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METHODS OF FUNCTION BASED ENGINEERING OF AUTOMOTIVE SAFETY CRITICAL SEALING SYSTEMS

AUTÓIPARI BIZTONSÁGKRITIKUS TÖMÍTŐRENDSZER FUNKCIÓALAPÚ TERVEZÉSÉNEK MÉRNÖKI MÓDSZERTANAI

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Abstract

The growing use of battery electric vehicles brings new challenges to safety-critical sealing systems, as their reliability becomes increasingly important due to higher functional demands. This article presents engineering methods used to define, analyze, and validate sealing functions and related safety aspects. Tools such as FMEA, FAM, DRBFM, DfR and 8D are introduced through a case study of an ASIL D-classified sealing system. Special focus is placed on function-based design and model-based engineering.

Keywords

DRBFM, sealing system, rubber friction, percolation, safety critical, engineering methods

Absztrakt

A tisztán elektromos hajtású járművek elterjedésével új kihívások jelennek meg a biztonságkritikus tömítőrendszerek tervezésében, mivel megnövekedett funkcionális terhelésük miatt megbízhatóságuk egyre fontosabbá válik. A cikk olyan mérnöki módszertanokat mutat be, amelyek a tömítések funkcionális és biztonsági megfelelőségének meghatározására, elemzésére és igazolására szolgálnak. Az alkalmazott eljárások - mint például az FMEA, a FAM, a DRBFM, a DfR vagy a 8D - egy ASIL D besorolású tömítőrendszer esettanulmányán keresztül kerülnek bemutatásra. Kiemelt figyelmet kap a funkcióalapú tervezés és a modellalapú mérnöki megközelítés.

Kulcsszavak

DRBFM, tömítésrendszer, gumisúrlódás, szivárgás, biztonságkritikus, mérnöki módszertanok

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INTRODUCTION

Nowadays, the demand for battery electric vehicles (*BEV*) is increasing since they are proven to be more environmentally friendly [1], but the pressure is also there due to regulations targeting emission reduction [2]. Despite the many technical and environmental advantages that the *BEV* have over vehicles with internal combustion engines (*ICE*), there are also technical drawbacks. With the better efficiency of the *BEV* drive system, less heat is generated and thus less energy lost to evaporate environmental condensates in the engine compartment providing more favorable conditions for corrosion, therefore, demanding better, more reliable, and more efficient sealing systems for automotive safety critical applications (*steering, braking, etc.*).

Engineering of safety (*functional safety*) of automotive products has been standardized according to ISO 26262 [3]. This standard provides a framework for automotive safety engineering and defines metrics (see **Figure 1**) to determine how *safety-critical* a component is, based on the *severity* of the potential failure it may cause and how easily it can be prevented. The standard also recommends processes to ensure safety and has the following structure, covering a wide range of safety aspects:

- ISO 26262-1: Vocabulary: Defines common terminology by specifying terms such as *fault, error, failure, etc.*
- ISO 26262-2: Management of functional safety: Describes management practices for functional safety at both organizational and project levels throughout the vehicle lifecycle.

Decreased Controllability →

Increased Severity ↓

ASIL (Automotive Safety Integrity Level		Controllability (C)			
Severity (S)	Expopsure (E)	C0 Controllable in General	C1 Simply Controllable	C2 Normally Controllable	C3 Difficult to Control or Uncontrollable
S0 No Injuries	–	QM			
S1 Light and Moderate Injuries	E0 – Unusual	QM			
	E1 – Very Low Probability	QM			
	E2 – Low Probability	QM			
	E3 – Medium Probability	QM			ASIL A
	E0 – High Probability	QM		ASIL A	ASIL B
S2 Severe Injuries, Possibly Life Threatening	E0 – Unusual	QM			
	E1 – Very Low Probability	QM			
	E2 – Low Probability	QM			ASIL A
	E3 – Medium Probability	QM		ASIL A	ASIL B
	E0 – High Probability	QM	ASIL A	ASIL B	ASIL C
S3 Life Threatening or Fatal Injuries	E0 – Unusual	QM			
	E1 – Very Low Probability	QM			ASIL A
	E2 – Low Probability	QM		ASIL A	ASIL B
	E3 – Medium Probability	QM	ASIL A	ASIL B	ASIL C
	E0 – High Probability	QM	ASIL B	ASIL C	ASIL D

1. Figure: Classification of automotive safety levels according to ISO 26262 (QM – Quality Management, ASIL – Automotive Safety Integrity Level) [4]

