and function	Product architecture	Simple mechanical architecture: cylinder body, piston rod, piston with flow valves; steel structural components.	Integrated mechatronic system: mechanics, hydraulics, electronics and control software; more extensive system architecture.	The broader set of dependencies between components and subsystems requires a more comprehensive DFMEA structure and validation strategy.
Product and function	Damping characteristic adjustment	Fixed damping characteristic; no adjustment during operation.	Real-time damping adjustment based on sensor inputs and ECU control.	Functional requirements should be linked to the control algorithm and verified across multiple operating states.
Product and function	Subsystems affecting shock absorber performance	No additional control subsystems beyond the hydraulic system of the shock absorber.	Hydraulic, electronic and mechanical subsystems operate concurrently; the ECU communicates with other vehicle systems.	Quality planning should cover cross-domain dependencies and consistency between cooperating subsystems.
Validation	Verification of damping characteristics	Assessment of a single fixed damping curve.	Higher number of functional measurements; analysis of characteristic curves for different current levels supplied to the active valve.	The test burden increases, as does the importance of a consistent validation plan.
Special characteristics	Significant characteristic	min = 28 ; max = 56	min = 30 ; max = 68	This category predominates in both groups; the range is broad and depends on shock absorber architecture and OEM requirements.
Special characteristics	Critical characteristic	min = 0 ; max = 2	min = 0 ; max = 0	Critical characteristics occur rarely; none were identified in the analysed electronically controlled shock absorbers.
Design complexity	Average number of BOM components	103	133	A higher component count broadens the scope of DFMEA and quality planning and increases the number of control points requiring coordination and verification.
Risk	Average RPN value	91	98	RPN is used here as a comparative indicator only; the observed increase does not imply that product complexity directly determines S, O or D ratings.

BOM, the number of significant characteristics, the scope of validation, and, as a supporting indicator, the average RPN values. This approach allows the moving beyond a general product description and showing its complexity at the shock absorber level, which is directly relevant to the further interpretation of D-FMEA results.

The mechatronic product shows higher values for both the number of components and the number of significant characteristics. The average values are 103 components and 42 significant characteristics for the conventional group, and 133 components and 49 significant characteristics for the electronically controlled group. These differences indicate a broader scope of controlled characteristics and a greater burden on the quality planning process, but they should not be interpreted as an automatic increase in risk in every analysed case. In this study, the RPN values were retained solely as a comparative indicator to support the analysis of the two product groups.

The comparison presented in Table 1 shows that the differences between the two analysed product groups concern not only the number of components, but the way the function is performed, the number of interacting subsystems, and the scope of confirming product performance, as well. In the conventional product, the

damping function can be analysed primarily at the component and its direct hydraulic subsystem levels. In the mechatronic product, however, it is necessary to account for the interactions among mechanical, hydraulic, electronic, and control components and subsystems. From the D-FMEA perspective, this means that a broader function description is needed, together with a more developed analysis of relationships between subsystems and a stronger link between the analysis and validation.

The scope of activities used to confirm that the product meets its requirements is also an important factor. A typical validation plan included 25 to 38 tests, supplemented by additional subsystem tests where required. However, in the more complex solutions, not only did the number of tests change, but above all the scope of testing and the way the results were interpreted. In addition, separate tests were required for further subsystems. This means that, at the shock absorber level, product complexity is reflected in the product structure, the scope of functions, the number of parameters requiring control, and the scope of confirmation of compliance with requirements. This provides a direct basis for further analysis of how the preparation and execution of D-FMEA should change as product complexity increases.

Table 2 Selected D-FMEA entries illustrating the evolution of risk interpretation for conventional and mechatronic products

Category of Failure	Failure	Product	S	O	D	RPN	AP	Explanation of Differences
Mechanical Hydraulic	Hydraulic fluid leakage	P_1	6	4	3	72	Medium	Simple design minimizes leakage points and ensures easy detection.
		P_2	8	6	6	288	High	Advanced system critical to rollover control; leakage impacts safety significantly.
Functional	Lack of pressure control in the system	P_1	-	-	-	-	-	Not applicable to products without dynamic pressure control.
		P_2	9	5	6	270	High	Pressure imbalance destabilizes rollover control, reducing vehicle safety.
	Failure to achieve damping targets	P_1	5	3	4	60	Medium	Simple mechanical system limits the causes of damping deviations.
		P_2	7	4	6	168	High	Precision of dynamic damping control may be reduced in specific driving conditions.
Electronic	Disruptions in control system	P_1	-	-	-	-	-	Not applicable to products without electronic components.
		P_2	8	5	6	240	High	The lack of coordination between the pump and ECU disrupts the system's ability to control vehicle roll, reducing stability, can affect safety.
Assembly	Installation difficulties	P_1	5	3	3	45	Medium	Simple design ensures easy installation, with minimal risk of errors.
		P_2	8	6	7	336	High	System complexity (hydraulics, electronics) and space requirements significantly increase risk.