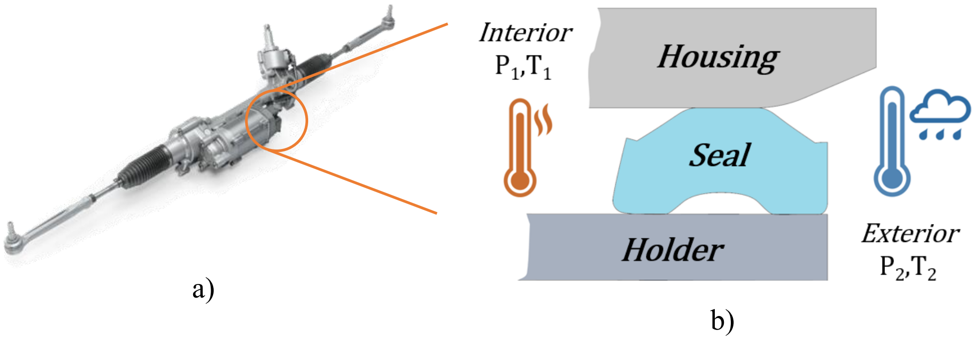
- ISO 26262-3: Concept phase: Covers the concept phase of development, including the identification of hazards and risks (*Hazard Analysis and Risk Assessment – HARA*) and the formulation of the *functional safety concept* with corresponding *safety goals*.
- ISO 26262-4,-5,-6: Product development at the system/hardware/software level: Focuses on the design and development of system/hardware/software by creating the *technical safety concept* (i.e. deriving safety goals into system requirements), also incorporates the safety validation plan.
- ISO 26262-7: Production, Operation, Service, and Decommissioning: Describes functional safety of a product throughout its entire lifecycle.
- ISO 26262-8: Supporting processes: Describes auxiliary processes such as change management, documentation, verification guidelines, and reuse of "*proven-in-use*" system components.
- ISO 26262-9: Automotive safety integrity level (ASIL)-oriented and safety-oriented analysis: Provides guidelines for hazard classification. Recommends assignment of *ASIL*s (*A, B, C, D*) to represent different risk levels, with *ASIL D* being the most critical. A classification of *QM* (*quality management*) indicates that standard quality control is sufficient to ensure the safety of the product (**Figure 1**).
- ISO 26262-10,-11,-12: Guidelines on ISO 26262: An in formative guidance supporting application of the standard with examples and detailed explanations for other application domains, such as motorcycles and semiconductors.

Although ISO 26262 covers a wide range of safety aspects, it addresses safety only at a *higher, abstract* level. Many engineering methods have been developed over the years to identify, control, and assess technical risks at the *design detail level*. Some focus on the early identification of potential *failure modes* from a *functional* perspective (such as *FMEA – Failure Modes and Effects Analysis*)[10], [11] and some mapping the domains where the engineering know-how is limited (*FAM – Focus Area Matrix*) [12].

Other methods focusing on *in-depth* analysis of the physical behavior of *design elements* (such as *DfR – Design for Reliability*) [13] and *synthesis* application of *DRBFM* (*Design Review Based on Failure Mode*)[14] to achieve *safe* and *robust* design.

However, due to the high technical complexity, the large number of design parameters, and the production volumes (introducing statistical variability) associated with an automotive product, the *failure* of some design elements is inevitable. Therefore, engineering methods have been developed to manage and mitigate the *risks* once they occur (*PS – Problem solving*) [15] by swiftly handling complexity and identifying the *technical root cause* as early as possible (*analysis* application of DRBFM).

The main part of this article will introduce the most commonly used of these engineering methods, using an *automotive sealing system* as an example.



2. Figure: Automotive sealing system[5]:
a) Steering gear, the main product b) Sealing system of a steering control unit

The subject *sealing system* is a sub-component of a *steering gear*'s servomotor. The servomotor provides the assist to control the steering torque, i.e. the resistance felt by the driver to turn the steering wheel, see **Figure 2 (a)**. The sealing system of the servomotor includes a *form seal* mounted on a plastic component (referred as the *holder* in **Figure 2. (b)**) which provides the sealing effect between the *holder* and the *housing* as well as seals the interior from the humid, wet external environment.

Due to atmospheric effects, a pressure difference may develop between the interior and the exterior, which can lead to water intrusion in the event of *functional failure* of the seal. A temperature difference may also occur, as the internal parts can be heated by operational losses, while exposed to harsh environmental conditions externally.

This *sealing system* is classified as *ASIL D*, as its potential failure - *specifically, water ingress into the encapsulated electronics causing short circuits* - can lead to a sudden loss of (steering) assist. This may easily result in a traffic accident, as the driver may not have time to respond to the abrupt increase in steering resistance, especially during dynamic maneuvers. To assess the functional performance of such a sealing system in line with the *state-of-the-art*, modern theoretical approaches should be considered, such as *percolation theory* [6], [7].

ENGINEERING METHODS OF AUTOMOTIVE SAFETY AND QUALITY

In this section, the most commonly used methods are introduced using the previously presented sealing system as an example, to better illustrate how these methods are applied in practice.

FMEA - Failure modes and effects analysis

This method was originally developed by the *US Military* [16], later adopted by *NASA* and then by *Ford*, who spread the method in the automotive industry. Today, FMEA is considered as a legal document and is mandatory for all automotive suppliers where the *state-of-the-art* of the relevant engineering domain must be considered during thepreparation.

Function	**Failure mode**	**Potential Impact**	**#SEV**	**Potential Casues**	**#OCC**	**Detection Mode**	**#DET**	**#RPN**
For what the customer pays for?	What has gone wrong	What is the impact on the key output?	How severe is the effect? (1-10)	What causes to go wrong?	How frequently is this likely to occur? (1-10)	What are the existing controls to prevent the failure from occurring or detect it?	How easy is it to detect? (1-10)	Risk priority number (1-1000)
Seal of steering motor	*Water inside the electronics*	*No steering possible*	*9 (loss of assist)*	*Sealing damaged during assembly*	*2 (rarely happens)*	*Monitoring of assembly forces*	*1 (easy to detect)*	*18 (SxOxD)*

1. Table: Basic template of an FMEA with practical example of functional failure of a sealing system (own construction based on [17])

By principle, FMEA maps potential *functional failure modes* at an early stage of development in order to define measures to mitigate the *risk of the failure* as follows (see **Table 1** with example related to sealing functionality):