3.3 Selected D-FMEA entries showing the evolution of risk interpretation

The differences presented in Sections 3.1 and 3.2 are directly reflected in the way the selected D-FMEA entries are interpreted. In this subsection, the full D-FMEA analyses for both product groups are not presented; instead, a selected set of entries is used to illustrate the differences in the approach to design risk analysis between the conventional and mechatronic products. The designations P1 and P2 refer, respectively, to the two product types analysed in this article: P1 denotes the conventional product, that is, a shock absorber with a classical mechanical-hydraulic architecture, while P2 denotes the mechatronic product, that is, an electronically controlled shock absorber.

The examples presented in Table 2 show that the evolution of D-FMEA is not limited to increases in ratings for the S, O, and D criteria, but primarily involves changes in the logic of the risk interpretation. In the conventional product, many potential nonconformities can be analysed within a single component and its basic function. In the mechatronic product, the same or similar risk areas gain a broader functional context because they affect the interaction among several subsystems, the control system, and functions that depend on operating conditions. For this reason, Table 2 includes both entries common to both product types and entries not present in the conventional solution but relevant to the mechatronic product. This comparison shows that, as product complexity increases, D-FMEA must cover a broader range of functions, a larger number of relationships, and a more developed interpretation of the effects and causes of nonconformities.

3.4 Proposed approach to D-FMEA adaptation based on increasing product complexity

The proposed model (Figure 2) is termed a model because it does not define a rigid algorithm but instead provides a structured representation of the decision logic by which D-FMEA should be adapted to increasing product complexity. Its purpose is to show how the level of analysis should be selected according to the range of functional impact of a potential product failure, and how this affects the scope of review and update across component, subsystem, and system levels. The basic assumption of the model is that the analysis boundary should not be determined only by the number of components, but by the assessed range of the effects of a given failure mode, that is, whether they remain at the component level, extend to the subsystem level, or affect the function of the whole system [15]. In this approach, increasing product complexity does not mean that each D-FMEA entry must automatically be expanded, but rather that the level of review and the scope of analysis update must be selected more consciously.

The model is based on a three-level logic: component-level, subsystem-level, and system-level reviews. If the impact of a potential failure is limited to a single component, the analysis may remain at the component level. If the effects involve interactions among several components and affect the function of a subsystem, the analysis should be extended to the subsystem level. If, however, the potential failure affects the interaction between subsystems, control functions, or the fulfilment of a system-level function, a system-level review is required. The model, therefore, shows that the scope of D-FMEA should be determined primarily by the propagation of functional impact.

The second important element of the model is the link between the review level and the corresponding scope of D-FMEA review and update. In simpler solutions, the review and update may be limited to a single component and its direct function. In more complex products, however, it becomes necessary to also include the relationships among mechanical, hydraulic, electronic, and control components and subsystems. This means a shift from a local update to an update covering the broader functional context of the product, including the relationships between subsystems.

The model also defines the relationship between the D-FMEA and validation. Validation results do not serve only as confirmation but may also signal the need to extend the analysis from the component level to the subsystem or system level. In practice, this means that in more complex products, the D-FMEA should be updated not only after a component change, but when the function of a subsystem changes, when the interaction between subsystems changes, or when the scope of confirmation of product performance changes, as well. In a PLM-supported digital engineering environment, traceable links among requirements, product structures, D-FMEA records, engineering changes, and validation results can automatically flag potentially affected risks across component, subsystem, and system levels, while the final S, O, D, and AP assessments remain subject to expert evaluation. As a result, the model presents D-FMEA as a structured process, moving from component-level to multi-level analysis, carried out in line with the actual range of potential nonconformity effects.