0.) FMEA is usually *generated* by following the mechanical structure of the product.
1.) Identification of the **function** of the component: *What's the purpose of the component? What is it supposed to do?*
2.) Identification of the **failure mode**: This is usually defined with involvement of *technical experts* of the subject area, as a single function can have *multiple* failure modes: *What could adversely affect the function*?
3.) Estimation of the **impact of the failure**: *What will the customer experience in event of failure?*
4.) **Severity** rating:
    - **1-3**: Insignificant - almost no impact on function.
    - **4-6**: Minor - partial malfunction, limited impact on functionality.
    - **7-8**: Major - high degree of negative impact on function and *customer satisfaction*.
    - **9-10**: Critical - serious impact that may lead to a *safety hazard* and violation of legal regulations.
5.) **Potential causes**: *What could cause the failur*e?
6.) **Occurrence** rating:
    - **1-3**: Rare - almost no chance of occurrence.
    - **4-6**: Low - low probability of occurrence.
    - **7-8**: Likely – failure is likely to occur.
    - **9-10**: Frequent – failure is almost certain to occur.
7.) **Detection** of the occurrence: *What methods can be used to detect the failure?*
8.) **Detection** rating:
    - **1-3**: High – failure can be confidently detected.
    - **4-6**: Moderate - high chance of detection.

- **7-8**: Low – low chance of detection.
- **9-10**: None – failure cannot be detected.

9.) Determination of **Risk Priority Number (RPN):** The *RPN* is calculated by multiplying the ratings of **severity** (4.), **occurrence** (6.), and **detection** (9.).

Based on the risk rating, further measures can be defined, some focusing on improving the detection, while others aim to eliminate the risk by modifying the design.FAM – **Focus area matrix**

A less formal and less commonly used method than FMEA. Also referred to as *Focus Analysis*. Usually prepared with rougher details of the design of the product, on a *high level* (low complexity). Used to *evaluate* the maturity of the *engineering know-how* in a specific domain, or aspect of the product, considering the known and the new engineering *requirements*. See **Table 2.** for an example where sealing system solutions originally applied in vehicles with *internal combustion engine (ICE)* are evaluated for use in *battery electric vehicles (BEV)*.

Requirements		**Form seal** *Low contact length with high contact pressure*	**Liquid seal** *High contact length with low contact pressure*	**Labyrinth seal** *High contact length with no contact pressure*
BEV(new)	*ICE(old)*			
Thermal load *Low*	Thermal load *High*	*Known and quantified ageing behavior*	*Known and quantified ageing behavior*	*Not affected*
Humidity *High*	Humidity *Moderate*	*Moderate performance expected*	*Unknown performance*	*Very poor performance expected*

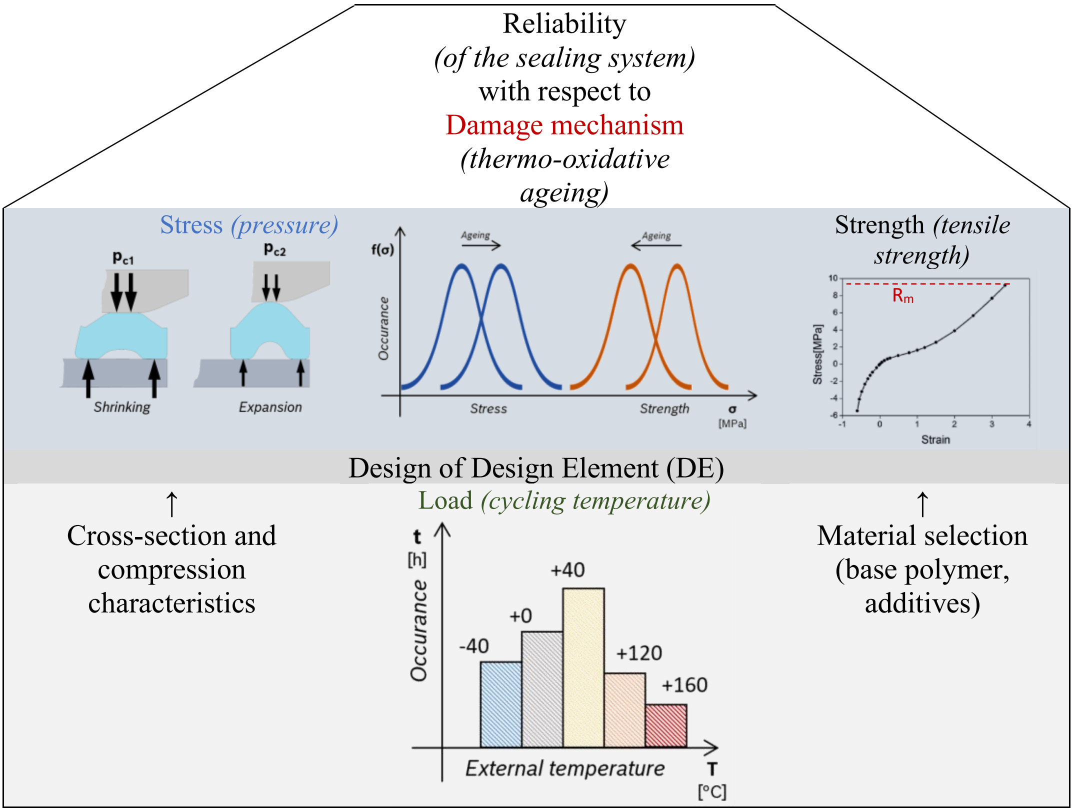
2. Table: Representation of FAM with a practical example of sealing solutions

Based on results of **Table 2,** further engineering tasks can be defined to *quantify* the performance of *liquid seal* (silicone) solution by analyzing percolation [6] of the seal, as well as to asses occurrence of *corrosion*.

DFR – Design for reliability

An engineering method focusing on the details of the design of a specific set of components (*design elements*) using the approach of the *House of Reliability* [18] and the *Five Finger Rule*. It incorporates statistics and a holistic system approach by partitioning the (overall) reliability of that system. The *House of Reliability* (see **Table 3.**) represent the *failure model* (concept) as follows:

- **Load**: sum of external loads acting on the design element *(mechanical, thermal, chemical, etc.). In case of a sealing system, the external temperature variation may induce thermo-oxidative degradation* [19], [20] *and may also generate mechanical loads.*



3. Table: House of reliability – representation of reliability aspects of sealing design element subjected to temperature-driven thermal shrinkage/expansion

- **Stress**: the effect of loads on the design element in relation to the damage mechanism. *In the sealing system example, temperature fluctuations alter the gap into which the seal is assembled (i.e., the available space for the seal), increasing compression forces (stress) within the material. This internal stress is also influenced by the elastic modulus, which itself is affected by thermal degradation.*
- **Strength**: the limiting value of a stress that the *design element* may withstand against the damage mechanism. *Rubber materials typically exhibit a higher degree of variability in material properties. In this case, the tensile strength in their virgin (unaged) state is also affected by aging, as the material becomes brittle over time.*
- **Damage mechanism:** the physical process depending on the duration and intensity of the stress and leads to the degradation of functional characteristic of the design element. *In the case of a sealing system, chemical changes in the material structure - driven by temperature (aging) - cause the material to stiffen. As stiffness increases, so does percolation (i.e., leakage, which is a functional characteristic). Furthermore, for the same level of compression, higher internal stresses develop, increasing the risk of catastrophic failure of the material structure.*

The goal of reliability design is to ensure that the *parameters* of the *design elements* are selected such that the applied stress remains consistently lower than the strength throughout the product's service life, while also fulfilling other *requirements*, such as legal obligations.

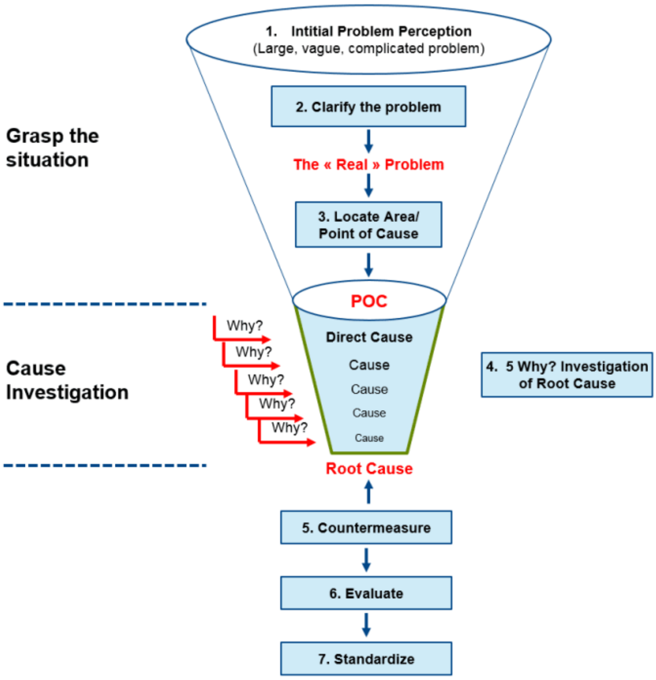
The *Five Finger Rule* is used to define the reliability requirements for the system and *design elements* by considering the following:

- **Functions** as defined in the *FMEA*.
- **Loads**, derived from environmental data and product *specification*.
- **Service time**, as specified by the customer.
- **Reliability targets** of the design elements, as derived through *reliability* partitioning.
- **Failure criteria** defining the conditions that constitute a *functional failure*.

PS – Problem solving

A collection of various engineering methods (*Shainin ,Six Sigma, 8D,etc.*) utilizes a wide range of techniques (*5-Why, Ishikawa, Funnel, etc.*), focusing on handling product failures that occur during development, production, or service [21]. One of the most widely used and well-known methods of automotive sector is the 8D (*Eight Disciplines*), a structured approach, where the problem is defined as a deviation from a defined target caused by an unknown *root cause*. The disciplines are (see **Figure 3.**):

- **D1 - Establish problem solving team**:
  Define a clear list of participants and their responsibilities, including a dedicated team leader and a management sponsor.
- **D2 - Problem definition:**
  Provide a detailed and exact description of the observed deviation, supported by relevant facts and data.
  Example: *During a test production run, a randomized sample was selected from the first batch of seals. In the leakage test, 50% of seals (5 out of 10) showed excessive leakage (Q>30ml/min) when subjected to the pressure of p=5bar at room temperature (23°C) using pure nitrogen (N_2) as test medium.*
- **D3 - Containment action:**
  Define and apply immediate measures to contain the impact of the observed problem and prevent further outflow of defective parts.
  Example: A 100% inspection of seals is performed during production, and any components failing the leakage test are scrapped.
- **D4 - Cause and effect analysis:**
  Identifies the root cause of the problem. There are recommended engineering methods to find the *root cause*, such as *5-Why*, *Ishikawa fishbone diagram.* For complex problems, advanced methods may be required (such as DRBFM).
  Example: Recent percolation theories indicate that the root cause of leakage can be related either to the leakage setup (right setting – pressure difference, right media – viscosity) or to design factors (surface roughness and rubber hardness influencing the percolation channel or contact pressure through geometry and rubber hardness). In this specific case, the supplier had changed certain process parameters of the rubber compound processing, resulting in increased hardness (stiffness) of the seals, which led to excessive leakage.