4 Discussion

The results indicate that, as the product complexity increases, the importance of D-FMEA as a quality planning tool increase, helping structure the analysis throughout the product development process. In the case of the conventional product, many issues can still be considered within a relatively narrow scope, whereas in the mechatronic product, risk analysis requires a broader functional view of the product and consideration of the relationships between cooperating subsystems. From the perspective of industrial practice, this means

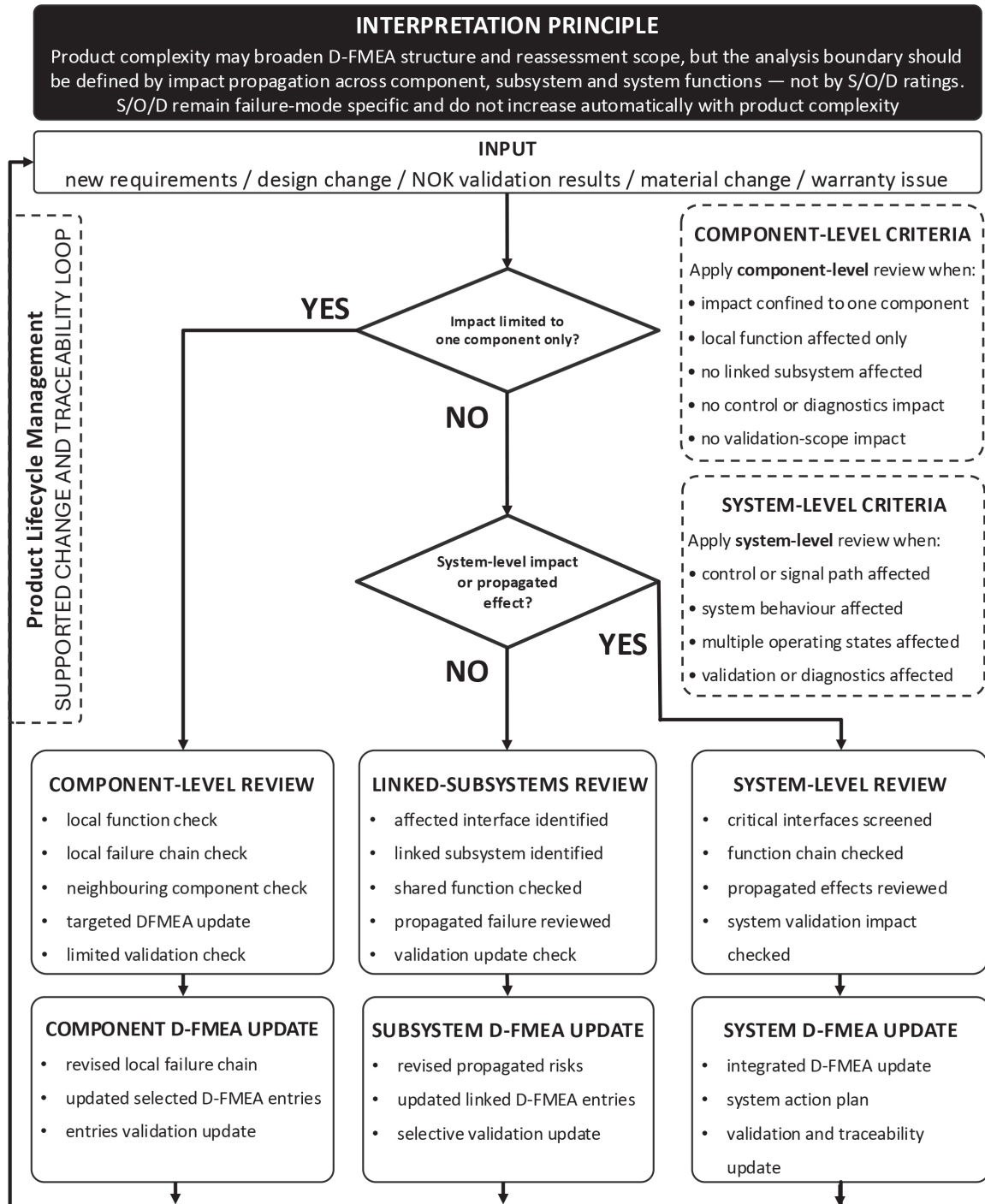


Figure 2 Proposed model for adapting D-FMEA review and update to increasing product complexity

that the usefulness of D-FMEA is determined not by the number of records included in the analysis, but by the consistency of the analysis structure, the correct assignment of functions, and the proper link between the analysis and verification and validation activities.