3. Figure: Lean Problem Solving "The Toyota Way" [21]

- **D5 - Corrective action:**
  Corrective actions must be defined to address both the *Technical Root Cause* (*TRC*) and the *Managerial Root Cause* (*MRC*).
  Example: *In this specific case, the TRC was the change(extension) of curing time of the compound leading to excessive-cross linking of the polymer chains and increased stiffness of the material. The corrective action was to revert the curing time to its original setting. The MRC was that the change can be implemented without detailed analysis of its impact and no hardness measurement were performed on the sealing before shipping.*
- **D6 - Implementation:**
  Implementation and validation of the effectiveness of the corrective actions. *Containment actions* may be withdrawn after successful verification.
  Example: The verification must be done with leakage measurements on the line.
- **D7 - Preventive actions:**
  Define measures to prevent future occurrence of similar problems.
  Example: Implementing in-process hardness measurements can provide early warning that the sealing rubber material may no longer be suitable, helping to prevent leakage-related failures.
- **D8 - Final meeting:**
  Assessment of the problem solving with the participation of all stakeholders.

Nowadays, in many areas of automotive engineering, *Problem Solving* (8D) is a standard practice and typically mandatory in the event of a customer claim. Another often used method in production is *Shainin (Red-X)* [22], which aims to quickly narrow down *the root cause* of the problem.

DRBFM - Design review based on failure mode

DRBFM is one of the many engineering methods of *Toyota Motor Company* [23]. It was developed to analyze and predict the impact of changes (*risk analysis*) in a product (such as *design, material, tolerances, etc.)* through *function* and *model*-based methodology aimed at preventing future failures (*risk management*). As a modern engineering method, it focuses not only on technical details but also on meta-aspects of engineering, such as communication, in order to improve the efficiency of engineering analysis and to consciously managing of complexity.

The method is based on the following principles [24]:

- **GD^3**: *good design* (well understood and robust), *good discussion* (fact-based and goal-oriented), *good design review* (open, well-structured).

4. Figure: A design review meeting as depicted by Toyota Motor Company [23]

- **Transparent engineering**: engineering decisions and assumptions must be clearly stated and made transparent.
  Example: in the case of a sealing assembly analysis using finite-element simulation, many physical parameters must be assumed, such as the coefficient of friction. If an assumed value is treated as a fact, it can become a source of error.
- **Review culture**: every engineer can - *and should* - contribute to the engineering analysis if participation is enabled, regardless of experience or company status. This is made possible through an open, well-structured, clearly visualized, and goal-oriented review process.
- **Mindset**: show openly the gaps of knowledge with the aim to building understanding on the right complexity level using the most suitable approach (*calculation, simulation, measurement*) as required by the project.
- **Quantification**: both the *requirements of a function* and the *functional performance* of the product can - and should - be quantified in order to accurately manage *risks*, using engineering *models* with the right and *transparent* assumptions.

DRBFM-Techniques

The following techniques are often incorporated in a DRBFM analysis:

- "**Zoom-in**": the proper introduction of an engineering analysis, on the right level of *abstraction* and *resolution* (complexity of details) tailoring the relevant information and adapting the content based on the technical background of review participants (*technical experts, project members, management, etc.*).
- **Work package management**: division of the investigation into sub-tasks taking *priority* and *dependency* into account, enabling the *technical* project management of the sub-tasks of the analysis (e.g., the DRBFM) with clear *scope* and *deliverables*.
- **System view**: conscious handling of the scope of analysis considering *cross-effects* and *hierarchical dependencies* within the product.
- **Function-based engineering:** clear separation of the *problem space* (task of the product) and the *solution space* (design of the product or implementation). This principle is one of the cornerstones of the DRBFM methodology.
- **Physics-design connection** (model-based engineering): principle focusing on understanding the meta-connection between the content of engineering *drawing* and *functional performance* of the product. Another fundamental pillar of the DRBFM methodology.
- **Calculation-simulation-measurement** "triangle": a principle focused on selecting the appropriate engineering tool – *calculation, simulation, or measurement* - based on a clear understanding of its capabilities, limitations, and validity, see **Table 4**.

	Calculation *(Analytical model)*	**Simulation** *(Numerical model)*	**Measurement** *(Experiment)*
Engineering effort	Low-Mid	Mid-High	High-Very high
Cost	Low	High	Very high
Temporal effort	Low	High	Very high
Complexity (that could be handled by..)	Low	High	Very high
Validity	General	Specific	Specific
Confidence (in results)	Low-Mid	Mid-High	High

4. *Table: Aspects of engineering toolsets in DRBFM*

- **Cause-effect chain**: the failure mode is understood as a sequence of events leading to deviation in the *implementation* of the *working principle*.
- **Root cause analysis**: quantified analysis of the *failure mode,* using the *working principle* to enable the selection of the most *effective* and/or economically *feasible* measures to ensure *robustness* against the *functional failure*.
- **Complexity handling**: structuring an engineering analysis both *visually* and *meta-visually* - *in drawn, spoken and written form* - with the appropriate level of details

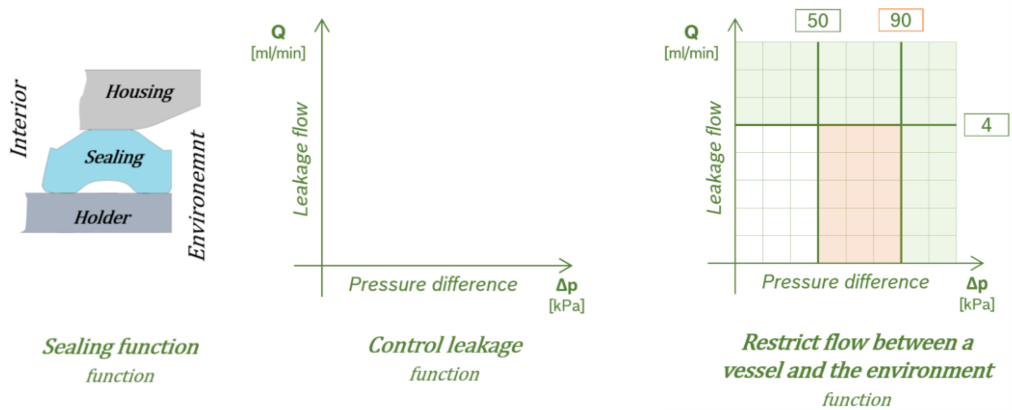
and simplification, adjusted based on the background of review participants (e.g., *experts, managers, etc.*)

Methodical cornerstone of DRBFM : functional definition of a seal

Function-based engineering is one of the most important techniques in the DRBFM methodology, therefore, a more detailed explanation with an example is provided in this section. *Functional* design approach used in automotive engineering aims to clearly separate the *problem space* (*i.e., What problems need to be solved?)* from the *solution space* (*i.e. How are those problems solved?).* This approach enables the *independent* selection of the *working principle (refer to model-based engineering)*, which serves to further distinguish the *solution space* from the *implementation* (*i.e. How it works versus How it is made*).

A definition of a function can be *qualitatively* characterized by how *abstract* and how *complete* its definition is. The appropriate level of abstraction and completeness depends on the engineering intent:

- **Abstract** and **Incomplete:**
  Used when an *impact* or a *risk* requires broad analysis of a poorly known and/or poorly understood system, or when *immediate* engineering (*risk*) assessment is required, see **Figure 5. (a)**,
- **Approximate** and **Partial:**
  Applied during functional system *synthesis* (i.e., *generative* design) to select the *working principle* with the greatest *robustness* (i.e., the least sensitivity to geometrical tolerances and environmental effects), see **Figure 5. (b)**,
- **Exact** and **Complete:**
  Used in functional system *analysis* to *evaluate functional performance* of an existing design, see **Figure 5. (c)**.



a) Abstract and incomplete *b) Approximate and partial* *c) Exact and complete*

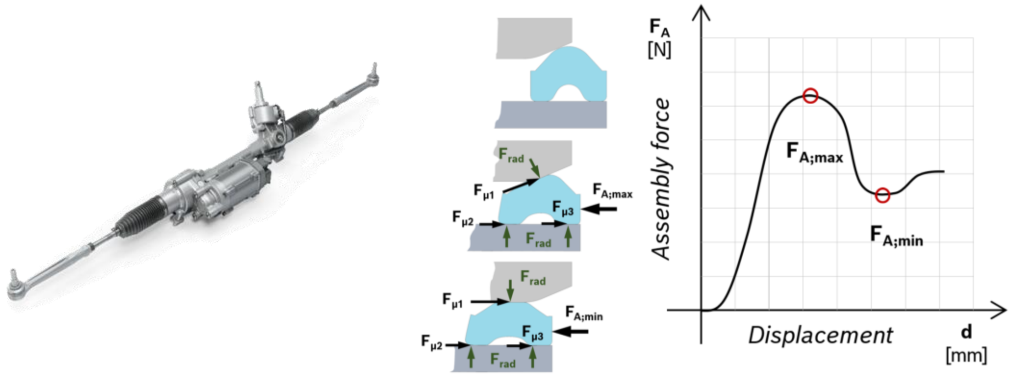
5. Figure: Examples (visual representation) for the functional aspects of automotive sealing

Methodical cornerstone of DRBFM : model-based engineering of a seal

Another cornerstone of the methodology is the model-based engineering, therefore detailed example is also provided – *just as in the case of functions* - to support the better understanding and to provide insight into how it is used in combination with the other cornerstone.