This interpretation is consistent with the approach presented by Henshall, Campean, and Rutter [16], who indicated that, for complex automotive products, one of the main problems in D-FMEA is maintaining a consistent analysis structure across the hierarchy of system, subsystems, and components, and ensuring

clear links between product functions, dependencies at the boundaries between the subsystems, and verification activities. The authors also emphasised that overly extensive and inconsistent analyses, which combine different levels of detail reduce the usefulness of D-FMEA both for design improvement and for verification planning. These conclusions are reflected in the results of the present study. For the analysed shock absorbers, the difference between the conventional product and the mechatronic product is not limited to a higher number of components, but it requires extending the analysis

to areas arising from subsystem interactions as well. For this reason, the proposed model may be viewed as a practical clarification of how D-FMEA should be developed in the face of increasing product complexity, while remaining consistent with the AIAG & VDA approach.

An additional consequence of increasing the product complexity concerns the composition of the D-FMEA team. For conventional shock absorbers, the core team may be dominated by mechanical and hydraulic expertise, whereas electronically controlled products require systematic participation of specialists in electronics, embedded software, control logic, systems engineering, and validation. The team should therefore evolve not merely by increasing its size, but by aligning its expertise with the interfaces and failure-propagation paths included within the analysis boundary. A stable core team, supplemented by domain experts when subsystem- or system-level effects are reviewed, can improve the completeness of failure chains while maintaining analytical consistency. In this arrangement, the moderator should ensure that assumptions, interfaces, and responsibilities remain traceable across engineering domains [4,16].

It is also important to note that increasing the product complexity should not be interpreted as a direct cause of higher ratings for the S, O, and D criteria. In the presented results, the number of components increased by 29.1%, the number of significant characteristics by 16.7%, and the number of validation activities by 52.0%, whereas the average RPN value changed only slightly, by 7.7%. This means that greater product complexity does not automatically determine a higher risk rating in every case; rather, it changes the conditions for analysis and interpretation. From a practical point of view, the key issue is therefore not only the identification of individual failure modes, but also the proper recognition of functional relationships, which determine how detailed the D-FMEA analysis should be for a given product.

Looking ahead, the increasing dependence of mechatronic suspension systems on embedded software and networked controls suggests that the proposed D-FMEA adaptation model could be complemented by Software FMEA (S-FMEA) and cybersecurity risk assessment. The S-FMEA would address unintended software failure modes related to control algorithms, timing, interfaces, and diagnostics, whereas cybersecurity analysis would consider threat-driven scenarios affecting data integrity, communication availability, or control authority. These analyses should remain methodologically distinct since the software faults and cybersecurity threats arise from different causal mechanisms, but their results should be linked at shared functions and interfaces. Such a coordinated approach could extend the proposed

model towards a more complete assessment of software-intensive automotive products and constitutes a relevant direction for future research [17].

5 Conclusions

The conducted study conclusion is that increasing the product complexity primarily affects how D-FMEA is organised and carried out. The comparison of the conventional product and the mechatronic product showed that, as complexity increases, greater importance is placed on the correct definition of analysis boundaries, the level of analysis development, and the links between function analysis, risk assessment, and validation. This means that, for more complex products, D-FMEA should be developed in a more structured, multi-level manner.

At the same time, the obtained results indicate that product complexity should not be understood as an automatic increase in the values of the S, O, and D criteria. For the analysed products, a higher number of components, significant characteristics, and validation activities did not lead to a proportional increase in RPN risk ratings; rather, they mainly changed the conditions for their analysis and interpretation. Therefore, as product complexity increases, the scope and structure of the D-FMEA analysis change the most, while the ratings remain dependent on the specific failure mode, its effect, the probability of occurrence, and the possibility of detection.

Based on the obtained results, a practical conclusion can be drawn that the effective adaptation of D-FMEA to products of increasing complexity requires consistency across component, subsystem, and system levels, as well as between risk analysis and validation. The proposed model provides a structured view of the differences in the D-FMEA approach for conventional and mechatronic products and may serve as useful support for quality planning and product quality development activities.

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Conflicts of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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