The sealing effect is created by *compressing* a *soft elastomeric* material with an *assumed* smooth surface against a *hard, rough* (often metallic) surface according to [9]. This compressed state can be achieved through various assembly methods, such as *radial type – press-fit* or *axial type – heat shrinking.*

In the following section, a *model-based engineering* approach of *axial* sealing assembly will be presented. For *this* specific example, results from a seal-assembly study previously published by the authors of this article are used, see **Figure 6.** [5].



a) Steering system *b) Assembly process*

6. Figure: Assembly process of an automotive seal [5]

The *geometry* and the *material* of the seal must be selected according to the following conditions of the assembly:

- Due to the parallel assembly process, the sealing must *withstand* a temperature range of $T = 180°C \dots 250°C$. Given the selected material - *ethylene-acrylic elastomer* – which has a known limit to thermal exposure (time of $t = 5s$) the minimum assembly speed can be defined. To reach the target position of $d = 15mm$ within the allowed time, the speed must be $v = \frac{d}{t} = 5\,{}^{mm}/_{s}$
- According to *percolation theory* [7], the fulfillment of the sealing *function* (see **Figure 6.**) requires that the seal exert a minimum of *contact pressure* $p = 1MPa$ with minimal *contact length* $l = 0.6mm$ under all potential operating conditions, defined by the *environmental temperature* range$T = -30°C \dots 100°C$. Due to product design constrains – such as *thermal expansion* and *geometrical tolerances* – the seal must accommodate *variable* gap in the range of $g = 1 \dots 3mm$. These variations directly influence the *radial stiffness* of the sealing. By designing the seal with *non-linear spring characteristics*, it is possible to minimize the *stresses* while still maintaining the sealing performance in *large gaps*.
- Based on geometry defined in (2), further aspects of the assembly can be engineered. Since the seal is deformed from *stress-free* to a *compressed* state with *axial* assembly method (*press-fit*), a chamfer must be applied with standard angle of $\alpha = 20°$, which restricts the *apparent coefficient of friction* $\mu = atan(\alpha) = 0.367$ to avoid self-locking - a *functional failure*.

- An additional requirement arises from the need to detect proper assembly. As established in step (2), it is known that this sealing geometry generates a *normal force* $F_N = 3500 \ldots 800N$. During detection, *the axial force* is measured which must be at least $F_A = 100N$ to confirm the right position of the seal. This imposes a constrain to the minimum *apparent coefficient of friction* to satisfy $\mu = {}^{F_A}/_{F_N} = 0.125$.

From step (2) to (4) it becomes clear that the forces during assembly can be controlled by *controlling the friction* – which itself emerges as a *new function*. It is well known that rubber friction (*friction phenomenon* of the seal assembly) is strongly influenced by multiple factors, including *temperature* [25], sliding *speed* [26], *viscoelastic* behavior of the rubber [27], as well as the structure of the *surface* [28]–[30] demanding accurate description of the *friction phenomena* occurring during the assembly, highlighting the need for more research in this engineering field.

SUMMARY AND CONCLUSIONS

This article gives a practical overview of engineering methods used to evaluate and improve the functional reliability of automotive sealing systems, with a focus on safety-relevant applications. It compares several methodologies and highlights their specific purpose and when they are best applied:

- **FMEA** – Used early in development to define functions and identify potential failure modes, useful for structured risk assessment in known systems.
- **FAM (Focus Area Matrix)** – Applied when the system is not yet fully understood, helps to identify knowledge gaps and critical areas.
- **DRBFM (Design Review Based on Failure Mode)** – Supports detailed design reviews, especially after changes; effective in tracking how modifications affect reliability.
- **DfR (Design for Reliability)** – Applied throughout design phases to ensure robustness.
- **8D** – Used mainly during production or field failures for structured problem solving; focuses on root cause elimination and corrective actions.

The presented methods support structured engineering thinking and help ensure functional safety in sealing applications with increasing performance demands. By selecting and applying the right methodology at the right stage - *whether it's early risk identification, design validation, or problem solving* - reliability can be improved in a focused and traceable way.

REFERENCES

[1] "Electric vehicles from life cycle and circular economy perspectives - TERM 2018," Nov. 22, 2018. https://www.eea.europa.eu/en/analysis/publications/electric-vehicles-from-life-cycle (accessed Feb. 05, 2025).

[2] *Regulation (EU) 2021/1119 of the European Parliament and of the Council of 30 June 2021 establishing the framework for achieving climate neutrality and amending Regulations (EC) No 401/2009 and (EU) 2018/1999 ('European Climate Law')*, vol. 243. 2021. Accessed: Jan. 03, 2024. [Online]. Available: http://data.europa.eu/eli/reg/2021/1119/oj/eng

[3] "ISO 26262-1:2018(en), Road vehicles — Functional safety — Part 1: Vocabulary."

[4] "What is ISO 26262? Automotive Electronics Safety," *Arrow.com*. https://www.arrow.com/en/research-and-events/articles/understanding-iso-26262 (accessed Feb. 05, 2025).

[5] Sári-Barnácz V. and Goda T. J., "Indirekt hiperelasztikus anyagmodell identifikáció autóipari gyártósor tömítésszerelési adatainak felhasználásával," *Gép*, vol. 75, no. 3–4, pp. 91–96, 2024, doi: 10.70750/GEP.2024.3-4.20.

[6] B. N. J. Persson, O. Albohr, U. Tartaglino, A. I. Volokitin, and E. Tosatti, "On the nature of surface roughness with application to contact mechanics, sealing, rubber friction and adhesion," *J. Phys. Condens. Matter*, vol. 17, no. 1, pp. R1–R62, Jan. 2005, doi: 10.1088/0953-8984/17/1/R01.

[7] B. N. J. Persson and C. Yang, "Theory of the leak-rate of seals," *J. Phys. Condens. Matter*, vol. 20, no. 31, p. 315011, Aug. 2008, doi: 10.1088/0953-8984/20/31/315011.

[8] B. Lorenz and B. N. J. Persson, "Leak-rate of seals: effective medium theory and comparison with experiment." arXiv, Nov. 16, 2009. doi: 10.48550/arXiv.0911.3019.

[9] B. Lorenz and B. N. J. Persson, "Leak rate of seals: Comparison of theory with experiment," *Europhys. Lett.*, vol. 86, no. 4, p. 44006, Jun. 2009, doi: 10.1209/0295-5075/86/44006.

[10] "The Basics of FMEA," *Routledge & CRC Press*. https://www.routledge.com/The-Basics-of-FMEA/Mikulak-McDermott-Beauregard/p/book/9781563273773 (accessed Jan. 07, 2025).

[11] A. Webmaster, "Details." https://www.aiag.org/store/publications/details?ProductCode=FMEAAV-1 (accessed Jan. 07, 2025).

[12] "The Design of Focus Area Maturity Models," *ResearchGate*. https://www.researchgate.net/publication/221581365_The_Design_of_Focus_Area_Maturity_Models (accessed Jan. 07, 2025).

[13] "Design for Reliability - 1st Edition - Jerry C. Whitaker - Dana Crowe." https://www.routledge.com/Design-for-Reliability/Crowe-Feinberg/p/book/9780849311116 (accessed Jan. 07, 2025).

[14] "Introduction to Design Review Based on Failure Modes (DRBFM) Web Course RePlay - SAE Training." https://www.sae.org/learn/content/pd331047on/ (accessed Jan. 07, 2025).

[15] "Download for free - 8D Problem Solving for Automotive Engineer e-book," *Automotive Quality Solutions*. https://www.automotivequal.com/free-quality-ebooks-8d-problem-solving-for-automotive-engineer/ (accessed Jan. 07, 2025).

[16] "MIL-STD-1629 A PROCEDURES PERFORMING A FAILURE MODE." http://everyspec.com/MIL-STD/MIL-STD-1600-1699/MIL_STD_1629A_1556/ (accessed Jan. 08, 2025).

[17] G. Forrest, "FMEA (Failure Mode and Effects Analysis): A Quick Guide to Minimizing Defects and Faults in Your Projects," *isixsigma.com*, Sep. 23, 2024. https://www.isixsigma.com/fmea/fmea-quick-guide/ (accessed Jan. 07, 2025).
[18] M. Braglia, G. Fantoni, and M. Frosolini, "The house of reliability," *Int. J. Qual. Reliab. Manag.*, vol. 24, no. 4, pp. 420–440, Jan. 2007, doi: 10.1108/02656710710740572.
[19] J. DUARTE and M. ACHENBACH, "On the modelling of rubber ageing and performance changes in rubbery components," *Model. Rubber Ageing Perform. Chang. Rubbery Compon.*, vol. 60, no. 4, pp. 172–175, 2007.
[20] A. Plota and A. Masek, "Lifetime Prediction Methods for Degradable Polymeric Materials—A Short Review," *Materials*, vol. 13, no. 20, Art. no. 20, Jan. 2020, doi: 10.3390/ma13204507.
[21] P. B.-M.-C. Manager @fabriq, "Lean problem solving tools and methods," *Fabriq*, Sep. 06, 2024. https://fabriq.tech/en/2024/09/06/lean-problem-solving-tools-and-methods/ (accessed Mar. 10, 2025).
[22] "Red X Problem Solving | Solve Complex Problems Fast," *Shainin LLC*. https://shainin.com/red-x/ (accessed Mar. 10, 2025).
[23] "TOYOTA MOTOR CORPORATION GLOBAL WEBSITE | 75 Years of TOYOTA | Research and Development Support | Improvements to the Engineering Planning and Development Process." https://www.toyota-global.com/company/history_of_toyota/75years/data/automotive_business/products_technology/research/engineering_planning/details.html (accessed Mar. 19, 2025).
[24] H. Shimizu, Y. Otsuka, and H. Noguchi, "Design review based on failure mode to visualise reliability problems in the development stage of mechanical products," *Int. J. Veh. Des.*, vol. 53, no. 3, p. 149, 2010, doi: 10.1504/IJVD.2010.033827.
[25] K. A. Grosch, "The Relation between the Friction and Visco-Elastic Properties of Rubber," *Proc. R. Soc. Lond. Ser. A*, vol. 274, pp. 21–39, Jun. 1963, doi: 10.1098/rspa.1963.0112.
[26] A. Schallamach, "A theory of dynamic rubber friction," *Wear*, vol. 6, no. 5, pp. 375–382, Sep. 1963, doi: 10.1016/0043-1648(63)90206-0.
[27] K. C. Ludema and D. Tabor, "The friction and visco-elastic properties of polymeric solids," *Wear*, vol. 9, no. 5, pp. 329–348, Sep. 1966, doi: 10.1016/0043-1648(66)90018-4.
[28] B. N. J. Persson, "Theory of rubber friction and contact mechanics," *J. Chem. Phys.*, vol. 115, no. 8, pp. 3840–3861, Aug. 2001.
[29] J. A. Greenwood and J. H. Tripp, "The Contact of Two Nominally Flat Rough Surfaces," *Proc. Inst. Mech. Eng.*, vol. 185, no. 1, pp. 625–633, Jun. 1970, doi: 10.1243/PIME_PROC_1970_185_069_02.
[30] M. Ciavarella, "A simplified version of Persson's multiscale theory for rubber friction due to viscoelastic losses." arXiv, Jan. 13, 2017. doi: 10.48550/arXiv.1701.03810.

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